2. Overview

2.1 Objectives

In view of the scale of the project, it was understood from the start that the conceptual design had to reach a level of technical maturity higher than usual for such a phase. For this reason, issues of feasibility of at least the principal subsystem were given high priority during the study.

The main goals of the Conceptual Design phase were the following:

- To develop a design for a 100m telescope based on scientific requirements
- To explore technical solutions leading to a minimization of cost
- To identify items requiring extensive R&D
- To validate the feasibility of the chosen solutions through analysis, tests and/or dedicated industrial studies
- To include in the design safety, maintenance and operations considerations that would contain the eventual operating costs
- To assess the feasibility of appropriate astronomical instrumentation
- To develop realistic schedule and cost estimates
- To identify the main risks of the chosen approach

This book describes the work done at ESO to achieve these goals.

It is to be reviewed by a panel of international experts, including some of the outstanding members of the telescope-design community whose arguments and criticism will greatly assist in the evolution of ESO's ELT effort.

It is also an occasion to document ESO's conceptual design work and to make it available to the community, to seek their feedback. To this end, the first day of the Review will be an Open Day of presentations with ample discussion time, to which anybody interested can participate. We plan to make this report widely available after the Review, although some parts containing confidential information from Industry will have to be omitted. Topical meetings on specific aspects of the design are also foreseen in 2006 in order to invite community help in shaping the next phase of the design.

The main objectives of the Review are the following:

- Assess the OWL approach, its strengths and weaknesses
- Analyze feasibility issues
- Evaluate cost and schedule estimates

- Identify the principal risks of the project
- Identify areas to be further explored
- Assess whether it is appropriate and desirable to move to the Preliminary Design phase, with the goals to:
    - Reassess the design parameters and solutions
    - Incorporate results from the European Commission sponsored ELT design Study
    - Explore other/better technical solutions
    - Produce a Preliminary Design of a viable/affordable ELT, to undergo PD Review within the next three years.
- Advise ESO about possible future courses of action.

A note on Instrumentation

Although preliminary reports of the instrumental conceptual studies under way by the Community and ESO are presented, these are not meant to be reviewed at the same in-depth level as the telescope design. The reasons are the following:

- These studies have started only recently (consolidation of the optical and mechanical design as well as of the science cases having been a prerequisite for the studies)
- The main aim of these studies is to assess the feasibility of instrumentation able to carry out the critical science goals and to feed back requirements to the telescope design if necessary
- The final design of the telescope (size, optics, mechanics) may change in Phase B and therefore the interfaces and parameters used are only indicative at this stage. A coherent instrumentation plan with the instrument priorities will be prepared during Phase B.

2.2 Scientific potential of a 100-m class telescope

State of the art optical and infrared astronomy over the last decade or so was driven by the current generation of 8 to 10m class telescopes, which produced a large fraction of all new discoveries. The vast improvement in sensitivity and precision allowed by the next step in technological capabilities, from today's telescopes to the new generation of 50-100m telescopes with integrated adaptive optics capability, will be the largest such enhancement in the history of telescopic astronomy. It is likely that the major scientific impact of OWL will be discoveries we cannot predict, so that its scientific legacy will also vastly exceed even that bounty which we can predict today.

Nevertheless, for the planning of such a powerful new facility, science drivers based on today's knowledge have to be considered. The science case for OWL is truly breathtaking. All aspects of astronomy, from studies of our own solar system to the furthest observable objects at the edge of the visible universe, will be dramatically advanced by the enormous improvements attainable in collecting area and angular resolution: major new classes of astronomical objects will become accessible to observation for the first time. Other objects, which we can either only barely detect or whose existence we can only indirectly infer today, will be accessible for detailed studies. Our understanding of the universe near and far will either be challenged or confirmed. A thorough review of the science driver for an ELT has been outlined in the Science Book produced by the OPTICON working group on ELT science. That book contains numerous specific science projects to be carried out with ELTs. It also contains three highlight science goals which have been used as reference for the design goals. These goals are summarized in Chapter 3. Here, we briefly review some of the topics where OWL will provide new insights.

Terrestrial planets in extra-solar systems.

Detection of exo-planets has become routine in only a few years. The field will now move on to identify planetary systems and their characterisation. Are their patterns of planet masses, orbits, structure and other properties with their parent stars? What can be learned about the formation mechanism and their evolution in different planetary systems? How do massive planets influence the formation (or destruction) of smaller planets? How does a binary companion star affect the formation of planets? These questions can be addressed by statistical samples of planetary systems. The larger the sample the better. An OWL-type telescope has access to this parameter space, which is largely excluded for smaller telescopes. The ultimate goal is, of course, the detection of earth-like planets in the habitable zone. The role of Jupiter to ‘protect' the inner solar system from comets and hence as a warranty for long periods without major impacts has long been recognised. The existence of a similar guardian planet can be assumed to be needed for life on another planet. The characterisation of exo-planetary systems is the next step towards exo-Earths.

A pre-requisite for life as we know it is water in liquid form. The places in a stellar system where water can exist is the habitable zone around the star, the size of which depends on the luminosity of the star. The search for planets within that narrow annulus around a star requires both extreme light gathering power to detect the faint planet and extreme telescope size to separate the planet from the bright star light. The challenge is to observe an object that is about 10^{10} times fainter than its parent star. Not all stars have planets and few will have planets in the habitable zone, so the largest possible sample of stars has to be surveyed to increase the likelihood of detecting planets on which life could exist. The required telescope for this kind of observations needs to be truly extremely large: the number of stars that can be studied is proportional to the spatial resolution to the cube (or to D^3, with D the telescope diameter). The time for different telescopes to achieve the same signal to noise in the background-dominated regime is proportional to D^4. A 100m telescope can in principle detect an earth-like planet around a solar-type star out to a distance of 100 light years, which means that there are about 500 stars of this type to be surveyed. Key to the achievement of this challenging goal is the light gathering that will allow improving the contrast between planet and star through the detection of in situ spectroscopic features. As a huge bonus, it would then be possible to characterize planetary surfaces and atmospheres. The search for biomarkers in the planet atmosphere has the potential to provide first indications of extraterrestrial life. It is clear that larger planets and planets with larger separation from their star would easily be detected by a 100m telescope and open up the field of planet demographics down to low-mass planets. Such statistics will provide the clues for the detailed understanding of the formation of stars and their planetary systems; for example which stars have planets, what is required to form planets, what is the chemical composition of the parent stars and are there planets around special stars (e.g. white dwarfs, very old halo stars). As an added bonus, targets for future space missions (and viceversa) will also be provided, fully exploiting the synergy between ground and space. The quest for high contrast imaging sets stringent requirements on the development of adaptive optics. Various methods are under investigation, e.g. coronagraphy, nulling interferometry, extreme Adaptive Optics, simultaneous differential imaging (SDI), and have already shown promises of high contrast (e.g. NACO/SDI at the VLT has achieved ~ $5{\cdot}10^4$).

Dark matter and dark energy.

Observations from space and ground imply that dark matter exists on the scale of galaxies and beyond, and that dark energy is pervading the universe. Particle physics has been unable to date to identify the dark matter particles and evidence for their existence as well as clues about their nature are still coming solely from astrophysics. It is interesting in this context that constraints set by astronomy on the mass of the neutrino are as stringent as the best upper limits from experiment. Similarly, through a detailed study of the growth of structure in the universe, it should be possible to derive further constraints on properties of dark matter.

Key constraints on the nature of the dark matter will come from observations of the assembly of galaxies at high redshift. OWL will not only resolve the distant galaxies into their luminous components, but will also be able to obtain spectroscopy for individual components which will then be used to trace the kinematics within the galaxies (and in their extended dark-matter haloes) and determine the amount of dark matter required to build them. These observations will provide mass measurements of galaxies independently of the brightness of the galaxies. OWL will be able to observe regular HII regions to very high redshifts (z ~ 5), and will be able to map the dark matter content of individual galaxies throughout the observable universe. This will provide astronomers with a detailed evolutionary history of the clumping of dark matter throughout the observable universe.

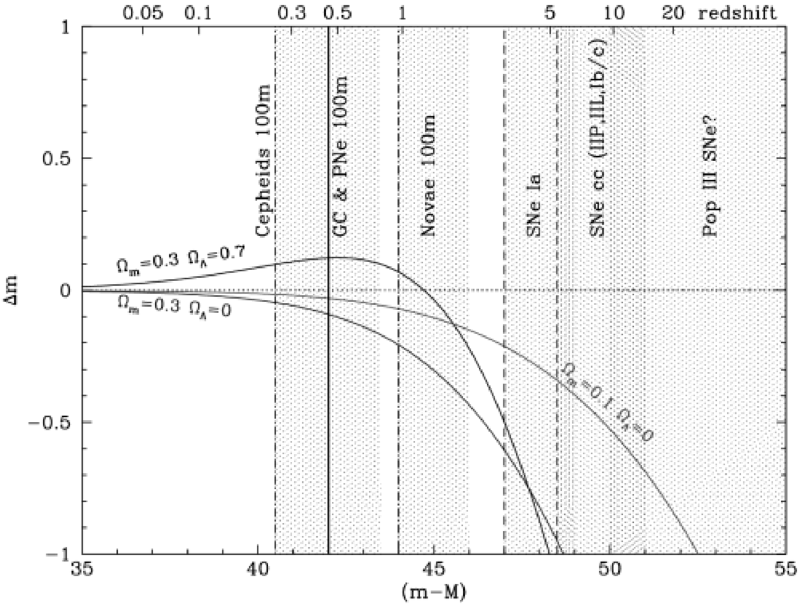

Figure 2-1. Using primary distance indicators to disentangle cosmological models. The plot shows the apparent magnitude difference relative to an empty universe of several cosmological models as a function of redshift. Regions of application for various methods of distance estimates with OWL are indicated.

The nature of dark energy is even more mysterious. Evidence for dark energy comes from observations of supernovae, which serve as standard candles to map the distance of objects as a function of redshift. Such observations shows that SNe at $z < 1$ appear fainter and therefore more distant than expected in an empty universe without dark energy, while those at $z > 1$ appear brighter and therefore closer. This is illustrated in Figure 2-1. The interpretation of these observations is that dark energy exerts a negative pressure and hence accelerates the universal expansion. The combination of the SN results with measurement of fluctuations in the cosmic microwave leads to the conclusion that about two thirds of the global energy comes from this dark (or vacuum) component. OWL can test the expansion history of the universe with several different astrophysical objects thus decreasing the dependency on possibly unknown systematic effects. Pulsating Cepheids, globular clusters, planetary nebulae and novae could be observed to distances where the effect of dark energy can be measured (Figure 2-1).

The differences between the cosmic expansion rate in different cosmological models increases strongly as a function of redshift. A 100m ELT will be able to detect supernovae possibly all the way to the time when the universe became transparent to light. By accurately determining the potential variations of the strength of dark energy in early times, one can answer the fundamental question of whether dark energy corresponds to Einstein’s cosmological constant or to some “quintessence field” as suggested by modern versions of quantum field theories. The need for these observations is critical. In the words of the Astronomer Royal, Sir Martin Rees, “Cosmologists can now proclaim with confidence (but with some surprise too) that in round numbers, our universe consists of 5% baryons, 25% dark matter, and 70% dark energy. It is indeed embarrassing that 95% of the universe is unaccounted for: even the dark matter is of quite uncertain nature, and the dark energy is a complete mystery”

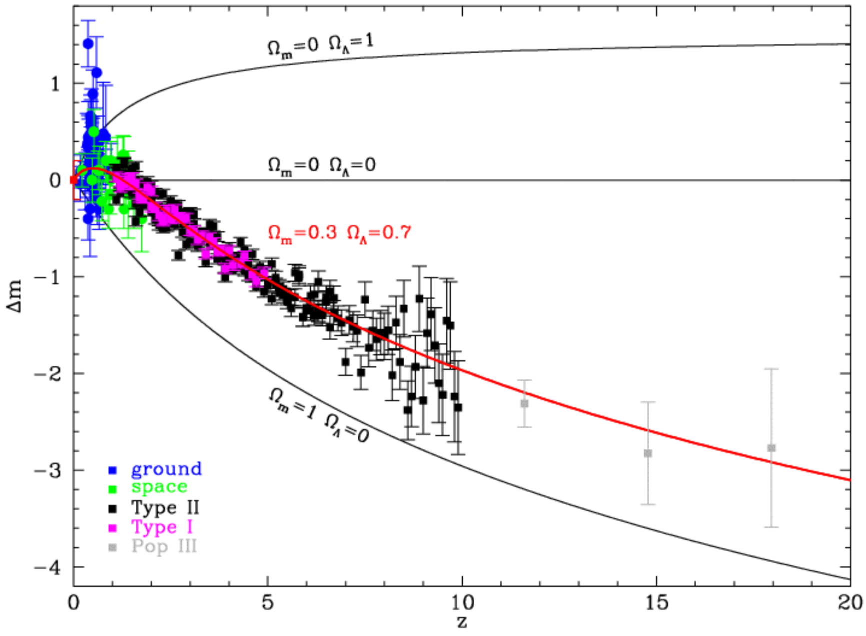

Figure 2-2 Simulation of observations of Supernovae with OWL.The current data from ground and space observations are shown. These observations will allow to determine the cosmic SN rate, and help disentagle cosmological models (e.g. whether a "quintessence field" or a "phantom energy" exist).

High redshift Supernovae

The detection and study of SNe is important for at least two reasons: (1) their use as *calibrated* standard candles provides a direct measurement of the expansion rate of the Universe *H(z)*, and allows to measure its acceleration/deceleration and to determin the exact epoch in which the universe experimented the transition between deceleration and acceleration; and (2) the evolution of the cosmic SN rate provides a direct measurement of the cosmic star formation rate (SFR). Indeed the rate of core-collapse SN explosions is a direct measurement of the death of stars with masses > 8 M⊙ while type Ia SNe provide the history of star formation of moderate mass stars, 3 - 8 M⊙. Simulations of observations carried out with OWL, which fully exploit the potential of diffraction limited observations in a 2×2 arc minute field in the K band, yield about 400 SNe (in about ~1000 hours of observing time), which can studied up to *z*~15. OWL would open also the possibility of detecting the very powerful SNe from the primordial stellar population (or Pop III) that are expected to be produced by pair-creation in zero-metallicity, very massive stars (140-260 M⊙). Figure 2-2 shows the result of the simulation, which includes the expected measurement errors and the cosmic variance in the SN brightness (i.e. the variability in absolute luminosity of individual SNe). Present day data from ground and space observations are also shown.

Direct measurement of the cosmic acceleration/deceleration.

Enormous collecting areas together with extreme instrumental stability also open the very exciting prospect of measuring the early deceleration of the universe in a direct way. The results mentioned above indicate that our universe has undergone a phase of acceleration following one of deceleration. So far most of the results in this area have come from measurements of the geometry of the universe, which do not directly probe the acceleration. A direct measurement of the acceleration itself has always been considered impossible with the present generation of telescopes. However, with a sufficient flux of photons, and with a spectrograph stability of the order of 1 cm s^{-1} over 10 years, changes in the recession velocity of absorption lines in the Lyman-α forest of bright quasars out to z ~ 5 can be detected. This would allow a real physics experiment to be carried out with OWL, whose results would be unequivocal, model-independent and assumptions-free. A stability of a few cm s^{-1} is challenging but has already been achieved with e.g. the HARPS instrument at the ESO 3.6m telescope. Development is needed to maintain this stability over a long period of time.

Resolved stellar populations

One of the important goals of OWL is to measure individual stars in all morphological types of galaxies. First HST and now the current 8-10m telescopes have opened this research field for galaxies in the Local Group and the brightest stars in other nearby galaxies. Spectroscopy with the ground-based telescopes is limited to the most luminous stars in the Local Group. This means that we still need to extrapolate our detailed understanding of stars in even the local Universe from what we know about stars in our Milky Way. OWL will make stars in galaxies out to the Virgo and Fornax clusters accessible. In particular, it would provide for the first time the opportunity to observe stars in elliptical galaxies (Centaurus A, Sculptor Group, Leo I Group and others at distances less than Virgo). The history of stars in dwarf, normal and elliptical galaxies are certainly different and we will not have a complete picture of stellar evolution until we understand the histories of stars in different galaxies.

Need for a proper instrumentation package

Defining and validating solid concepts for a comprehensive instrumentation package that has the potential to address the major science drivers of the proposed facility is an essential part of the feasibility assessment of any ELT project. Conceptual studies for OWL instrumentation started only a year ago, as the development of the project provided a first definition of the essential interfaces between the instruments and the telescope. These 7 studies, typically one-year long, are being conducted in many Institutes across Europe and their status and results are summarized in chapter 12. They cover a very large fraction of the parameter space, from the Visible to the sub-mm range and from imaging to high-resolution spectroscopy. The key science drivers of exo-planets detection and characterization and of follow-up of the very high-z Universe are addressed. This short program is considered as the first step to the more elaborate point design studies very soon pursued in the frame of the ELT Design Study and described in apprendix A-1.8.

It should be noted that instrumental activities relevant to OWL (or any other ELT) instrumentation actually started some years ago, albeit in a more diffuse way. The now 18-month old OPTICON FP6 program supports the development of a number of “1st generation” key components especially in the areas of adaptive optics (wavefront sensors, deformable mirrors, real-time computing), smart optics (cryogenic slicers, moving cryogenic buttons) and dispersers (cryogenic near-IR Phase gratings). Also some of the 2nd generation VLT instruments, currently under development, are actually exploring ELT instrumentation enabling concepts: the KMOS multi-object near-IR spectrometer uses cryogenic arms with slicers; MUSE is based on a large set of 24 strictly identical spectrometers; the recently completed Planet Finder feasibility study has investigated many important approaches to exoplanet searches including advance coronagraphy and differential imaging/spectroscopy.

2.3 Context

The decade 2010-2020 will see the maturity of the current generation of telescopes (VLT, Keck, Gemini, Subaru, LBT, GTC, HET, SALT, Magellan etc) equipped with a second generation of instruments often performing at the diffraction limit through advanced Adaptive Optics (AO) systems. Interferometry will have come out of its infancy to operate in the faint object regime (K~20) and to produce astrometric results in the µas range. ALMA will provide mm and sub-mm astronomers with a facility “equivalent” to optical ones (both in terms of service offered to the community and of resolution and sensitivity). And a new generation of ground based optical/NIR 30 to 100m telescopes now on the drawing board (TMT, GMT, Euro-50, OWL etc) may open a completely new window on the Universe and produce unprecedented results (with resolution ~ mas and sensitivity hundreds or even thousands of times beyond what is available today).

Evolution of existing facilities: Adaptive Optics. AO, now in its “adolescence”, will soon outgrow the current limitations (single natural (N) or laser (L) guide star (GS), limited field of view, small sky coverage) through the development of Multi-Conjugated AO (or other forms of atmospheric tomography). MCAO uses multiple NGS/LGS systems to provide a wider corrected field of view, and is now being developed at several existing observatories: for example, Gemini is building an MCAO system for its instrumentation. ESO is building MAD (McAo Demonstrator) to see first light at the VLT in early 2006 as an enabling experiment for the new VLT instruments and for OWL. An optimal implementation of AO is considered of outmost importance. Thus in Phase B telescope and instrument designs have to be iterated – taking into account the latest results from prototype experiments and advanced atmospheric modeling - to ensure the highest possible scientific return on investment.

Evolution of existing facilities: Second generation instruments. Among the second generation instrumentation considered by ESO (but similar ones are under study at many other observatories) are a multi micro-mirror, distributed classical AO system instrument (FALCON) to study in detail many individual objects in the telescope's FoV at the same time; AO-fed planet finders using nulling interferometry coronagraphs; NIR multiobject wide-field spectro-imagers; image slicer-based multi integral field spectrographs; very wide wavelength coverage “fast” shooters, able to do simultaneous spectroscopy from 0.3 to 3µm. The underlying philosophy is one of sampling the instrumentation parameter space (wavelength, resolution, FoV, image quality, multiplex, synergy with other space or ground facilities, etc) based on clear science requirements.

Evolution of existing facilities: Interferometry. Both Keck-I and VLTI have achieved fringes in 2001. VLTI, both with auxiliary 1.8m telescopes and with the VLT 8m telescopes, is currently in continuous science operations with its instruments MIDI and AMBER. It will soon evolve towards imaging, both with the present generation of instruments (e.g. AMBER, which has already demonstrated 3-telescope measurements of phase closure) and with PRIMA (Phase Referenced IMAging, a dual feed facility providing stabilization of the fringes of a faint object by tracking the fringes of a bright reference star within one arcminute). These instruments will be used to image planetary systems, the inner regions of AGNs, and objects as faint as K~20. It will also provide astrometric measurements down to a few µas, thus enabling the possibility of direct detection of extrasolar planets and their orbits.

ALMA. The Atacama Large Millimeter Array, an example of major project collaboration between Europe and the US, is a variable configuration array of 50 12m antennas working in the 0.3 to 10 mm wavelength range to be put at 5000m in Chajnantor in the Desert of Atacama. ALMA is a 50/50 partnership, with ESO managing the European side and AUI the American side. It will have high angular resolution (to below 0.01" with baseline >10 km) and high sensitivity (area ~ 5,600m^2). ALMA will be able to study galaxy formation in the very early Universe, resolve the far infrared background in its wavelength range, study star formation deep in dark clouds, search for protostars, analyze star and planet formation processes, and study the bodies of our solar system. The project is in its Phase 2 (construction, 2005-2012), and is scheduled to start interim operations with a reduced number of antennas as early as 2009.

Space missions. JWST, XEUS, TPF/Darwin precursor missions and others will explore the heavens from above the atmosphere, exploiting the freedom from turbulence, sky absorption and sky background. In view of the possibilities opened by adaptive optics, the optical/NIR capabilities of a “small” (5 to 10m) telescope in space may not be always competitive with those of 30 to 100m telescopes on the ground. It is not inconceivable that 10 years from now it may make more sense to go to space only for those wavelengths for which the advantage is overwhelming (x-ray, UV, thermal IR etc, which is the case of the projects mentioned above), leaving the optical and NIR to adaptive ground based telescopes that for similar costs could provide much higher angular resolution and sensitivity (but probably not as large field of view). It is not premature to consider such a possibility, even acknowledging how much it depends on very demanding developments in adaptive optics. However, in the long term, the cost of putting matter into orbit may be substantially less than today: in this case, not having to contend with air and gravity may become attractive enough that we consider moving *all* our telescopes to space. This is probably a choice for the generation of telescopes after the next.

2.4 The OWL concept

Over the last few years several design studies are being carried out of the telescopes the astronomers believe they will need in the 2010s. They range between 20 and 100 meter in diameter and, to a more or less critical extent, they all try to break one or both of the traditional laws of the art of telescope making: the *cost law* ($\propto D^{2.6}$) and the *growth law* (the next generation telescope is twice as large as, and ~ 35 years after, the previous one). The rationale for having larger than two increases in diameter comes from the science cases; the one for reducing costs to “reasonable” totals is the goal of achieving the required funding.

2.4.1 The history of telescope growth.

Figure 2-3 shows the history of the telescope diameter, with a few future telescopes (TMT and OWL) added for reference. There are two aspects that are immediately evident: (1) “local” scatter notwithstanding, the trend of diameter increase has remained substantially constant since Galileo (doubling every 50 years or so) and (2) the *quantum jump* between a 10 and a 100m telescope is similar to that between the night-adapted naked eye and the first telescope, which certainly bodes well for the potential for new discoveries. During the 20th century there has been some acceleration, with the doubling happening every ~35 years, (see e.g. the “California progression” with the Hooker [2.5m, 1917], Hale [5m, 1948], and Keck [10m, 1992] telescopes).

One point that perhaps is not immediately evident, though, is that in the last 50 years there has been a larger increase in telescope sensitivity due to improvements in detectors than to increases in diameter (Figure 2-4). Now that detectors are at efficiencies close to 100%, *large improvements can be obtained only through large increases in diameter*. For example, at the times of photographic plates, with efficiency of a few percent, even the 5-meter Hale telescope was only equivalent to a 1-meter “perfect” telescope (i.e. one with 100% efficiency).

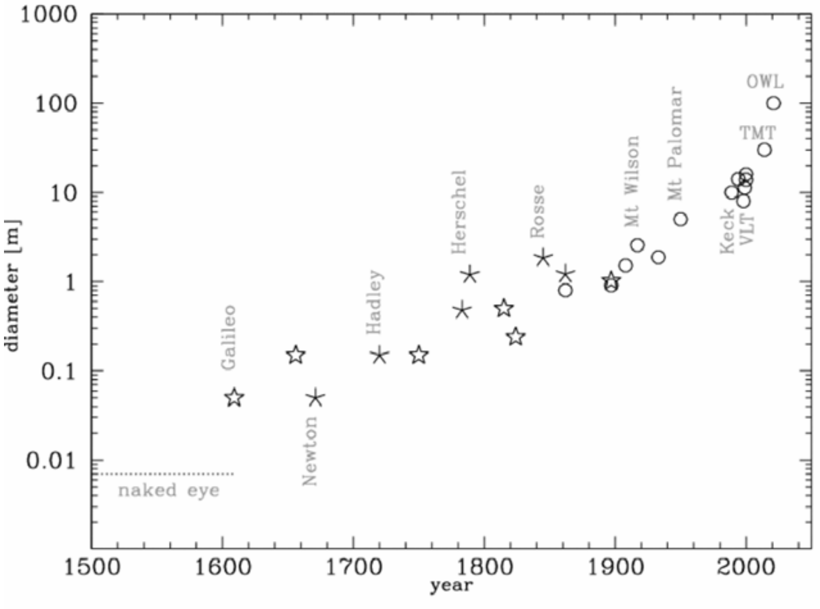

Figure 2-3 Brief history of the telescope. Stars are refractors, asterisks are speculum reflectors and circles are glass reflectors. Some specific telescopes are named.

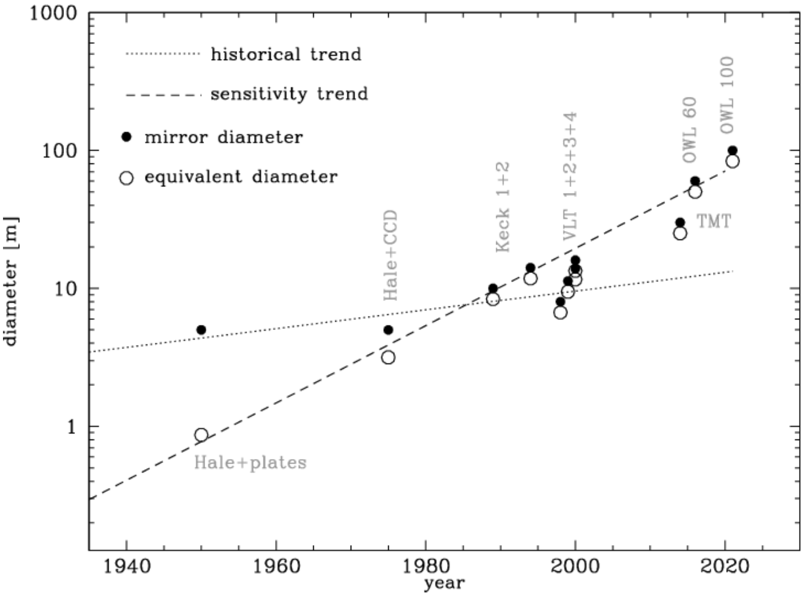

Figure 2-4 Improvement in sensitivity of telescopes expressed in "equivalent diameter of a perfect telescope" = √ (ηD^2), with η the telescope overall efficiency (the dashed line is an aid to the eye, not a fit).

2.4.2 A giant telescope in an industrial context

Traditionally, larger telescopes were most demanding in terms of industrial effort because the burden of providing larger apertures depended on suppliers taking significant technological risks. To a limited extent the VLT moved away from that tradition, its active optics allowing significant relaxation of fabrication tolerances. Still, the casting and polishing of 8-m class primary mirrors, not to mention the design and fabrication of a lightweight, fast steering secondary mirror, represented risky and costly challenges at the time. OWL moves one decisive step further in the direction of supplier-friendly solutions, with a design such that most costly subsystems, in particular mirror segments & supports, telescope structure and drive systems, do rely on proven, low risk technologies. The reward of the implied design compromises is a most favorable cost in relation to size. Indeed, the benefits of low risk processes and serial production cannot be overstated, with modules unit costs at one fifth to one tenth of their single unit prices[1] and with attractive lead-times. According to industrial studies[2], OWL segments (7,000 m²) can be produced in 8-9 years at a cost of about M€ 300 (i.e. 43 k€/m²). These figures[3] should be compared with the VLT's 200 m² in 10 years at a cost of 67 M€ (330 k€/m²). Similarly, the fractal design of the telescope moving part, based on very few simple standard or serially produced components, leads to a low-cost, small lead-time, yet very performant structure.

Indeed, modular design and serial production automatically imply serial integration and favorable supply lead-times. Also, this can be matched by a favourable integration lead-time, thereby largely compensating for the apparent schedule disadvantage of an extremely large telescope with a diameter much beyond 30-m.

This does not mean that there are no challenging technological developments associated with OWL. *Au contraire*, such areas as getting the successive generations of adaptive optics based

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[1] according to industrial data.

[2] Five competitive studies for the blanks production and two for their polishing; see RD6, RD7, RD8, RD9, RD10, RD11, RD12.

[3] which include industrial facilitization. One year has been discounted from the actual VLT schedule to account for the fact that REOSC, with ESO's agreement, delayed the last VLT primary by more than one year in order to accommodate the Gemini mirrors in its production plans. The VLT primary mirrors price has been adjusted to 2002, starting with 1989 prices.

field correction and, less daunting but still highly demanding, the instrumentation that could fulfill its ambitious science drivers will require enduring and coordinated effort at both the European and World level throughout the entire life of the facility.

2.5 Top level requirements

The science case can be distilled into a set of requirements that the telescope and instruments have to meet to achieve the goals. Primary among these are the large collecting area and the best possible image quality. The ensuing Top Level Requirements are discussed in detail in Chapter 4 and are summarized here.

The telescope collecting area requirement is 6500m^2 or larger. This is driven by the highlight science cases of earth analogue exo-planets and resolved stellar populations in a representative section of the Universe. The Codex instrument science case (measuring directly the deceleration of the expansion of the Universe) also drives to the largest possible size, as do many other specific science goals (e.g. primordial stellar populations).

The wavelength coverage requirement covers the range from the V band to 25µm, with UV-Blue as a goal. A strong case for mid infrared coverage up to the sub-mm range is made (where OWL would be a wide field complement to ALMA), so extending the coverage to these wavelengths is also a goal.

The focal ratio of the telescope should be such that the focal plane has a “reasonable” (less than 2m) dimension for the required field of view: a lower limit of F/6 is set, to be traded off with the consideration that larger F/ratios would simplify the instrumentation.

The image quality requirement for the telescope optics is to provide diffraction limited performance over the science field of view (see below). The image quality requirement for adaptive optics depends on the AO mode and on wavelength and is specified in RD41. Reference values are 0.65 (goal 0.75) Strehl in the K band for single conjugate AO, 0.40 (goal 0.50) Strehl in the K band for multi conjugate AO, 0.90 (goal 0.94) Strehl in the K band and 0.40 in the V band for extreme AO. The corresponding requirements for the first generation of instruments are 80% of these values.

The emissivity of the telescope needs to be minimized for observations in the thermal infrared. Every effort should be made in Phase B to develop high reflectivity coatings and proper baffling so that the total emissivity of the telescope is kept below 15% (goal 10%).

The field of view science requirement varies from extremely small fields (a few arcseconds) to several arcminutes and may not be always compatible with the image quality requirement. The possibility of having a “large” field with partial or little AO correction is implicit in several science goals, but seeing limited performance in imaging may be physically impossible to achieve (at least in broad bands) as the sky background may saturate the pixels in a much shorter time than the fastest read out time (so that even if possible an observation would have unacceptably long overheads). The science field of view requirement (diameter) is 0.5 (goal 1) arcminutes in the V band, and 2 (goal 3) arcminutes in the K band. The total field of view of the telescope must allow the selection of guide stars for guiding, active optics and adaptive optics. A minimum of 8 arminutes will provide acceptable sky coverage (although laser guide stars may be needed for adaptive optics).

The transmission of the telescope will be maximized, and studies shall be performed in the design phase to identify appropriate coatings. Based on the properties of various existing types of Ag-based coatings, the requirement is set at 98% (goal 99%) per reflecting surface at 1 µm, with less than 1% degradation during operations.

At least 4 (goal 6) focal stations should be provided. At least one of them should be gravity invariant.

The available fraction of sky will depend on site selection. The sky coverage of the telescope shall be to 60 (goal 70) degrees of zenith distance. The zenith avoidance area shall be the smallest compatible with the maximum rotational velocity of the structure, and be no more than 1 (goal 0.5) degree. Ways to correct for the effect of relative differential displacements in “wide” field observations due to atmospheric refraction shall be developed in Phase B (e.g. post-processing, active optical elements, operational strategies etc).

Site selection will be made before the engineering level 1 requirements need to be frozen. The choice of the site shall be the result of a thorough trade off analysis of atmospheric, logistical, seismic and ground properties, and of astronomical considerations (e.g. available fraction of the sky, light pollution). Low cloud coverage, low precipitable water vapour, moderate ground-level wind, adequate turbulence characteristics (turbulence profile, amplitude, and coherence time) will be major selection criteria. The site shall as a goal be suited to observations also in the mid to far (sub-mm) infrared.

The operational lifetime of OWL shall be larger than 30 (goal 40) years.

Parameter	Requirement	Goal	Comments
Telescope area	> 6500 m^2	> 7000 m^2	
Wavelength coverage	0.4 to 25 μm	0.30 to > 850 μm	
Image quality (AO)			
SCAO	0.65 Strehl @ K	0.75 Strehl @ K	By telescope in
MCAO	0.40 Strehl @ K	0.50 Strehl @ K	<seeing> = 0.6”
GLAO	3.5× EE gain	5× EE gain	
ExAO	0.90 Strehl @ K	0.96 Strehl @ K	0.40 Strehl @ V
Emissivity	< 15%	< 8%	Protected Ag in Phase A
Field of view	> 6 arcmin	> 10 arcmin	
Throughput (0.55 – 25 μm)	> 90%	> 92%	Protected Ag in Phase A
Focal stations	> 4	> 6	At least one should be gravity invariant
Sky coverage	1 – 60 degree (ZD)	0.5 – 70	
Operational lifetime	> 30 years	> 40 years	
Technical downtime	< 3%	2%	3 years after start of operations
Operating cost	< 3% per year	2%	Of capital cost. Does not include new instruments
ADC: residual dispersion	0.2 pixel	0.1 pixel	Over any one Johnson band

Table 2-1 Summary of top level requirements

Maintenance concepts leading to simple procedures shall be developed so that the telescope meets the top level requirements during operations, with a technical downtime of 3% (goal 2%). The technical downtime requirement applies when the observatory is in routine operations (i.e. 3 years after start of science)

The operating costs of the OWL observatory shall be kept below 3% of the capital investment[4] (this figure does not include costs for new instrumentation). This will be achieved by design (high reliability and easy to maintain telescope and instruments) and by appropriate operations plans.

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[4] This is roughly what costs today to operate Paranal, excluding instrumentation costs.

Atmospheric dispersion correction shall be provided, either by the telescope or, if too complex, by the instruments. Active, closed loop compensation may be necessary at the angular resolution of OWL: this shall be studies in Phase B. The residual dispersion after correction shall be smaller than 0.2 pixel for a given instrument at a given wavelength. Ways should be explored in Phase B to assess feasibility of using atmospheric dispersion as a dispersive element of some instrument (e.g. with partial correction so that it is kept constant over some range of zenith distance).

The top level requirements are summarized in Table 2-1.

2.6 Design overview

The design of the OWL observatory builds on VLT experience and, within the limits imposed by science objectives, pays highest attention to fabrication constraints. More specifically, it gives priority to maximizing aperture and to providing a multi-purpose facility at minimal construction and operation costs, within a competitive time schedule and in compliance with predictable industrial capacity. To the maximum possible extent it relies on proven, modular solutions compatible with serial production schemes, thereby allowing it to break away from traditional cost scaling laws. Such breakthrough, however, seems only possible with a very large telescope size. Modular design and serial production may no longer be highly cost- and schedule-effective below 50- to 60-m as the number of identical parts (e.g. segments, actuators, structural modules, friction drives, etc.) decreases substantially.

Figure 2-5 shows the layout of the telescope structure and of the sliding enclosure on a hypothetical site. Table 2-2 gives the overall optical characteristics of the design.

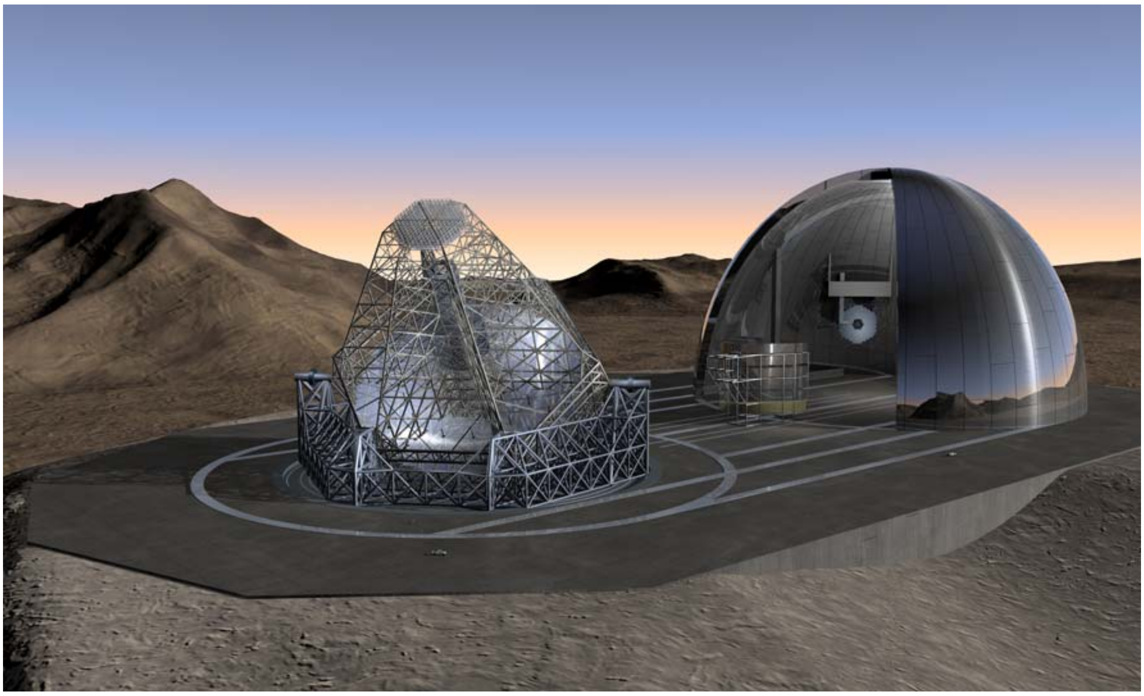

Figure 2-5. Layout of the OWL observatory.

2.6.1 Telescope optics

Quite a number of optical designs have been evaluated. The crucial objective of maximizing aperture while minimizing costs inevitably led to evaluating spherical primary mirror solutions against aspherical ones.

Solutions have been rated at system level against merit functions incorporating feasibility, performance, maintainability, risk and cost (see 6.2.1). In addition, the opto-mechanical design is required to provide suitable surfaces for field stabilization, active and adaptive optics functions. Active optics corrects for large amplitude, low spatial and temporal frequency errors, and adaptive optics for moderate to low amplitude, high spatial and temporal ones. A single subsystem cumulating all active and adaptive functions is deemed too challenging if feasible at all.

Characteristic	
Telescope diameter	100m
Focal ratio	6
Primary mirror focal ratio	1.25
Total field of view (diameter)	10 arc minutes
Unvignetted field of view (diameter)	6 arc minutes
Optical quality at the edge of the curved field	0.056 arc seconds RMS
Diffraction-limited field of view[5] (diameter, curved field)	
Visible (0.5 μm)	2.37 arc mins
IR (2.2 μm)	4.08 arc mins
IR (5.0 μm)	6.00 arc mins
Secondary mirror diameter	25.6m
Central obscuration (linear)	35%

Table 2-2. Baseline design, optical characteristics.

Monolithic relay mirrors were constrained to a diameter not exceeding 8.3-m in order not to require new developments in blank fabrication. VLT experience also showed that beyond ~8.4-m, transport in Europe would become fairly complex as waterways (locks) would no longer fit with the implied container dimensions. This is a fairly severe constraint; attractive 100-m designs requiring 10- to 11-m class monolithic mirrors were ruled out but would have to be re-considered if the telescope diameter were reduced to ~70-m or less, with a corresponding reduction of the diameter of the monolithic mirrors.

Finally, strong emphasis was put on sensitivity to misalignment over large scales, e.g. primary-secondary mirror centring. Flexure of the telescope structure under gravity, thermal, and wind loads will inevitably be large (plausibly maximal) at the location of the secondary mirror[6]. An optical solution which minimizes depointing and wavefront errors associated to unit M1-M2 decentres will therefore be favourable in terms of correction range.

A detailed trade-off involving a representative sample of the solutions explored so far is presented in section 6.2.1. The baseline design eventually selected is a 6-mirror solution (Figure 2-6), with segmented, spherical primary and flat secondary, and a corrector made of 4 elements, including two 8-m class active mirrors and two adaptive mirrors, 2.3-m and 3.2 –m (M6 and M5), conjugated to ground and 8-km, and corresponding to first and second generation adaptive systems, respectively. In the first two years of science operation, and while the aperture is growing from a 50-m equivalent collecting area, it is planned to use a temporary, passive M5 unit and operate in single conjugate or ground layer correction only.

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[5] Strehl Ratio ≥ 0.80, curved field.

[6] A lightweight secondary mirror would certainly be helpful, but the telescope structure will still bend under its own weight.

The flat secondary mirror leads to generous centring tolerances for the pair M1-M2 and, thanks to the structural design, lateral decentres are privileged over tilt. According to Finite Element analysis, the secondary mirror tilt is relatively low and could be compensated with the M2 segments position actuators[7], which are identical to those of the primary mirror segments. Tight alignment tolerances inevitably show up inside the corrector, however on a scale comparable to that of the VLT. The corrector itself needs to be centred within typically one mm and a few arc seconds of its ideal position.

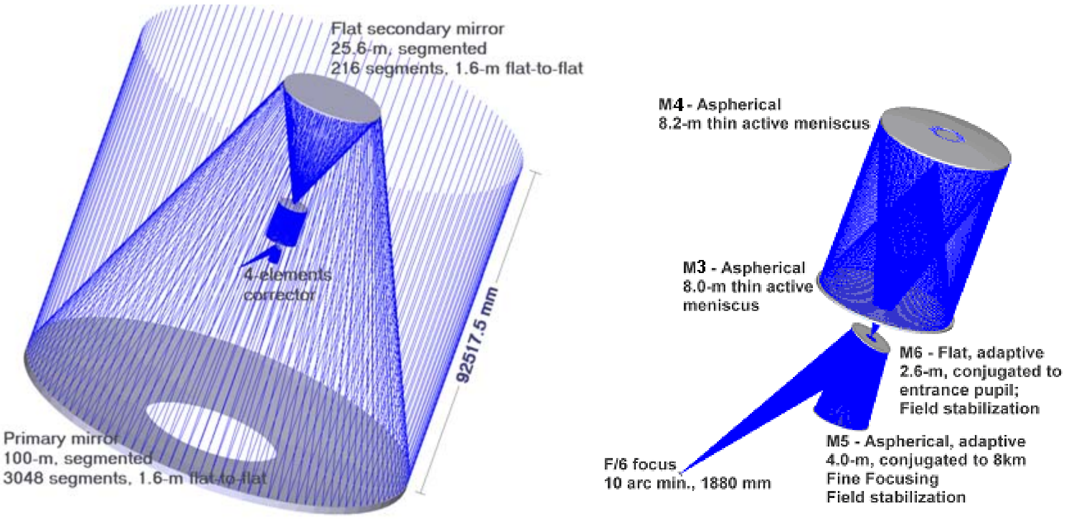

Figure 2-6. Layout of the baseline optical design.

The selection of a spherical primary mirror solution has been the result of extensive analysis, encompassing system and fabrication considerations.

Fabrication - The shape of the primary has an evident and strong impact on fabrication issues.

Aspherical solutions

There are two proven processes for the polishing of aspherical segments.

The first one is stressed-polishing, pioneered with the Keck telescopes. Warping harnesses are mounted onto circular segments, bending moments applied, and the segment polished spherical. The moments are predetermined to ensure that the segment will reach the desired aspherical shape upon their relaxation. The segments are then cut hexagonal, after which fine correction is done with computer-controlled, small tool or ion-beam polishing.

In order to ensure a predictable stress relaxation, stressed polishing requires the back face of the segment to be polished, and implies stringent specifications for residual stresses in the blank. For the same reason, a structured (lightweight) geometry of the segments is excluded, and the process works best with small aspherical departure from best fitting sphere, which privileges small segments (for the CELT, this was one of the reasons for choosing a segment size of 1-m outer diameter [3]).

The second process is the one used by REOSC (SAGEM) to figure the GTC segments. In that case, segments are directly computer-controlled ground and polished aspherical using relatively small tools. Temporary wasters are glued at the edges of the segments to prevent excessive turned-down edges. Again, ion-beam polishing is used in the final stages of figuring, after removal of the wasters. As shown in [4] the results obtained with GTC segments are outstanding, with residual surface errors in the 10 nm RMS range.

The main issue with aspherical segments is not figuring but testing. The test set-up shall be able to guarantee the matching of the segments, i.e. to measure their aspheric shape and

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[7] A relatively large actuator stroke (15 mm required, goal 30 mm) is required to compensate for the primary mirror cell deformations..

differential defocus with an accuracy of a few nm. With 36 segments, there are 6 different families of identical segments, and there is one family adjacent to each of the other five. For GTC, one segment of this family was polished first, and kept as a reference for the ensuing production. Segments were mounted next to and phased with the reference one, then tested at centre of curvature through a nulling system [4]. Care must be taken when adjusting the radial position of the segment under test, for a decentre would translate into decentring aberrations. This elegant solution, regrettably, cannot be extended to large apertures. Profilometry could be an alternative to interferometric measurements, albeit with poor time efficiency as very high spatial sampling is required through the entire figuring process to capture high frequency terms, in particular edge misfigure.

Spherical solutions

The polishing and above all testing of identical, spherical segments could follow a much simpler and safer process, with less potential restriction on material and lightweighting. The baseline solution proposed by suppliers (see RD11 and RD12) is to polish segments with full size stiff tools and test them against a unique matrix. In view of the large tool working area, the process is inherently more efficient (in terms of overall removal rate per unit of time) than small tools. In addition large stiff tools are also inherently more favourable than small ones for what concerns high spatial frequency errors. At this stage, glued wasters are still considered to prevent excessive edge misfigure, but there is circumstantial evidence that the edge misfigure would be much easier to control than with small tools, and that wasters might not be necessary. Further tests are planned on the silicon carbide prototypes of the ELT Design Study (see A-1.3). Although a significant proportion of the segments would probably meet specifications at the end of the stiff tool cycles, fine correction with small tool or ion-beam polishing is foreseen as well. The number of polishing machines required to meet the specified delivery rate (about 3,000 segments in 6 years) is relatively low (5-6 grinding machines and 5-6 polishing ones, plus one ion-beam or small-tool machine) – in any case much lower than what would be required for aspherical segments. Polishing of segments by batches on planetary polishers may be an attractive alternative, but the baseline solution appears more cost-effective beyond ~1-m segment size. In addition, parallelization of the production line is safer in relation to the impact of individual machine failure.

Experienced suppliers have expressed concerns about the timely feasibility of a large number of even moderately aspherical segments. The polishing of 42 aspherical segments for the GTC by a world-leading manufacturer will have taken about five years, required extensive development and costly solutions for the control of misfigure up to the edges of the segments[8], and required a facility comparable to that built to figure the VLT primary mirror[9]. The “pipeline” output at the end of this learning process is currently 1 mirror per 2 weeks. It does not appear possible to produce 3,000 such mirrors in a comparable timeframe without extensive R&D, followed by massive infrastructure investment. In contrast, the polishing of LAMOST spherical segments with large and stiff tools produced smooth surfaces up to the edges in a relatively straightforward manner [1]. Another relevant example is the polishing of 1.8-m aluminium mirrors under ESO contract in 1990: 28 hours machine time from ground state to final polish [2].

In brief, aspherical segments, whether polished by stressed polishing with harnesses tuned to individual segments or by computer-controlled small tool figuring, are far from ideally suited for reliable serial production. The same applies, perhaps to an even larger extent, to their optical testing, on top of possible reservations as to curvature matching.

In conclusion, fabrication (cost, risk, performance) considerations unequivocally point towards spherical primary mirror solutions.

System considerations - Fabrication, schedule, cost and risks, however, are far from being the only relevant considerations when selecting the primary mirror shape. A system analysis shows that beyond 20-30m aperture size, there is no practical way to meet optical performance requirements and implement all required wavefront control functions, including adaptive optics,

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[8] In comparison to Keck, edge misfigure tolerances are about an order of magnitude tighter in the GTC and future ELTs, OWL included.

[9] The facility actually *is* the VLT primary mirror production one, reconverted for GTC segments.

with less than four surfaces[10] –except by relying on a primary mirror made of adaptive segments with an extreme correction range. Serially produced adaptive segments seem presently out of question within a foreseeable timescale.

Even if adaptive segments could reliably be made within an affordable cost and timescale, such solution would imply that the telescope's most advanced –and perhaps the most evolutive-technology be frozen at the earliest stage of the project[11], and that future upgrades be essentially ruled out. Last but not least, adaptive segments do not resolve any issue which could definitively not be addressed by other means, in a less elegant but certainly more realistic and cost-effective manner.

Opto-mechanical design - The opto-mechanical design allows for 6 focal stations, switching being done by rotating the M6 mirror about the telescope axis. One focal station is reserved for technical instrumentation exclusively; the other 5 may be occupied by one science instrument each.

Two versions of the 6-mirror solution have been explored in detail, with an f/1.42 (see Reference Document RD1) or f/1.25 primary mirror (RD2). The latter is that referred to as baseline in the present document. The optical quality is significantly better than that provided by a Ritchey-Chrétien formula and exceeds the requirements by more than a factor two in terms of diffraction-limited field of view. The central obscuration is fairly large (35% linear i.e. central obscuration diameter = 0.35 x pupil diameter) and essentially imposed by the dimensions of the hole in the tertiary mirror and by the field of view such hole shall allow through.

Although the baseline design may seem less effective than traditional two-mirror ones in terms of transmission and emissivity, it provides all required wavefront control functions up to IR dual-conjugate adaptive optics, which a Ritchey-Chrétien would not.

For small field at 5.0 μm and beyond, the baseline 4-mirror corrector could be replaced by an optional two-mirror one (see section 6.2.3) delivering diffraction-limited image quality (Strehl Ratio ≥ 0.80) over 33, 52 and 74 arc seconds, at λ=2.2, 5.0 and 10.0 μm, respectively. The exit focal ratio is f/2.1 and the total field of view is 4 arc minutes[12], with a geometrical image quality of 0.21 arc seconds RMS at the edge of the field. The optional corrector includes a 6.1-m thin meniscus active mirror and a 4.1-m adaptive one. Both mirrors are strongly aspherical. In view of the large mirrors sizes, high frequency (>1 Hz) field stabilization would have to be provided in the instrument. The estimated downtime required for the exchange of the correctors is 48 hours.

The optical design is not considered final; phase B will start with a critical re-assessment of the entire optical design. In case the baseline 6-mirror solution would eventually be re-confirmed, the following adjustments would be explored:

- Allowing for a larger secondary mirror, and shortening the distance M1-M2 by ~12.83-m (the size of one structural module), or slightly increasing the primary mirror focal ratio;
- Increasing the allowable design volume for the adaptive M6 unit.
- Increasing the focal ratio.
- Decreasing the angle between the exit beams after M6 and the telescope axis.

The short focal ratio (f/6) is an evident area of concern for instrumentation, adapter and on-sky metrology. One should note, however, that the entire control system is driven by focal plane metrology. This implies very high dimensional accuracy and stability at the level of these metrology systems. Increasing the focal plane dimensions would proportionally relax tolerances. Flexures, however, would increase more rapidly with the increase of the focal plane dimensions. A thorough trade-off is planned in the design phase.

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[10] See also 6.1.

[11] According to current plans the final design of the primary mirror must be frozen by 2008 at the latest.

[12] 3 arc minutes unvignetted.

Tentative optimization runs indicate that implementing such changes might be possible to some extent. In addition, requirements set by instruments exploratory studies[13] may lead to significant re-designing of the telescope opto-mechanics, within the limits set by top level requirements, engineering constraints and by modular design compatible with serial production. Experience with the opto-mechanical design trade-off shows that the modular design allows for a relatively straightforward re-configuration of the telescope structure i.e. a re-configuration of the optical design does not necessarily imply a complete overhaul of the structural design.

Segments characteristics, segments production

Segment size has been the subject of an early trade-off, the main evaluation parameters being the complexity of the control system (number of degrees of freedom), risks and costs. At the upper limit (8-m) of proven mirror technologies, the estimated total cost[14] of raw blanks is M€ 510 (delivery ex works). Beyond 2.3-m flat-to-flat, standard transport containers are ruled out and beyond ~2.5-m, active supports are inevitably required to prevent excessive material costs. For these reasons the upper limit for the segment size has been set to 2.3-m.

Very small segments (a few tens of centimetres) would be favourable in terms of material costs, polishing, transport, handling and –at least when individually taken- maintenance. The number of degrees of freedom increases however rapidly with decreasing segment size. According to Chanan [6], ~4,000 units is the upper limit for on-sky calibration with current (Keck) techniques.

Characteristic		**Value**
Substrate		Zerodur, ULE or Astro-Sital
Shape / type		Hexagonal / solid
Dimensions	Flat-to-flat	1.6-m
	Thickness	70-mm
Radius of curvature	Primary mirror	250-m
	Secondary mirror	Flat
Support	Axial	18 points whiffle-tree
	Lateral	1 central support
Quantity	Primary mirror	3048
	Secondary mirror	216

Table 2-3.Segments characteristics.

Parametric studies undertaken by the industry (substrates, polishing) with dimensions of 1.3, 1.8 (initial baseline) and 2.3-m flat-to-flat, indicate that the optimal dimension in relation to cost is somewhere between 1.3 and 1.8-m flat-to-flat[15]. As a result, the dimension has been set to 1.6-m flat-to-flat and the thickness reduced from 80 to 70 mm, which should lead to a slight cost reduction. The segments size is also chosen as an integer divider (1:8) of the structural module size, thereby allowing for higher standardization of interfaces. A preliminary optimisation and analysis of a possible 18-points segment axial support system has been performed (see also 6.5.1.5). Quilting under gravity is ~60 nm wavefront RMS. Provided that the geometry of the polishing support is identical to that in the telescope, this error would be polished out and its opposite would only appear when the telescope is pointing away from zenith[16]. At the operational limit z=60°, it would have an amplitude of ~30 nm wavefront RMS (see 6.5.1.5). Alternatively, the surface deflection could be programmed into the polishing robots in the final

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[13] At the time of writing of this document, the results of such studies were too preliminary to allow for a thorough re-assessment of the telescope opto-mechanical design.

[14] Based on 2005 prices for an 8-m ULE blank (CORNING communication), with a 60% unit price reduction for large quantity (~140 units) and a 1.3 USD to 1.0 € exchange rate.

[15] See also RD6, RD7, RD8, RD9. RD10. RD11, RD12.

[16] Within the framework of the VLT project, REOSC polished a spherical gauge mirror, 1.7-m diameter, for the validation of the axial support interface and for the calibration of the spherometer in the fine grinding stage of the 8-m mirrors. Interferograms showed that quilting under gravity had been polished out, down to measurement accuracy (less than 10 nm RMS wavefront).

stage of polishing. For the secondary mirror segments, with a projected size of 6.25-m on the entrance pupil, partial compensation by the Adaptive Optics ought to be possible. The current baseline characteristics of the segments are listed in Table 2-3. At the time of writing of this document, the option of moderately (50%) lightweight blanks at marginal cost increase is under evaluation.

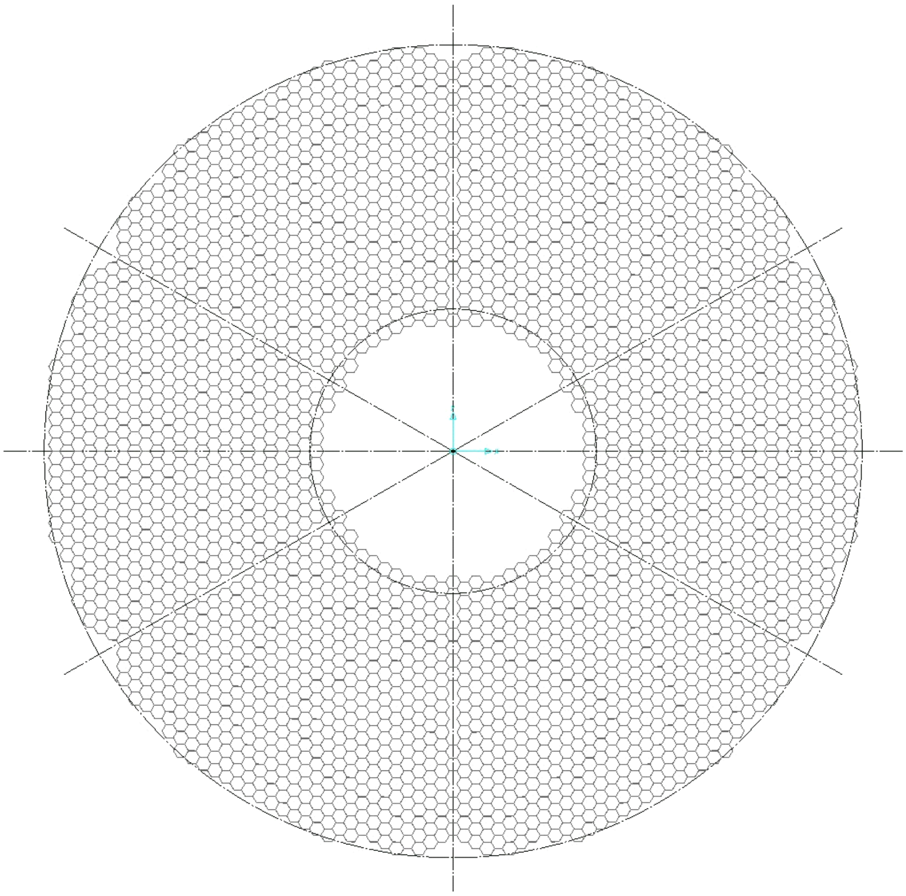

Figure 2-7. Primary mirror geometry (3048 segments).

The primary and secondary mirror geometries are shown in Figure 2-7 and Figure 2-8.

It is worth noting that suppliers reported that they now have adequate facilities for the production of OWL segments (melting tanks and ceramization furnaces).

Silicon Carbide is considered as a serious alternative to conventional low-expansion glass or glass-ceramic. According to industrial studies[17], feasibility per se is not a critical issue and cost, polishing included, would not be very substantially higher than with conventional materials. The reasons for such promising if somewhat surprising conclusion are twofold: serial production, and moderate specifications as to light-weighting[18]. Although cryogenic tests undertaken for space applications have repeatedly shown excellent properties in this respect, possible CTE inhomogeneities and bimetallic effects between the bulk of the substrate and its polishable overcoating might rule the technology out in view of the stringent requirements applying with segmented apertures (see RD3). The issue is investigated within the framework of the ELT Design Study (section 2.12), with the production of up to 8 prototypes, 1-m class. Specifications could be relaxed with active deformable segments but such solution would imply added cost and undesirable control complexity. In the case of M2, minor, low spatial frequency figure

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[17] see RD9, RD10, RD11, RD12.

[18] The specified aerial mass being 70 kg/m² or less, i.e. far more generous than for space applications.

changes should be acceptable as the projected size of segments onto the pupil (about 6.4-m) is significantly larger than the sampling of the lowest order adaptive optics corrector.

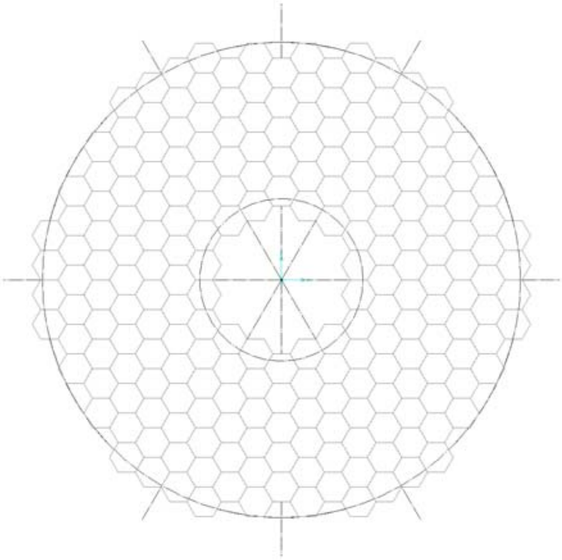

Figure 2-8. Secondary mirror geometry (216 segments).

Owing to their all-identical characteristics, including spherical shape, the polishing of OWL segments implies enormous simplification and substantial performance advantages with respect to aspherical ones. Experienced suppliers expressed serious concerns about figuring aspherical segments to tight specification in a timely manner. In brief, they fail to see a cost-effective solution towards industrial polishing and testing of about 3,000 aspherical segments in a timeframe comparable to what is needed by a world-leading optical manufacturer to polish the 42 GTC ones[19].

It was initially thought that figuring of OWL segments could be done by replication or polishing on planetary machines [5]. Replication has been ruled out as the durability of a master could probably not be guaranteed beyond a few dozen replications. According to suppliers, planetary polishing might be convenient for small segment sizes (1.3-m) but would entail large investments and unpredictable performance for larger ones. The preferred solution is to set a sufficient number of polishing robots for the parallel figuring of segments. Optical testing would be done interferometrically against a convex matrix, an optimal solution in terms of curvature matching of the segments.

Industrial studies referred to herein conclude that OWL segments could be produced within a competitive timeframe and at a cost broadly in-line with ESO's internal assessment – namely 6 years production cycle after a 2-3 years facilitization, and a total cost of the order of 300 M€, polished segments, ex works.

2.6.2 Structural design

The design of the telescope structure has evolved considerably (see section 9.3) since the setting of the first concept [5], with a moving mass decreasing from 45,000 to 13,400 tons and a first locked rotor eigenfrequency increasing from 0.5 to 2.7 Hz.

The telescope structure (Figure 2-9) relies on a modular design, with most parts made of mild steel. Modules (Figure 2-10) will be made of standard pipes and serially produced nodes. Modules will be assembled on-site; all pipes and pre-assembled nodes can be transported in standard containers. Kevlar ropes provide for pre-stressing and torsional stiffness. The overall

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[19] Including 6 spares, and taking into account the tighter requirements underlying diffraction-limited performance.

structure has a 6-fold symmetry, thereby allowing for an ideal match with the segments geometry and a clean geometry of the aperture hence of the theoretical diffraction pattern.

The aptly named *fractal design* (see section 9.4.2) not only allows for highest standardization hence low cost, ease of supply, integration and maintenance, it also allows for distributed load transfers from the optical subsystems to substructures and eventually foundations –thereby preventing excessive stress concentration.

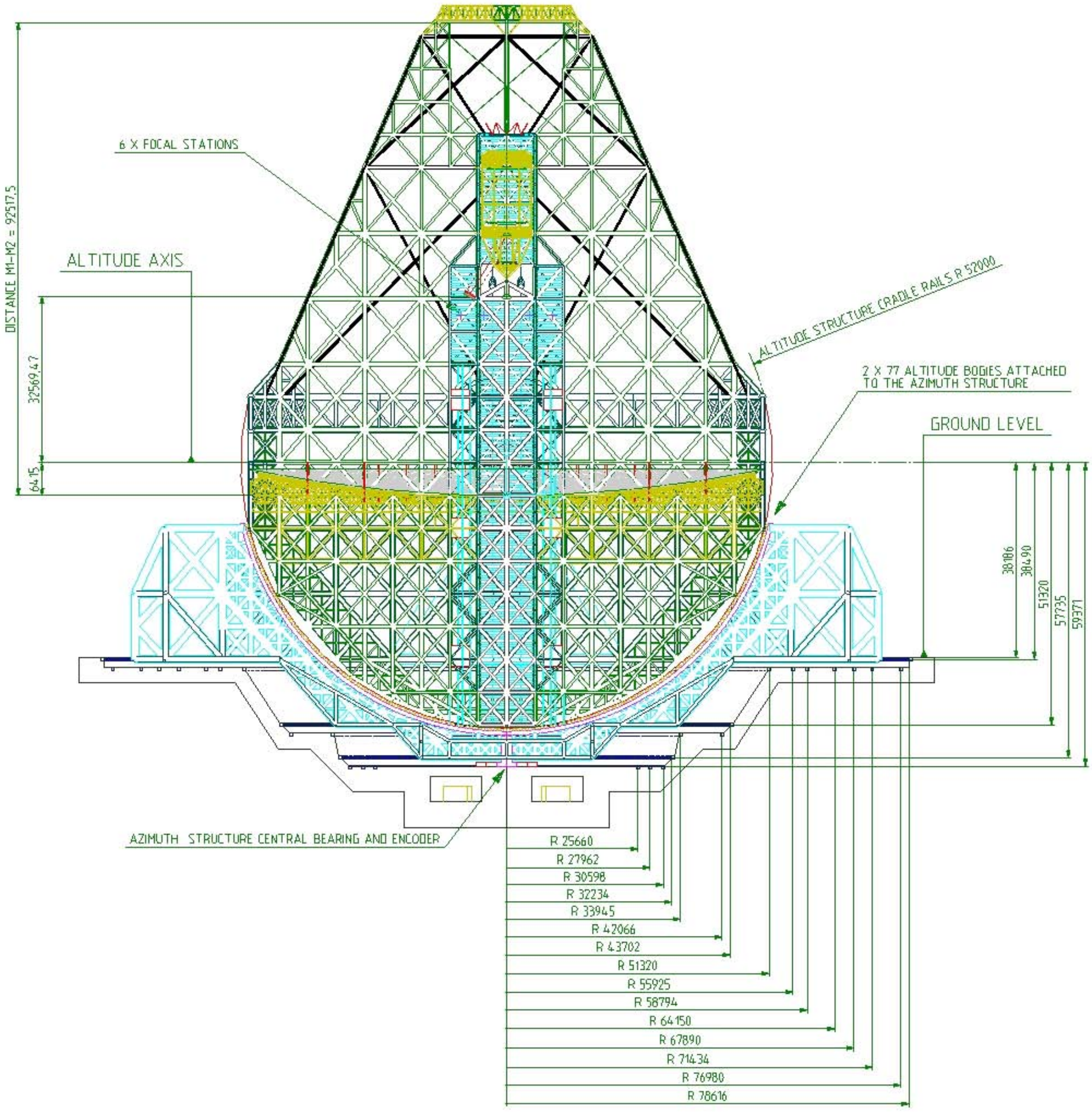

Figure 2-9. Telescope structure, overall layout.

The Alt-Az kinematics of the telescope is provided by way of friction drives (Figure 2-11), with 246 units on 12 azimuth tracks and 154 units on two altitude cradles. Friction wheels are slightly spherical to prevent excessive stresses generated by misalignment (see RD13). Individual drives interface to the structure by means of hydraulic jacks, which can be connected for e.g. seasonal re-adjustment of the load distribution.

The operational range is 0 to 60 degrees zenithal distance, with a blind spot of 0.5 degrees radius about zenith. The maximum slewing speed is 0.1 degree/s, i.e. pointing is realized in a timescale comparable to that of the VLT. The kinematics allows the telescope to point horizontally for maintenance purposes. A series of preliminary analysis (see RD16) show that the telescope should be able to track within 0.3 arc seconds RMS, friction and 10 m/s wind speed taken into account. The residual error shall be compensated by the fast tip-tilt mirror M6.

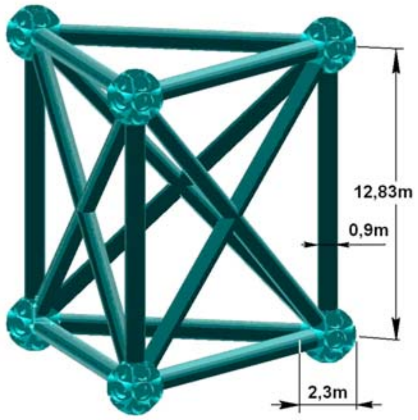

Figure 2-10. Structural steel module

Hydraulic bearings and tracks were ruled out because of the associated tight dimensional tolerances and of the length of the tracks. Magnetic levitation is an attractive alternative in view of the implied relaxation of dimensional tolerances[20], of its potential ability to provide high stiffness by way of the control system, and of safety aspects. This option will be assessed in the framework of the ELT Design Study (section A-1.4).

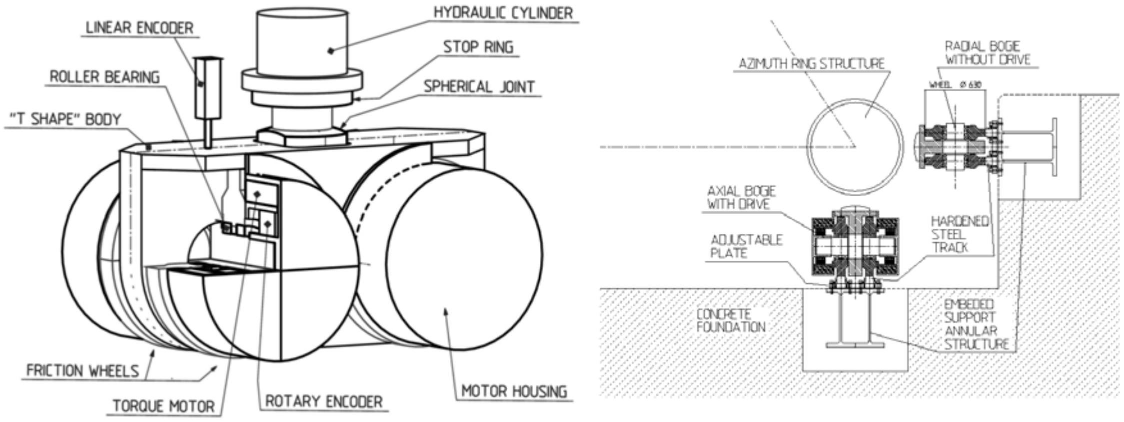

Figure 2-11. Friction drive

2.6.3 A controlled opto-mechanical system

Regardless of its opto-mechanical design, a telescope much larger than VLT or Keck must inevitably integrate extensive control systems, including but not limited to adaptive optics. Indeed adaptive optics deals with relatively limited error amplitudes, and cannot realistically solve all problems at once. A system the size of OWL must accommodate for large deflections and integrate all control systems necessary to bring it into a state where the adaptive control loop can be closed rapidly.

The wavefront control concept will be described in details later in this document; we give a brief summary below. The general strategy is to implement successive control systems, with decreasing correction amplitude and increasing bandwidth. We distinguish 6 control loops

1. **Pre-alignment**, which deals with coarse alignment of the secondary mirror, of the corrector, and of the surfaces within the corrector. The essential objective is to allow the subsequent acquisition of guide stars and to allow the active optics loop to be closed. The errors to be corrected result essentially from gravity load and changing thermal conditions. The required

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[20] An order of magnitude more generous than with friction drives.

bandwidth is low (typically less than 0.1 Hz), and the accuracy (typically10 ppm) compatible with simple metrology solutions, e.g. fibre extensometers between M1, M2 and the corrector, and within the corrector. The secondary mirror tilt alignment can be achieved with the segments position actuators[21].

2. **Tracking and field stabilization**, which shall ensure that the target remains at a stable position on the detector. This includes several loops, with increasing bandwidth and accuracy, and decreasing amplitudes:
   - Tracking by the telescope drives –down to an estimated accuracy of 0.3 arc seconds RMS, taking into account 10m/s wind speed and friction in the telescope drives. The metrology signals are provided by the telescope encoders and by the guide probes; the bandwidth is limited by the stiffness of the structure (2.6 Hz locked rotor frequency). The errors corrected by this loop include mostly the effect of low frequency wind buffeting, friction, of gravity and thermal changes.
   - Mid-frequency (up to ~10 Hz) field stabilization with the M6 tip-tilt unit. The corresponding error source is mostly wind buffeting. The expected amplitude requirement is less than ~1 arc seconds RMS on sky or 20 arc seconds of M6 tip-tilt, plausibly less. As this tip-tilt correction is to be provided by fast steering the entire M6 unit, this is considered as a critical requirement. The metrology signal shall be provided by the guide probes.
   - High frequency (up to ~100 Hz) field stabilization using the adaptive M6 thin shell. The corresponding error sources are atmospheric tilt and residuals associated with wind buffeting. Under normal conditions (outer scale ~30-m) atmospheric tilt will most likely be negligible. A 0.1 arc seconds error on-sky corresponds to ~2 arc seconds on the mirror i.e. ±13 μm at the edge of the adaptive mirror. The metrology signal shall be provided by the adaptive optics wavefront sensors.

   At the time of writing of this document, conceptual designs of the M6 are pursued under ESO contracts. We assume that the tip-tilt compensation by M6 will be provided in two stages, the subunit being mounted on a gimball mount or equivalent for low frequencies, high frequencies up to ~100 Hz being compensated by the adaptive support.

   The above assumes that several guide probes (5 to 7) tracking different references will allow disentangling field-independent tilt from the field-dependent atmospheric one[22]. These probes are required for active optics (see below) as well.

3. **Active optics**, which deals with residual alignment and focus errors, surfaces misfigure, and possibly low frequency (<1 Hz) wind buffeting. This includes several loops:
   - Active alignment. The goal is to finish off the pre-alignment[23] and in particular compensate for decentring coma without introducing significant de-pointing or decentring astigmatism (linear with the field of view). Decentres of powered surfaces inside the corrector may be used to cancel out field-independent decentring coma. As 3rd and 5th order terms need to be addressed, two surfaces among M3, M4 and M5 must be actuated. Actuating all three mirrors would allow correcting 3rd order decentring astigmatism as well. This will probably not be required but further analysis will be performed in phase B for confirmation.

     To prevent de-pointing, the surfaces shall be rotated about their centre of curvature. Taking pre-alignment into account, the amplitudes are fairly small.

     As an alternative, constant 3rd and 5th order coma could be corrected by an active deformation of M4 (pupil). Preliminary calculations indicate that this might be possible,

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[21] The primary and secondary mirror segments are mounted on identical actuators, and the required range of these actuators is set by the deformations of M1 cell. Flexures in the M2 cell being substantially lower, the unused range can be used to re-position the secondary mirror as a rigid body.

[22] If any; the telescope diameter being much larger than the expected outer scale of turbulence, atmospheric tilt ought to be negligible.

[23] Which is expected to align the corrector and secondary mirror to typically ± 1 mm in x-y-z and 2 to 4 arc seconds in tip-tilt, and the surfaces inside the corrector to typically ± 0.1 mm in x-y-z and ~1 arc seconds in tip-tilt.

but a more thorough analysis will be undertaken in phase B to ascertain that the M4 force budget is sufficient, before taking a final decision.

Active alignment shall also compensate for the residual misalignment between the corrector and the interface with instrumentation, by way of M6 tip-tilt and M5 refocus.

- Active focusing. Coarse focusing up to ~0.1 Hz is provided by M2, using the segments position actuators[24]. Fine focusing is to be provided by M5 up to ~1 Hz down to an accuracy compatible with the M6 adaptive range. Curvature changes of the primary and secondary mirrors must be tracked to prevent scalloping of the wavefront (first derivative discontinuity at inter-segment edges) and the position actuators reaching their range limit. A first option would be to monitor lateral displacements of the segments by way of the position sensors, as in the South African Large Telescope. A second option would be to measure the scalloping of the wavefront by way of an active optics Shack-Hartmann wavefront sensor with 7 or 19 sub-pupils per segment. This second option implies longer integration time for the wavefront sensor and is limited to ~0.05 Hz bandwidth.
- Active deformation of M3 and M4. The goal is to compensate permanent or slowly varying, low spatial frequency terms. The M3 and M4 mirrors have mechanical properties comparable to that of the VLT primary mirrors, and the design of their active support system will be similar. Assuming low (a few microns at most) amplitudes at the highest temporal frequency (~1 HZ), the implied extrapolation from the VLT active support system seems reasonable. Since M4 is conjugated to the entrance pupil but M3 is not, several reference stars are required to disentangle constant terms from field-dependent ones. The conjugation M4-M1 also requires that M1 curvature (not detected by position sensors) be monitored to prevent that either position or force actuators reach their maximum range. Monitoring of segments lateral displacements, as in the SALT, is an option; another one is to measure the scalloping of the wavefront with a properly sampled Shack-Hartmann sensor.

All active optics functions use the same wavefront sensors at the f/6 focus. It is assumed that the adaptive optics subsystem will periodically offload low frequency (≤ 1Hz) terms to active optics, thereby preventing excessive range of the adaptive correctors.

4. **Phasing**. Segments phasing errors must be corrected locally i.e. there is no way to compensate one mirror phasing errors by moving the segments of another one (except if these mirrors are conjugates and have identical segmentation geometries). The general principle is identical to that of the Keck and GTC i.e. phasing will be performed in closed loop on inter-segments position sensors, which will be periodically re-calibrated on-sky. Non-interlocking capacitive sensors developed for the SALT have far better characteristics (accuracy, drift, ease of implementation) than the 20-years old Keck ones, and in all likelihood will meet the not-to-exceed cost requirement of € 1,500 per unit for a production of about 20,000 units. An alternative technology (inductive sensors) will be evaluated in the framework of the ELT Design Study.

   According to Chanan et al [6] the Keck on-sky calibration solution could be extended up to ~4,000 segments. Several alternatives are being evaluated, and will be checked on-sky by way of the Active Phasing Experiment (see appendix A-1.3). As several segments may have to be replaced daily for re-coating, the process must guarantee that upon individual re-integration segments are phased to an accuracy compatible with the capture range of the calibration technique (see 7.5.2).

   A significant drawback of OWL design is multiple segmentation (primary and secondary mirrors). The segmentation patterns are however perfectly determined, and disentangling the primary and secondary mirror phase errors is a matter of proper signal processing of pupil images or adequate conjugation of wavefront sensors images.

5. **Active atmospheric dispersion compensation**. A notional design of a Longitudinal Atmospheric Dispersion Compensator (LADC) has been briefly explored. A combination of Corning glasses A88-66 and B81-41 seems to give satisfactory results over the wave band

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[24] Identical to the primary mirror segments actuators i.e. overdimensioned for gravity loads at the level of M2.

400 to 500 nm. The fast f/6 focal ratio is, however, inconvenient as it leads to significant coma and chromatism. Active deformation of M3 and M4 could, to some extent, compensate for non-chromatic terms but this would imply that the ADC covers the entire field of view, including active and adaptive on-sky metrology references, which translates into 2-m class prisms. Atmospheric dispersion compensation will have to be implemented in the instruments that require it, possibly in closed loop on sky. Exploratory work has started in the framework of the ELT Design Study (see A-1.8).

Wavefront sensors shall have their own ADC, but accuracy requirements are more generous.

The effect of anomalous refraction has been assessed and found to be negligible over OWL wave-bands (see RD4).

6. **Adaptive optics.** So far, adaptive optics based correcting systems have filled important new observing niches on 8-10 m class telescopes by providing near-infrared imaging, and very recently imaging spectroscopy, up to their diffraction limit. “Classical” instruments, using seeing-limited images directly delivered by the telescope, remain however their main staples. This is going to change completely with the new ELT generation: even with a 30-m “only” telescope, most observations will require some degree of AO correction; with a 60 to 100-m, virtually all observations will require much enhanced imaging quality, quite often up to the diffraction limit, to fulfil their scientific potential as mentioned briefly in section 0 and presented in detail in Chapter 2.

   Although the technological challenges posed by adaptive optics are arguably the most demanding of the entire system, there is optimism as the development of successive generations of key concepts and components is picking up considerable momentum. Notably at the European level, numerous R&D activities are being conducted in that field in the frame of OPTICON and of the ELT Design Study. Equally lively and largely complementary activities are being pursued on the other side of the Atlantic, mainly through the Center for Adaptive Optics and the NSF Adaptive Optics Development program. OWL plans encompass a gradual implementation of AO capabilities. It should be noted that adaptive units are not required for first light; provisional M5 and M6 units are foreseen in order to allow engineering time before the implementation of adaptive optics.

   First generation Adaptive Optics – OWL first generation adaptive optics (see section 8.2) will allow start of science operations and encompass IR Single-Conjugate Adaptive Optics (SCAO, see section 8.2.1), and Ground-Layer Adaptive Optics (GLAO, see 8.2.2). The deformable mirror will be the flat, elliptical M6 (2440 x 2660 mm²), with an interactuator spacing of ~25 mm and a total of 6670 actuators i.e. 98 actuators across the pupil diameter (see also section 8.2.1.2.1). Mirror M6 nearly coincides with the exit pupil but its tilt angle (16^{o}) will limit its performance in wide-field adaptive optics (see section 6.3.6). At the time of writing of this document, feasibility studies have been contracted to industry for the entire M6 adaptive unit. The baseline wavefront sensor would be a 97 x 97 subapertures Shack-Hartmann; an infrared Pyramid Wavefront sensor is evaluated as an alternative. In the latter case, the required low read-out noise detector exceeds dimensions available today. One can reasonably assume that such (512 x 512) detector would be readily available in time for OWL first generation AO. As for the Real-Time Computer (RTC), the technology is essentially available today –albeit at a presumably high cost and with a non-optimal architecture.

   Distributed Multi Object Adaptive Optics (MOAO, see 8.2.3) may also become part of OWL first generation adaptive optics if the corresponding instrument (MOMFIS, see section 12.2.3.4) is eventually implemented.

   The first generation OWL adaptive optics will rely exclusively on Natural Guide Stars (NGS).

   Second generation Adaptive Optics – The second generation adaptive optics capability of OWL (see 8.3) starts with the replacement of the passive, temporary M5 unit with an adaptive one. This should allow for a limited Multi-Conjugate Adaptive Optics (MCAO) i.e. for a limited but not negligible increase of the corrected field of view. Mirror M5 is conjugated to an altitude of ~7 km. The diameter of this mirror would be 3920 mm for 10 arc minutes unvignetted field of view but this diameter could be reduced to 3630 or 3420 mm if slight vignetting (a few percent area) in the active, respectively adaptive control fields could be tolerated (see also section 6.3.2) and provided that it would not impair wavefront sensing on Laser Guide Stars (this is still to be addressed).

MCAO is not yet fully proven on-sky. A demonstrator (Multi-conjugate Adaptive optics Demonstrator or MAD) is currently in the last phases of integration and will be installed at a VLT focus for testing on sky. MAD recently achieved first MCAO light in the laboratory (Figure 2-12).

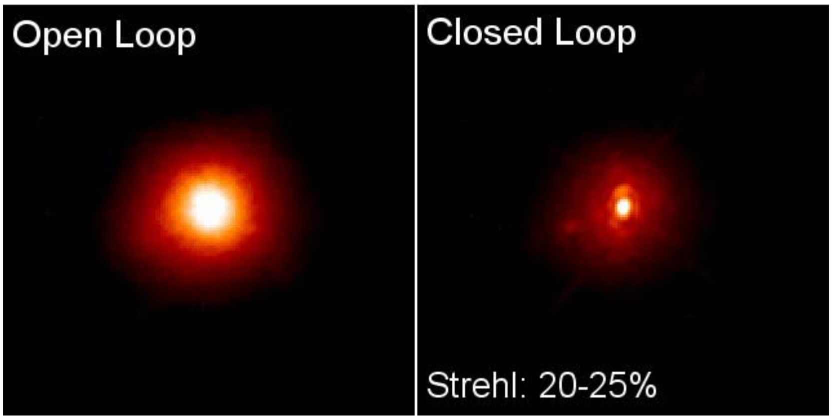

Figure 2-12. First light results with MAD (laboratory conditions). Atmospheric turbulence is emulated with phase screens. Seeing 0.5 arc seconds, coherence time 5 ms, wavelength 2.2 μm. Adaptive loop frequency 210 Hz.

In the current baseline, the MCAO control scheme is star-oriented, by opposition to layer-oriented. As for the GLAO system, on-sky metrology would rely on six wavefront sensors patrolling a field of view of up to 6 arc minutes. This scheme is however preliminary and a thorough trade-off between layer- and star-oriented correction schemes will be conducted in the detailed design phase.

The second generation adaptive optics capability will rely on Natural Guide Stars. The requirements and implementation concept are described in section 8.3.

The second tier of OWL 2^{nd}-generation AO capability covers extreme and high contrast adaptive optics and is currently addressed by EPICS (see 8.3.2), with exoplanets as its primary science target. In brief, EPICS is an instrument incorporating advanced coronagraphic techniques and post-focus high order AO correction on a small field, with a bright guide star. The post-focal deformable mirror could be based on the emerging MOEMS technology – actuator pitch <300µm- or on a significant extension of the piezo-technology with actuator pitch <1mm. The low order correction will be covered by the M6 unit.

The second generation OWL adaptive optics will rely exclusively on Natural Guide Stars and would enter operation about two years after the first generation, while segments integration will still be proceeding, with the telescope having an equivalent diameter of ~80-m.

Third generation Adaptive Optics – The third generation AO systems shift emphasis from correction capability to implementation of Laser Guide Stars (LGS), hence of increased sky coverage. The main issues at stake are essentially related to the facts that LGS are at finite distance –cone effect, image elongation- and that they are generated by beams propagating upwards through the atmosphere, thereby preventing measurement of global tilt. With Extremely Large Telescopes, the distance to the LGS spot is not negligible in relation to the telescope focal length, and their images are not only strongly affected by defocus, but also by predictable but unavoidable aberrations. In brief, the telescope is required to do macro photography and normal imaging *at the same time*. In addition, distance to the LGS changes with zenithal distance. The brute force solution would be to implement active elements in the on-sky metrology, allowing measurement noise on the LGS to be brought down to acceptable levels, while relying on Natural Guide Stars for the compensation of low order aberrations (see RD1). There might, hopefully, be alternatives (see 8.4), whereby the LGS themselves would be generated or the light beams received from them spatially filtered in a way as to minimize the effect of finite distance. Substantial effort in such directions is being spent in the framework of the ELT Design Study (see A-1.6). It is evidently too early to conclude whether brute (almost certainly complex and expensive) force will prevail. Concepts shall be developed in OWL phase B down to preliminary but not final design level.

According to current plans, the third generation adaptive optics systems will enter operation at the time of completion of the segments integration.

2.6.4 Enclosure, open air operation

Enclosure requirements and concepts have evolved considerably in the last decades, with a dramatic shift of priorities, maximal shielding from external excitations –mostly wind- at the cost of generating significant local turbulence giving way to natural flushing of local turbulence at the cost of higher wind excitation. Such shift is closely related to the evolution of control systems, and in particular to the fact that local, thermal turbulence is less predictable and occurs at higher spatial and spectral frequency. It is thus more difficult to compensate than wind buffeting on the telescope structure and optical components, actually requiring –and taxing the capabilities of- a full blown adaptive optics system.

Wind tunnel tests performed in 1992 and 1994 (see RD523 and RD524) to characterize the wind flow inside the VLT enclosure and behind a wind screen showed a significant reduction of pressure at low frequencies. Above ~0.1 Hz, however, the situation was reversed, with the Power Spectral Density (PSD) inside the enclosure systematically higher than that of open air turbulence (Figure 2-13). This is due to a smaller outer scale and higher intensity of turbulence at high frequencies after interaction between the incoming free flow and the structures of the wind screen.

According to tests (see RD523 and RD524), from which representative turbulence PSD have been derived using a von Karman model, wind screens provide some level of shielding at all frequencies, the actual efficiency depending on screen porosity and wind orientation. Shielding is most effective at all frequency when the porosity (ratio of free to closed areas) of the screen is in the range of 20%.

Wind pressure leads to tracking errors and may generate primary and secondary mirror shape errors. Preliminary simulations under 10 m/s wind speed indicate that the telescope kinematics should be able to track within 0.3 arc seconds RMS, friction in the drives taken into account. The residual error could be compensated by M2 or M6, at the cost of either a field-independent coma term (compensation with M2) or a field-dependent defocus (compensation with M6). It should be noted that with a flat secondary mirror the design is insensitive to lateral M1-M2 decenter.

Compensation of the effect of wind pressure on the primary and secondary mirrors is essentially a matter of bandwidth of the phasing control system, not of amplitude (gravity-induced deflections imply much larger amplitudes anyway). Simulations using a relatively crude (Von Karman) wind model show that with a proper controller, residual phasing errors are virtually negligible (see also 7.5.5). With 10 m/s wind speed and assuming a 60 Hz first eigenfrequency of the segment axial support system, absolute position error is 9 nm RMS with a closed loop bandwidth of 5 Hz, 6 nm RMS with 10 Hz and 4 nm RMS with 20 Hz. These numbers assume 2 nm RMS sensor noise. They correspond to local, high spatial frequency residuals and assume the segments are exposed to free air flow.

Due to the key importance of mastering wind effects, long before any metal is cut, we are nevertheless pursuing aggressively a comprehensive set of studies. Computational Fluid Dynamics (CFD) analysis performed under ESO contract in 2001-2002 led initially to suspiciously optimistic results. Indeed it was found out that frequencies above ~0.5 Hz were not properly sampled, and external experts expressed doubts about the current ability of CFD to produce realistic data at higher frequencies. Simple models are currently used in wind tunnel tests to evaluate CFD in relation to measurements; wind tunnel tests are foreseen in the ELT Design Study (see A-1.5) and in the course of OWL phase B. In addition, pressure measurements on the Jodrell Bank radio telescope have started and the results are being fed back into the models.

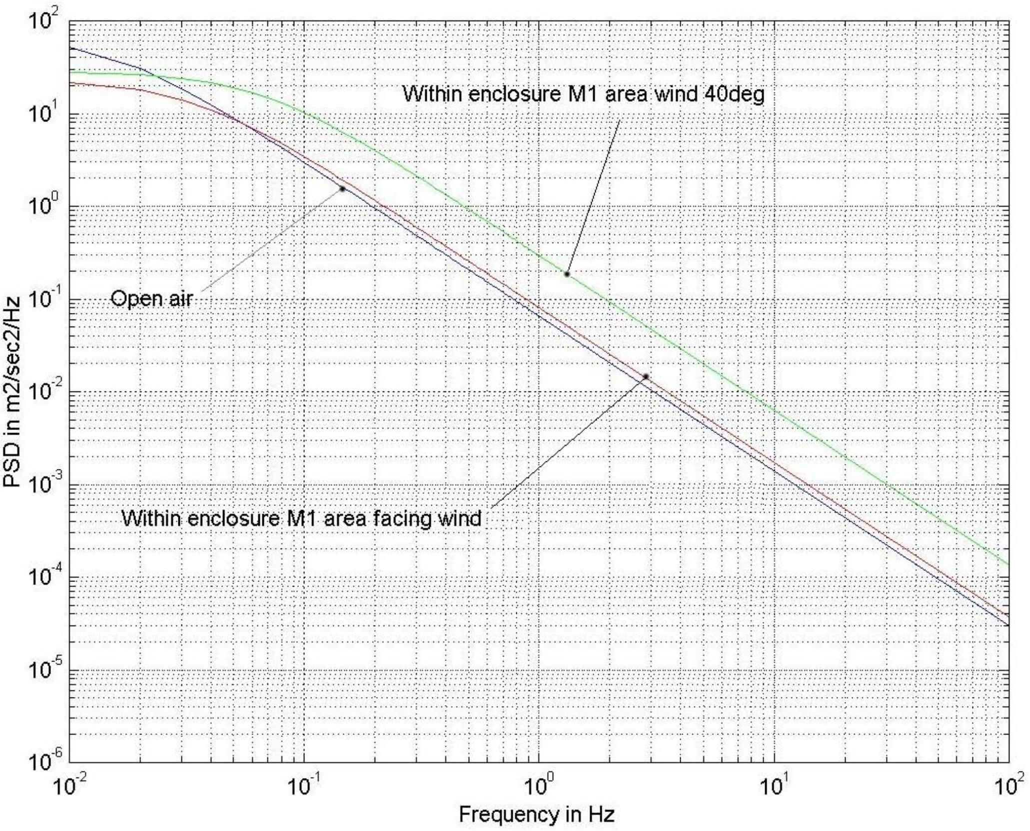

Figure 2-13. PSD of turbulent wind speed in open air and inside VLT enclosure (no wind screen).

Representative data will be obtained in the framework of the ELT Design Study with the Wind Evaluation Breadboard (WEB, see section A-1.2), and fed back into the specifications and design of the telescope, including its control systems.

In view of the above, the current baseline is open-air operation. As a backup, wind screens embedded into the azimuth structure could shield the primary mirror up to ~30 degrees zenithal distance. It should also be noted that low average ground wind speed is a crucial site selection criterion for adaptive optics.

The telescope will be protected against adverse meteorological conditions by a sliding enclosure (Figure 2-14). The enclosure would slide down along the statistically prevailing wind, with a travel distance such that pressure turbulence induced by the enclosure would be mostly averaged out before hitting the telescope in case of unfavorable wind direction. This enclosure will provide passive thermal shielding only; dedicated mirror covers, corrector and instrument housings are foreseen to provide daytime cooling of sensitive subsystems. The mirror covers (6 petals for each primary and secondary mirror) slide out of the telescope for operation. One cover is to be equipped with handling and cleaning units for segments maintenance.

Secondary mirror covers would most plausibly be unnecessary if the segments are made of silicon carbide, whose favorable thermal conductivity would allow the segments to follow ambient temperature.

Alternative enclosure designs have been briefly evaluated but so far different configurations implied considerably higher steel masses hence significantly higher costs, without providing critical advantages. The trade-off may however have to be revisited if the site eventually selected does not provide sufficient space for the travel of a sliding enclosure concept.

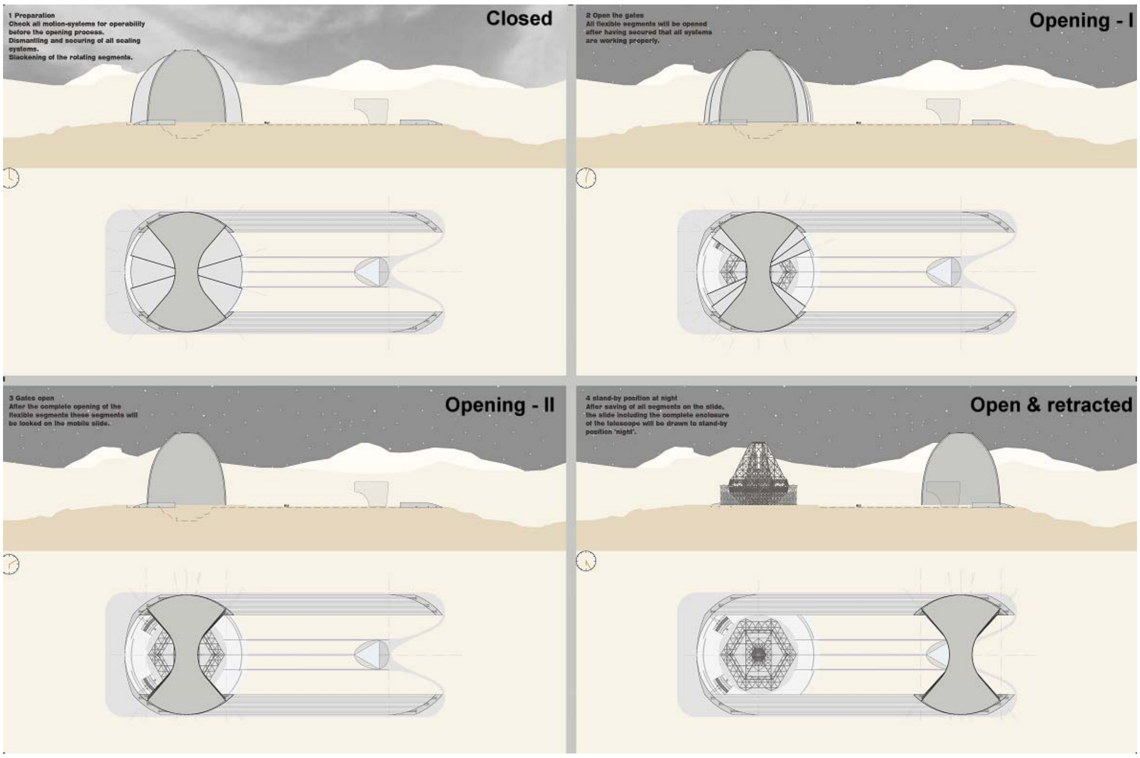

Figure 2-14. Sliding enclosure (courtesy CL-MAP)

2.6.5 Instrumentation

It is generally recognized that it is essential to develop instrument concepts very early in the design of a new telescope. Instruments represent the vital link between the photon-collecting bucket, however sophisticated and powerful, and the scientific goals of the project. As such instrument studies probe effectively the telescope interface and operation scheme and they verify whether the required scientific observations can be obtained with feasible and affordable instruments. This path has been followed by the VLT project where an instrumentation plan was developed almost a decade before first light. For OWL, ESO has launched in 2004 8 instrument concept studies (see Table 2-4) in collaboration with several European institutes.

In the selection of the initial instrument concepts, we have been guided by the science cases identified in the OPTICON study of the science case for a generic 50-100 m ELT and by preliminary studies on the OWL scientific goals. The selected instruments offer various imaging and spectroscopic modes of observing and operate in different wavelength bands from the blue to sub millimetres. They are well representative of the different possible modes of operation of OWL and probe well the telescope ultimate capability. The sample is however by no mean exhaustive of all potentially unique observations to be done with an ELT of the OWL class. High resolution spectroscopy in the near infrared, astrometry at the diffraction limit are examples of two interesting modes not explored in this phase.

Six of the studies were led by P.I. from different European Institutes, two were coordinated by ESO. The instruments study teams were asked to identify the specific science drivers and use them to define the requirements, to develop an instrument concept and to evaluate its performance at OWL. They had to compare them with what it is expected in the next decades from major ground-based and space-born facilities like ALMA and the JWST. They had also to address the dependence on telescope diameter in the range 50-100m and to underline any critical aspects by interfacing with the telescope.

This first survey of possible OWL instruments saw the active involvement of more than 100 astronomers and engineers who through this exercise become familiar with ELT properties and produced a first batch of attractive optomechanical solutions. For many of the astronomers in particular it was a first impact with the "overwhelming" capabilities of a 100m but also with the differences, and in some cases the limitations, with respect to the 10m class telescopes we are used to work with. All responded in a quite enthusiastic way to the new challenge.

Instrument	**Wavelength range**	**Main Capability**	**Primary Science Goals**	**Institutes**
CODEX	0.4-0.7 μm	High velocity accuracy, visual spectrograph	To measure the dynamics of the Universe	ESO, INAF-Trieste, Geneve Obs., IoA Cambridge
Quant EYE	0.4-0.8 μm	Photometry at 10^{-3} - 10^{-9} second resolution	Astrophysical phenomena varying at sub-millisecond time scale	Padova Univ. & Lund University
HyTNIC	1.1-1.6 μm	High-contrast diffraction-limited imaging	Imaging of massive planets, bright galactic and extra-gal. sources	LISE- Collège de France
EPICS	0.6- 1.9μm	Camera-Spectrograph at diffraction limit	Imaging and spectroscopy of earth-like planets	ESO + ext. experts
MOMFIS	0.8-2.5 μm	Near IR spectroscopy using many deployable IFUs	Masses of high z galaxies, regions of star formation, GC stars	CRAL, LAM, OPM
ONIRICA	0.8-2.5 μm	NIR Imaging Camera on a field up to 3 x 3 arcmin	Faint stellar and galaxy population	INAF Arcetri & Heidelberg MPIfA
T-OWL	2.5-20 μm	Thermal, Mid Infrared Imager and Spectrograph	Search, study of planets, high redshift Hα galaxies	MPIfA Heidelberg, Leiden Univ., ASTRON, ESO
SCOWL	250-450-850 μm	Imaging at sub-millimetre wavelengths	Surveys of dusty regions, of extragalactic fields for star-forming galaxies	ATC

Table 2-4 Instrument Concept Studies

The eight studies had from 4 to 12 months to be completed. The results are summarized in section 12.2 and the full study reports are reference documents to this volume. Overviews of the interface aspects, of the Adaptive Optics and of the Detectors array requirements are given in section 12.2.5, 12.2.6 and 12.2.7, respectively.

According to the wavelength range where they operate, the instrument highlights can be outlined as follows:

- There are two of the instruments foreseen to operate in the Blue-Visual and Red wavelength bands with natural seeing image quality: CODEX and QuantEYE. They both use the outstanding collecting power of OWL to do unique science. CODEX makes use of the photon plethora to achieve high S/N ratio, high resolution spectroscopy of faint stars and quasars with unmatched (~1 cm/s) velocity accuracy. Main science goal is the direct measurement of the dynamics of the universe, but several other fields of astrophysics will be boosted by CODEX observations. QuantEYE on the contrary explores the temporal dimension of the photon flux. By covering the time resolution 10-3 – 10-9 s, it will permit for the first time to explore the quantum properties of the light from a variety of astrophysical sources.
- There are two "wide" field instruments for NIR wavelengths (0.8 – 2.5 μm): ONIRICA, the imaging camera, and MOMFIS, the multi field-unit spectrograph. Both address many of the "classical" ELT science cases and as such reveal the power but also the peculiarities of observing with OWL. The ONIRICA team has identified diffraction limited imaging over a field of ~ 30" as the primary observing mode. Using a MCAO system one can expect Strehl of 30 % in the diffraction peak of the PSF over the field in periods of good natural seeing.

With this performance the imaging capability of ONIRICA clearly surpasses JWST in limiting magnitudes of stellar sources. Detailed studies of stellar population in Virgo and beyond become possible. The baseline concept of MOMFIS foresees 30 IFU units which can be positioned over a 3' x 3' field of OWL. Its main scientific goal is spectroscopy of high redshift galaxies ($z > 4$). Their expected half-light sizes are typically ~ 0".1 and this value drives the IFU size to sub arc second and the sampling to 20-30 mas. At a spectral resolution of 4000, MOMFIS would be more powerful than JWST in spectroscopy of faint high redshift candidates identified by multi-color JWST imaging. While working far from the diffraction limit, MOMFIS requires a distributed AO system (MOAO) to deliver a moderate concentration of light at the sampling resolution. A first run of simulations with natural guide stars has shown that this might be possible but with limited sky coverage.

- One of the key science cases for OWL is the search for Earth-like planets close to nearby stars. Starting from the results of the Planet Finder studies for the VLT, EPICS addresses various observational approaches to detect and characterize Earth and Jupiter-like planets: differential imaging, polarimetry, NIR IFU spectroscopy and FTS spectroscopy. The spectral range where these modes should operate span from the Visual to the J band. EPICS will require a third generation AO system (XAO) to achieve the diffraction limit with high Strehl at the wavelengths of operation. A set of simulations carried out during the study suggest that an Earth-like planet could indeed be detected with EPICS at a 100m OWL telescope. The selection of the final instrument configuration, of its primary observing modes and the prediction on its ultimate performance will have however to wait for more extensive modelling in the successive phase of the project.
- T-OWL is an imager-spectrograph to operate in the thermal infrared between 2.5 and 20 µm. In this spectral region the requirement on the AO system are relatively modest. In the bands where the atmosphere is transparent, T-OWL will outperform MIRI at the JWST in the observations of point-like sources. A wide range of targets from dusty planetary systems to black holes in the nuclei of active galaxies will be the primary science goals of T-OWL.
- SCOWL is a large field (~ 2'.5) submillimetre camera to observe in the three submillimetre bands at 350, 450 and 850 µm. It capitalizes on the expertise acquired with SCUBA1 and SCUBA2 instruments and uses it to draw the concept of a powerful survey instrument. SCOWL would supply the ALMA interferometer with a wide range of newly-discovered sources for detailed investigation. It benefits from the diffraction limit given from the OWL size (~1 ") without the need of an AO system. It does require a very high and dry site.
- HyTNIC presents the concept of hypertelescope as a multi-element imaging interferometric array having a densified pupil. It allows direct imaging with high resolution during the segment-filling phase of the M1 preparation with a very simple NIR camera, providing observations of unique scientific value before OWL's completion.

As a conclusive statement of this section, we underline that the instrument concept studies have become available toward the end of the Blue Book preparation. While some advanced feedback from the studies has been already taken into account, the global results of the studies will be fully folded in the telescope design at the beginning of the next phase of the OWL project only.

Finally, with a look at the future steps in this area, we remark that the OWL Instrumentation effort has been coordinated with the work on ELT instruments foreseen within the ELT Design Study (see A-1.8**)**. At the kick-off meeting of the ELT instrument "Small Studies" in September 2005, 8 instruments were identified which very much will extend or complement the work carried out for OWL. Many of the OWL Instrument Concept Study teams are involved in this effort and will put to best use their newly acquired expertise there.

2.7 Progressive implementation

A by-product of segmentation is that the telescope can deliver sky images before full completion of the aperture. Such feature has been taken advantage of with the Keck and will be with GTC. With only 36 segments, however, the integration time scale is too short to allow for anything but engineering work until the aperture is filled. With OWL, a segments integration time scale in the range of 5 to 6 years, in-line with the segments production scheme, would leave far more time than required for engineering purposes. Taking into account the fact that the start of segments integration is, according to current plans, contingent to on-site acceptance of major subsystems, including enclosure, telescope structure and kinematics, alignment metrology, corrector and provisional, passive M5 and M6 units, to name a few, and allowing for 19 months of engineering and 5 months of commissioning time, science operation with a partially filled aperture ought to be possible long before completion of the entire project: already several hundreds of segments will be able of delivering useful images. Actually the integration plan for the segments does require the telescope to be fully operable on-sky and will indeed make critical use of this to phase newly installed segments. Even so, a large fraction of the nights will be free for possible science use. The instrument studies have started assessing the possibility of working with a partially filled aperture. More analysis is necessary to determine whether a solution based on specific instrumentation and AO system for a given equivalent size (which would then last for an extended period) may be an alternative.

The progressive implementation scheme is also optimized to allow maximum development time for the adaptive units and to allow on-sky engineering with provisional, passive units before their delivery. In addition, a stepwise, progressive integration and testing of the system –in particular control systems- allows for equally progressive debugging.

The path to first, seeing-limited light is determined by the final design and construction of the telescope enclosure, structure, kinematics, and essential control systems: internal alignment, phasing, active optics, field stabilization. Taking into account the fact that the actual critical path is the supply of the 8-m mirrors of the corrector rather than the supply of the highly standardized enclosure, telescope structure and kinematics, seeing-limited first light ought to be possible within 6 years of ordering the fabrication of the 8-m mirrors[25].

Segments integration will start after integration of a dummy corrector and testing of the telescope kinematics and internal metrology. Preliminary requirements for the segments integration and maintenance are given in RD5. The enabling milestones for the start of integration of the primary mirror segments are outlined in Table 2-5. According to the current design and plans, segments integration and maintenance are only allowed during daytime.

The expected integration rate is two segments per day, the necessary infrastructure is basically that required for segments maintenance. Indeed the maintenance infrastructure has a capacity much larger than required for the sole integration purposes, and implies no particularly advanced technology (see RD5). The maximum required capacity of the maintenance line peaks at an average of 5.1 segments per day, replaced or newly integrated in the sixth year of integration, assuming relatively short-lived, conventional aluminium coatings. The maintenance rate decreases to an average of 4.2 segments per day in normal operation. Rotating spares and using multiple lines to wash and coat individual segments (in contrast to a single line able to handle several segments at once) allows for a robust maintenance scheme, with generally progressive and/or low impact of failure at any given stage of maintenance (see RD5).

Segments integration will follow the four phases described below. Timelines are indicative and correspond to the baseline plan.

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[25] The first VLT 8-m blank was delivered within 5 years after ordering (from SCHOTT) and the first finished mirror within 6 years after signature of the polishing contract (with REOSC, now SAGEM). Both contracts implied the construction of dedicated facilities. In the meantime, the SCHOTT facility has been dismantled and the REOSC one converted for the production of GTC segments.

Subsystem	Status	Enabling milestone
Telescope enclosure	Fully functional	On-site Provisional Acceptance
Telescope structure incl. kinematics	Fully functional	On-site Provisional Acceptance
M1 & M2 Mirror covers No 1 incl.		
Covers structures & kinematics	Fully functional	On-site Provisional Acceptance
Handling tool[26]	Fully functional	On-site Provisional Acceptance
Local storage racks	Fully functional	On-site Provisional Acceptance
Rack transporter	Fully functional	On-site Provisional Acceptance
M1 & M2 Mirror covers No 2 incl. in-situ cleaning unit(s)	Fully functional	On-site Provisional Acceptance
M1 & M2 covers No 3 to 6	Fully functional	On-site Provisional Acceptance
Corrector	Dummy corrector integrated and tested	De-integration of dummy corrector
Telescope pre-alignment metrology	Functional up to dummy corrector as rigid body.	Tests up to dummy corrector as rigid body completed.
Coating tanks	Fully functional	On-site Provisional Acceptance
Washing units	Fully functional	On-site Provisional Acceptance
Segments handling carts	Fully functional	On-site Provisional Acceptance
Segments maintenance lab	Fully functional	On-site Provisional Acceptance
Segments units	At least 7 M2 segment units ready for integration, coated, tested.	Successful phasing of a 7-segments module of M2 in the segments maintenance lab.

Table 2-5. Subsystems status at start of segments integration.

Phase 1 Blind integration of the M1 and M2 mirror segments.

The plan is to start integration of segments in blind mode only. Blind mode is meant for in-situ coarse phasing (no on-sky calibration). At this stage of telescope integration, the corrector is not yet available but the system has been tested with the dummy corrector.

Phase 1 starts when all conditions specified in Table 2-5 are met and ends at first light with the acceptance of the corrector, with temporary non-adaptive M5 and M6 units, and including the focal plane metrology systems.

According to current plans phase 1 lasts 6 months, at the end of which first light occurs with an equivalent diameter of 57-m (collecting area).

Phase 2 Daytime blind integration, night-time phasing on sky

Phase 2 starts with seeing-limited first light and ends with first AO light (single conjugate IR AO with M6 unit). In phase 2 the telescope is operating in seeing-limited, engineering mode only.

According to current plans phase 2 lasts 7 months, at the end of which the provisional M6 passive unit is replaced by the final AO one and first AO light occurs. At this stage the equivalent telescope diameter is about ~67-m.

Phase 3 Daytime blind integration, night-time phasing on sky.

During phase 3 engineering night-time related to segments integration and control shall decrease to negligible proportions. Phase 3 coincides with the commissioning of the first stage of adaptive optics and ends with the start of science operations. At this stage the telescope equivalent diameter is ~75-m.

Phase 4 Daytime blind integration, night-time phasing on sky.

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[26] Including its on-board phasing metrology.

> Phase 4 covers essentially the filling of the full aperture, with completion by mid-2021. During this phase, integration of segments and related control systems shall only exceptionally interfere with science operations.

First light will occur in seeing-limited mode with temporary, non-adaptive M5 and M6 units. Note that the LISE laboratory (OHP) is currently studying a focal instrument concept along the Labeyrie Hyper-Telescope approach to use such a diluted aperture for high resolution / high contrast imaging. IR single-conjugated AO will become possible after replacement of the temporary M6 unit by the final, adaptive one, with science operations starting shortly after. At this point it is expected that engineering night-time will be negligible in relation to science time. The telescope diameter will be about 50-m in terms of collecting area; the angular resolution will depend on the still to be determined filling geometry but could be that of a 100-m if integration of the segments would start from the outer edge of the pupil.

Dual conjugate IR adaptive optics will start less than two years later, with the provisional M5 unit replaced by the adaptive one.

2.8 Observatory operation

The OWL observatory will be operated in ways significantly different from even the largest current optical observatories. While inheriting innovative concepts that have been successfully implemented at the VLT/VLTI, the planned operations of OWL will also heavily rely on the experience gathered by ESO in the operation of ALMA. The possibility of building OWL on a new site, as was done with the VLT, would offer the advantage of planning the entire observatory infrastructure and operations around the facility.

As the paradigm at modern observatories already shows, the OWL observatory must be designed as a facility that includes not only the telescope, instrumentation, and on-site infrastructure and staff, but also all the remote locations where development and segments of operations take place, such as instrument building, software development including scientific data processing tools, data archiving and distribution, and support to the users community, among others.

The extended partial completion phase that OWL will undergo offers opportunities for the early scientific exploitation of an already unique facility, also enabling its progressive technical and scientific validation. There is a clear parallel with ALMA, which will take advantage of such extended transition stage to set up all aspects of operations including personnel training and systems validation. Furthermore, the continuous maintenance needs of such a complex facility will benefit from the experience acquired in that stage in which demanding technical and scientific activities will coexist.

The ultimate scientific legacy of OWL will reside in the quality of its data products. Such quality relies on the capabilities of the telescope and its instrumentation, but also on the careful implementation of operational procedures for their full characterization and calibration, quality control, and instrument health checking. Such procedures are in turn essential for the population of an archive containing science-ready products that facilitate their reusability, mainly by means of their publication in the Virtual Observatory that is expected to constitute a fundamental tool for observational research in astrophysics by the time that OWL becomes operational. The full-scale implementation of an end-to-end system at the VLT and VLTI has provided ESO with a very important capital of know-how and lessons learned from which ALMA will also greatly benefit, and that will be an essential part of the design of operations at OWL. The operations planning in the data flow area will have to adapt to the expected data rates. The data volume will not be much different from the upcoming surveys telescopes (e.g. VST, VISTA, LSST) and already routinely applied to particle physics experiments (CERN). Improvements in the technological development, even if slowed from the currently still holding expansion laws for CPU, data storage and data transmission increases, will be sufficient to handle the data rates from a telescope like OWL.

Whether the projects executed at the OWL will follow current time distribution paradigms at general-purpose facilities like the VLT, or be largely focused on experiments requiring the exclusive use of the observatory for an extended period of time in order to achieve far-reaching goals, or a combination of both, will depend on the demands of the scientific community and the general development of observational astrophysics in the next decade. Operation mainly or exclusively by specialized observatory staff is envisaged, and this will be taken into account when deciding on staffing, policies, procedures, and tools. Such specialized interaction will be frequently needed both to exploit the technical capabilities of OWL to the limit, and to maximize the scientific output of the limited time available.

An essential part of the success of a modern observatory is the availability to the research astronomers of tools that allow the full scientific exploitation of the datasets. This will be even more so for OWL, given the foreseeable complexity of its instrumentation and of the process of removal of the instrumental signature given, for instance, the structure of the delivered PSF. Dedicated software to be made available to the end users and able to fully process the data delivered by the instrument up to the science-ready level will be regarded as an integral part of each instrument. Such software will meet the requirements needed to be integrated in the main data reduction environments existing at the time of OWL operations, and will deliver products in compliancy with the Virtual Observatory.

2.9 Site considerations

Site characterization and selection has an overwhelming impact on eventual performance (operational efficiency, quality of science data) and, potentially, cost and schedule. The selection of Paranal as the VLT site may arguably have been the single most relevant decision in relation to VLT performance. Cost and schedule should not be underestimated either, as a significant cost increase may eventually require a reduction of the telescope diameter[27] and as a significantly longer schedule could make the project unattractive.

There is no such thing as the perfect ground based site; as with the telescope design, the eventual site selection is the result of a trade-off between at times conflicting constraints and priorities. The parameter space has grown considerably since the mid-20th century, and is due to grow considerably more for Extremely Large Telescopes. The performance of relatively wide-field adaptive optics, in particular, is contingent to the structure of atmospheric turbulence (see section 14.2.3). Good seeing is no longer good enough; instead of an integrated parameter, a thorough statistical description of the vertical structures and time constants of atmospheric turbulence become equally relevant.

Merit functions encompassing priorities and relevance to performance, cost and schedule must be established, with a view to allowing a difficult –and soon irreversible- decision to be taken in proper knowledge of its consequences. Such merit function will include fixed and reasonably well quantified parameters, such as topology, soil properties, and their predictable impact on the system performance and cost (e.g. the telescope foundations). Other parameters will be of a statistical nature, and will have to be assessed in a probabilistic context. Others will be inherently speculative, such as political stability or local manpower costs. Finally, long-term variation of relevant parameters must be taken into account to the maximum possible extent (see also section 14.3.3). Climate change is an established fact; its long-term prediction and modelling are, as of today, notoriously inaccurate. Ignoring them for such reason would however be irrational and, potentially, disastrous.

The OWL site characterization and the definition of figures of merit should encompass, as a minimum, the following criteria (the ordering of the list is without any prioritization):

1. Cloudiness;

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[27] Downtime related to weather conditions, for example, might be traded against statistical performance during “uptime” or against a significant reduction of the telescope diameter excluding certain science cases.

2. Humidity, Precipitable Water Vapor;
3. Atmospheric Extinction;
4. Seeing or turbulence coherence length;
5. Ground temperature, air temperature gradient and microthermal turbulence over the first 100 m;
6. Vertical structure of the atmospheric turbulence, with a resolution not worse than +- 500 m in altitude up to ca. 20km;
7. Isoplanatic angle;
8. Turbulence coherence time;
9. Outer scale of the atmospheric turbulence;
10. Sodium layer mean density and annual variation;
11. Wind speed and direction;
12. Precipitations (snow, rain, ice, fog);
13. Airborne aerosols, including dust chemical composition, particle size distribution and abrasive characteristics;
14. Site topology;
15. Soil properties, including typical stiffness,
16. Seismicity;
17. Survival loads (earthquakes, wind, precipitations);
18. Present and future potential light pollution; contrails;
19. Access to pre-existing infrastructures (roads, harbor, etc.); development costs;
20. To the foreseeable extent, long-term exposure to climate change;
21. To the foreseeable extent, potential long-term political stability.
22. Site-dependent operational costs, including, to the foreseeable extent, local manpower costs.

These parameters shall be characterized in a consistent form, and the instrumentation required to acquire them, where appropriate, shall follow standards allowing rigorous comparison of potential candidates (see also section 14.1.1). A detailed merit function will be set in the design phase, with weights reflecting priorities and, where sufficient data are available, individual sites ratings.

Gathering and compiling data form only part of the search for and characterization of an OWL site. Understanding sites properties on micro- (a few km) and macro- (a few 100 km or more) scales is essential to predicting performance-relevant characteristics and their probable evolution with time. Software tools have been elaborated in the framework of the OWL concept study, with a view to providing easy access to available meteorological databases over past decades (see section 14.3.3.2). Models can be established, cross-checked by comparing their prediction to measured performance at well documented sites (e.g. Paranal, La Palma), and then applied to the search for (or to predict performance) of other, less well documented candidates. Doing so should allow to bypass years if not decades of measurements, and to reach an informed decision in a faster and more efficient way.

Site search and characterization are evidently not exclusive ESO activities. The matter is the subject of a world-wide cooperation. Part of this effort is addressed within the framework of the ELT Design Study (see section A-1.9), whereby two well known sites (Paranal area and La Palma) will be characterized in relation to properties relevant to Extremely Large Telescopes. This is *not* meant for those two sites having already made it to the shortlist, but as an equivalent to point designs i.e. taking an a priori and fictive decision, then proceeding with design and analysis in order to understand its full consequences.

ESO's own experience in site characterization is extensive and dates back to the earliest days of the VLT programme. Considerable expertise has been accumulated since then (see 14.3.1) and shared with ELT proponents worldwide.

2.10 Plans for final design and construction

The schedule for design and construction of OWL is essentially determined by five factors:

1. the dates at which necessary financial commitments (including all resources required to execute the scope of work) can be made, and the dates at which such resources become available;
2. the telescope size, the implied industrial capacity to supply long-lead items, and the dimensioning of integration lines;
3. the ability of the supply, integration and maintenance plans and implied infrastructures to allow early operation and cope with a progressive implementation of scientific capabilities, without significant overheads on science time.
4. the progress of technology in the area of advanced wavefront control, in particular adaptive optics;
5. the duration of the preliminary and detailed design phase.

The first factor is arguably the most determinant; its impact can be alleviated to some extent if significant but not major commitments[28] can be made to secure, at an early stage, the procurement of long-lead items (essentially the 8-m mirrors), the final design of the enclosure and telescope structure, and the first generation adaptive mirror technology.

The second factor is strongly influenced by the design directions underlying the OWL concept, in particular the reliance on serial production and integration schemes and on proven and reliably predictable technologies. This not only allows for favourable cost scaling laws, but also allows for fast and flexible supply, production and integration cycles. As such, the penalty implied by large size can be offset by supply and integration times much faster than those associated to custom designs of subsystem, assemblies, and parts.

The same comment applies to the third factor, which influences the dimensioning of the integration and maintenance infrastructures. As impressive as those may eventually be, they are essentially a matter of adequate planning, optimized process flow, and investment.

The fourth factor corresponds to the main technological risk area and calls for continued investment in development and design, most particularly in the area of large and/or densified[29] adaptive mirrors.

The fifth factor only weakly depends of the telescope size and, as such, does not imply a significant schedule disadvantage compared to other Extremely Large Telescope projects. In this respect, it should be noted that OWL benefits from sustained design and analysis activities since 1997, including industrial studies. The implied competitive advantage should not be underestimated.

Detailed plans have been developed for the design and for the construction and integration phases (see chapter 16). These plans allow for maximum development time for critical technologies (such as adaptive optics and laser guide stars) and timely feedback from the ELT Design Study. Figure 2-15 shows the major milestones. After consolidation of the management and product assurance plans and procedures, the first two years would concentrate on conceptual design iterations, analysis, error budgeting, finalizing subsystems requirements, site

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[28] In practice, less than 10% of the total estimated cost.

[29] Actuator density.

search and characterization. The optical design would be frozen towards the end of the second year, after two feedback iterations -most notably to take into account the outcome of instrument studies. Also included in the first two years is the subcontracting of a process flow study, with a view to streamlining the construction and operation processes, to defining the optimal maintenance structures, and to incorporating the study results in the system design where appropriate. Although the ELT Design study already includes prototypes SiC segments, additional and complementary effort is foreseen in order to finalize the decision on segments substrates within the third year of design.

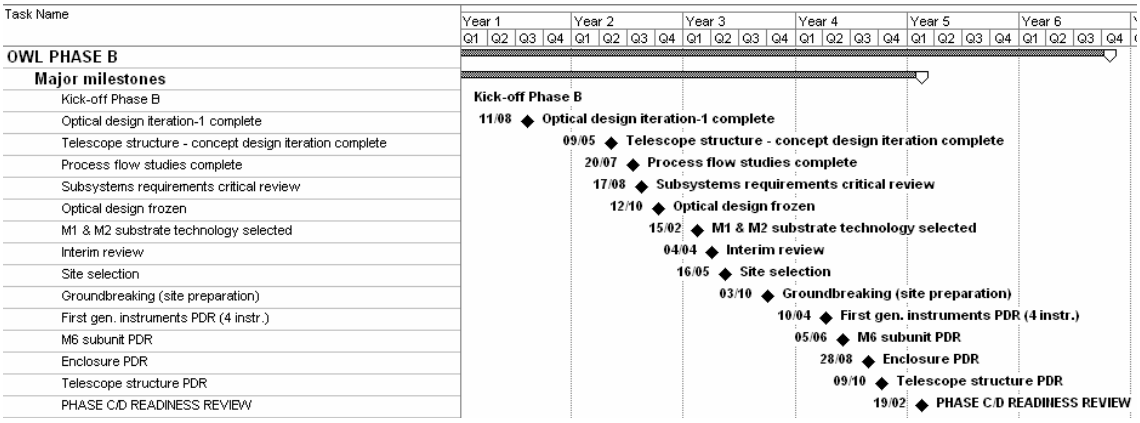


Figure 2-15. Design phase, major milestones.

By the end of the second year, results of the Active Phasing Experiment (APE, in ELT Design Study) will lead to the detailed definition of the control systems.

Site selection is planned mid-way through the design phase and is required to finalize requirements on the infrastructures, enclosure and foundations. The second half of the design phase would concentrate mainly on

- Preliminary and final design of the enclosure;
- Preliminary and final design of the telescope structure (including mirror covers and wind shields, if any),
- Preliminary design and prototyping of the first generation adaptive subunit (M6),
- Preliminary designs of at least two first generation instruments,
- Detailed definition, specifications, price inquiries for all major units / subunits, including all integration, verification, maintenance and operation infrastructures and equipment;
- Site preparation (access roads, storage areas, temporary infrastructures, first stage power supply);
- Finalization of Assembly, Integration and Verification (AIV) plans.

Ideally, each of the first 3 items above would be covered, for risk mitigation, by two competitive contracts until Preliminary Design (and, for M6, prototypes) before granting contracts for final designs.

The design phase also includes

- Iterations of the Top Level Requirements, in close cooperation with the scientific community, and subsequent iterations of Level 1 requirements and of error budgets;
- Substantial R&D effort in adaptive optics technologies, including laser guide stars, deformable mirrors, metrology systems; in wavefront control (including tests on GTC), and high contrast imaging;
- Extensive analysis, modelling and tests, including wind tunnel testing;
- Prototype segments (1:1 scale), including axial and lateral support systems.

The baseline plan for the design phase does not include any financial commitment ahead of phase C/D capital investments, except for initial site preparation and the first stage of the power plant.

Phase C/D would start after the readiness review planned at the beginning of the 5th year (2010, assuming a start of the design phase early 2006). The status of all subsystems, units, and subunits at the readiness review is detailed in chapter 16. At this stage, time-critical subsystems will be in the final design phase. Figure 2-16 shows the schedule of the major milestones.

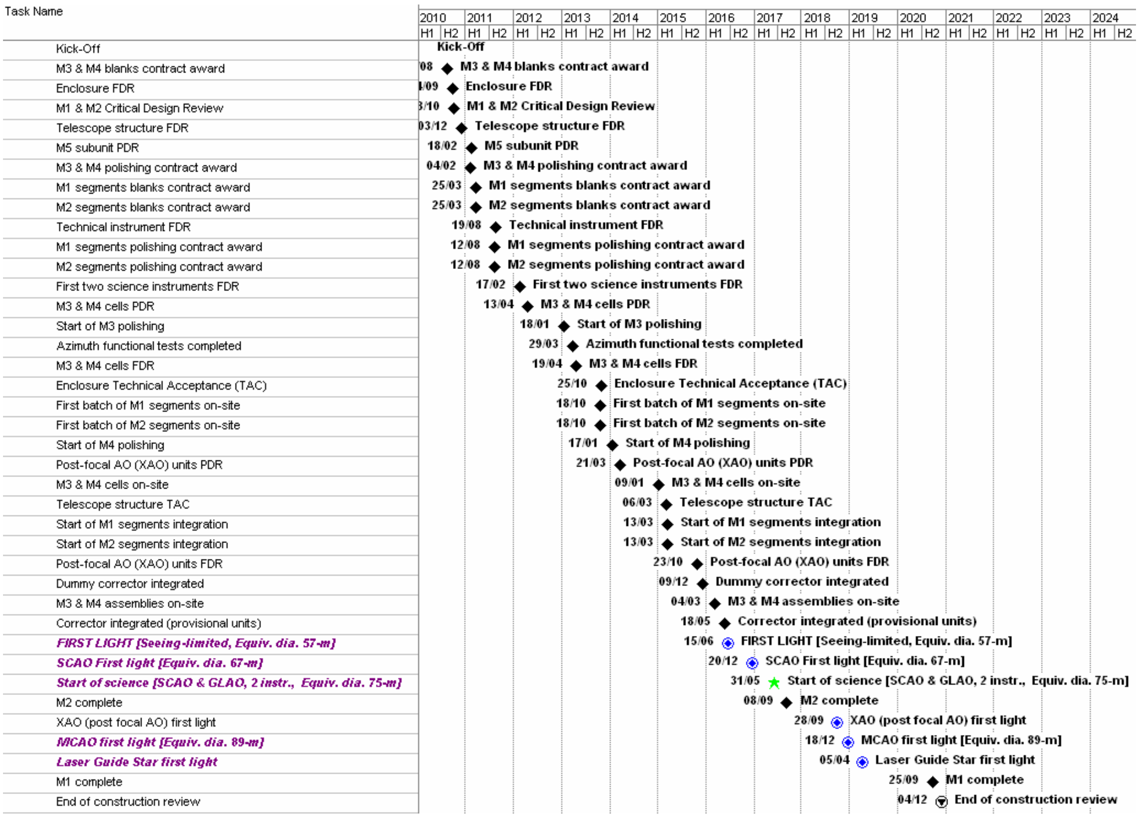


Figure 2-16. Phase C/D major milestones.

The telescope structure and kinematics would be integrated in parallel to the enclosure i.e. the structure and kinematics shall be designed to survive open air environmental conditions. Segments integration would start after completion of the telescope structure and kinematics (see RD5 for a complete definition of enabling milestones and of required equipment), and be interrupted for each major handling (e.g. of the corrector).

As a general rule, no glass goes into parent units or subsystems prior to dummy testing as a minimum, and no subsystem or unit goes to the telescope prior to extensive off-line testing. The same applies with integration and maintenance lines.

First light would occur by mid-2016 with provisional, non-adaptive M5 and M6 units. At that stage the telescope would have an equivalent diameter of 57-m. The total time for integration of the segments is identical to the production cycle (6 years). The equivalent diameter after first light depends on the capacity of the integration lines. Because such lines rely on essentially the same equipment as maintenance, and assuming that any segment would need maintenance more than once every 6 years, integration rate is accelerated in the first 1.5 year (however not to full capacity).

The 6 months following first light are devoted to extensive engineering tests and observing runs in seeing-limited mode. Thereafter the corrector is removed, the 8-m mirrors coated, the adaptive M6 unit integrated and the corrector re-integrated into the telescope for first light in SCAO mode. At that point the telescope would have a collecting area equivalent to that of a 67-

m one. After another 6 months and with an equivalent diameter of 75-m, the telescope would enter into science operation. The aperture would be completed by 2020.

In the baseline plan, segments deliveries occur about 1.5 years ahead of the required date; no attempt has been made yet to optimize the schedule and smooth the cash flow profile. The production of the 8-m mirrors is on the critical path to first light. The schedule to first light could most probably be accelerated by up to a year if the 8-m blanks were ordered one year before completion of the design phase.

The segments production and integration is on the critical path to full completion. Potential segments suppliers claim that facilitization of their production units would take less time than anticipated (2 years) but this has not been taken into account.

2.11 Cost estimate

The OWL cost estimate is collated from the results of industrial studies (most notably, segments production, telescope structure and kinematics, enclosure), internal estimates based on past experience (e.g. the 8-m mirrors), and allocations (e.g. adaptive mirrors).

Several estimates have been produced, depending on major technology choices –e.g. segments substrates, enclosure concept, etc. A detailed presentation is provided in chapter 16. The baseline or *best estimate* is based on conventional substrates for the segment blanks and assumes an enclosure cost close to the upper limit indicated by industrial studies. The total estimated cost for capital investment 1.255 B€ (Table 2-6), including 35.5 M€ in the design phase. These figures do not include ESO manpower, estimated at about 85 Full-Time Equivalents (FTEs) for phase B and 300 FTEs for phase C/D. The FTEs allocation assumes extensive subcontracting of most design and construction activities to expert suppliers, and no major in-house new software development.

The allocation for instruments is 50 M€ (excluding ESO manpower), assuming at least two first generation instruments. A significant allocation is made for maintenance infrastructures and facilities, under the assumption that such maintenance would be performed on-site. A study is planned in the design phase to ascertain whether this should be the case, or whether part of the maintenance could be relocated or even outsourced.

The estimate for control systems should be understood as reflecting the budget for central control only; subsystems own control systems are included in the corresponding subsystems estimates.

It should be noted that according to industrial studies, major cost saving could be realized

- if the segments were made of Astro-Sital or if low-cost silicon carbide solution(s) could be demonstrated;
- if the enclosure could rely on low-cost *tensiarity* principles proposed by AirLight (RD40).

In the most optimistic case the potential cost savings are in excess of 300 M€. As these options developed after drafting ESO's current long-range plan, no supporting R&D costs are currently budgeted in the design phase of the baseline plan. Risk mitigating measures, such as subcontracting competitive preliminary designs for the enclosure, for the telescope structure and kinematics, and for the first generation adaptive subunit are not included either,

A rough order of magnitude (ROM) estimate of the underlying R&D activities which would have to be undertaken in the design phase to properly evaluate these cost-effective alternatives amounts to 15 M€ (i.e. the capital investment in phase B would increase to 50.5 M€).

As indicated in section 2.10, ordering the 8-m blanks ahead of the construction phase would allow accelerating the schedule to first light by about one year. Depending on supplier, this may translate into a commitment of up to 35 M€ to be transferred from the construction into the design phase. Such commitment would have to be made within the third year of the design phase to secure the accelerated schedule.

Item	Phase		
Project Management		**143.6**	
Contingency	C/D		110.8
Process flow & costing studies	B		0.5
Overheads (transports & insurance)	C/D		32.3
Project Engineering		**12.4**	
Wind tunnel testing	B		0.8
R&D, major breadboards and experiments	B		11.6
Site infrastructure		**87.4**	
Enclosure		**169.6**	
Design	B		7.0
Enclosure foundations	C/D		28.8
Kinematics	C/D		16.9
Enclosure structures	C/D		115.0
Enclosure Maintenance Units	C/D		1.9
Telescope structure & kinematics		**186.6**	
Design	B		7.7
Azimuth structures	C/D		77.1
Altitude structures	C/D		60.4
Wind screens	C/D		2.8
Mirror covers	C/D		17.1
Telescope foundations	C/D		19.0
Telescope diagnostic systems.	C/D		1.9
Telescope structure & kinematics maintenance units	C/D		0.9
Optomechanical subsystems		**552.1**	
Actuators, position sensors - designs & prototypes	B, C/D		4.1
Segments development & prototyping	B		2.8
Primary mirror unit	C/D		329.5
Secondary mirror unit	C/D		23.3
Corrector unit	C/D		132.0
Focal stations	C/D		24.6
Telescope pre-alignment unit	C/D		0.4
Optomechanical subsystems maintenance facilities	C/D		35.5
Instrumentation		**72.0**	
Technical instrumentation	C/D		8.0
Science instrumentation	C/D		50.0
Post-focal AO units	C/D		10.0
Instruments maintenance facility	C/D		4.0
Laser Guide Stars Subsystem		**10.7**	
Laser units	C/D		5.0
Beam Propagation units	C/D		3.0
Control & Metrology units	C/D		2.0
LGS maintenance facility	C/D		0.7
Central Control Systems		**19.5**	
Site characterization		**0.8**	
TOTAL		***1254.6***	

Table 2-6. OWL cost estimate, capital investment.

2.12 The ELT Design Study

In March 2004 a proposal for a technology development towards ELTs was submitted to the European Commission for funding within framework Programme 6. The proposal has been approved and the project is running since January 1st, 2005.

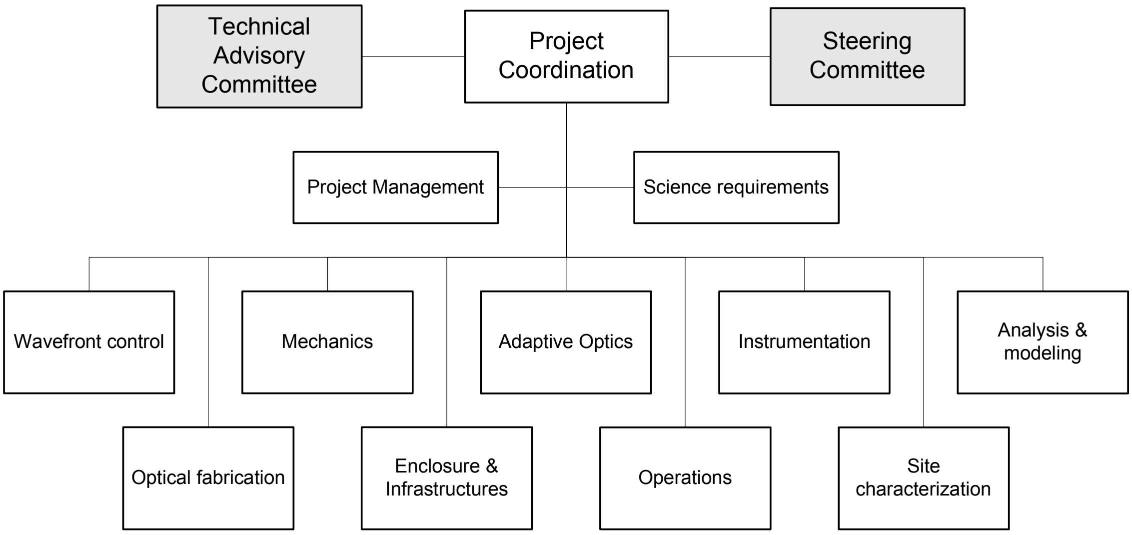
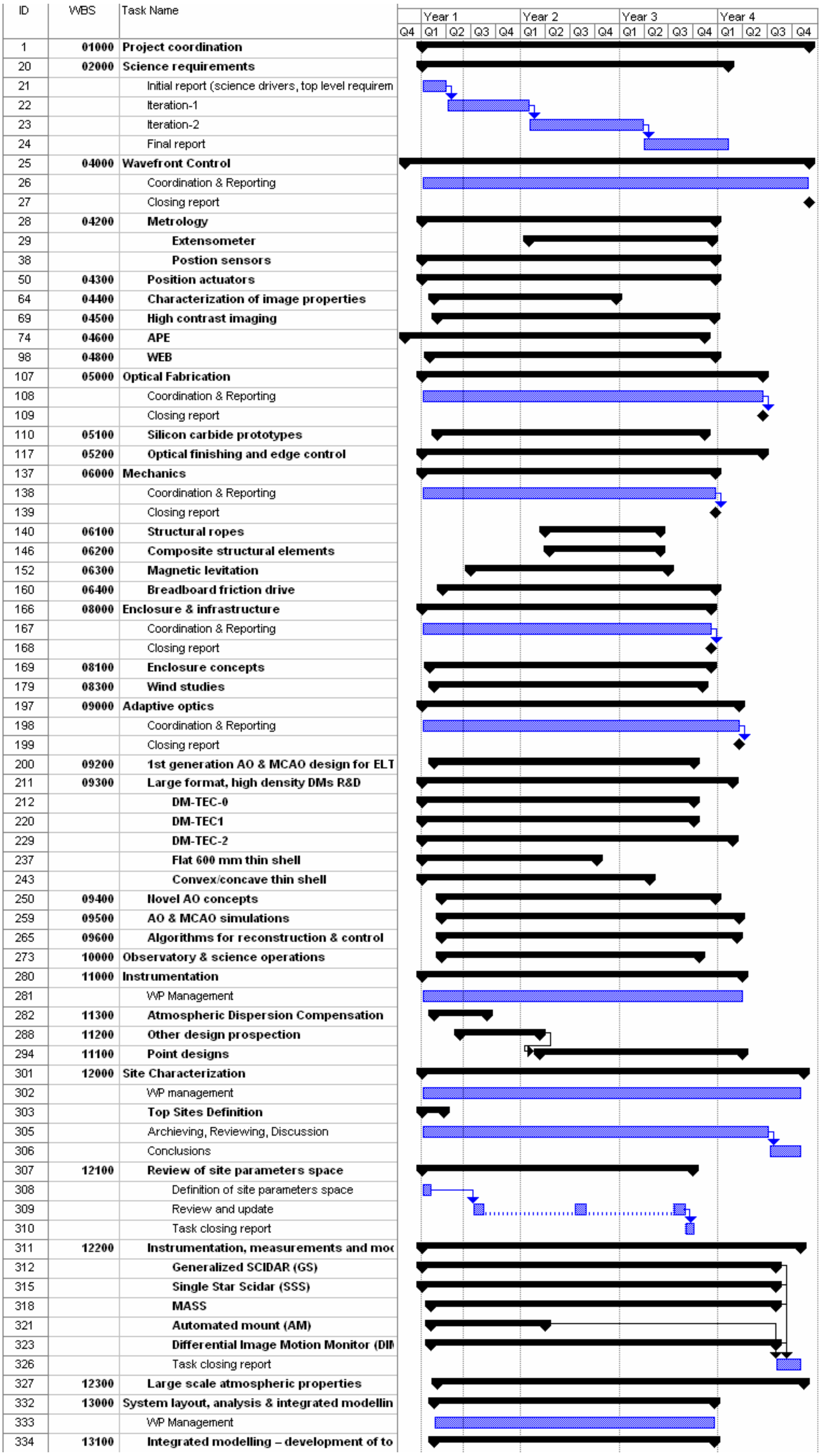


Figure 2-17. ELT Design Study, Work Breakdown Structure.

The project covers the development of enabling technologies and concepts required for the construction of a European extremely large optical and infrared telescope, with a diameter in the 50- to 100-m range. To this end, it builds on existing European design studies, on leading industrial and academic expertise in the relevant fields, and gathers resources across the European academic and industrial communities for a preparatory effort on crucial components, subsystems and concepts. To the possible extent, and contrarily to what its name would imply, the ELT Design Study is design-independent. Indeed, it focuses on technical issues relevant to any system design. The ELT Design Study is complementary to OWL design; both are conceived as parallel activities, the synergies and respective schedules allowing timely and cost-effective feedback between the two. It follows that, from OWL point of view, the ELT Design Study covers most of the concept and technology developments that would have to be undertaken in parallel with the detailed system design. As a result, the ELT Design Study does not imply a diversion of resources to another ELT project, but allows for the sharing of common efforts, to the benefit of the scientific community.

The project gathers 30 partners under ESO's lead (see Appendix 2 for a list of the participants). The total estimated cost is M€ 31.6, including M€ 8.4 in Community support. ESO's total contribution to the project amounts to M€ 11.740, out of which M€ 9.379 is covered by ESO internal funding. Figure 2-17 shows the Work Breakdown Structure and Figure 2-18 the estimated schedule.

An overview of the Work Packages is provided in Appendix 1. A complete definition of the scope of work is given in reference document RD509.



ID	WBS	Task Name
1	**01000**	**Project coordination**
20	**02000**	**Science requirements**
21		Initial report (science drivers, top level requirem
22		Iteration-1
23		Iteration-2
24		Final report
25	**04000**	**Wavefront Control**
26		Coordination & Reporting
27		Closing report
28	**04200**	**Metrology**
29		**Extensometer**
38		**Postion sensors**
50	**04300**	**Position actuators**
64	**04400**	**Characterization of image properties**
69	**04500**	**High contrast imaging**
74	**04600**	**APE**
98	**04800**	**WEB**
107	**05000**	**Optical Fabrication**
108		Coordination & Reporting
109		Closing report
110	**05100**	**Silicon carbide prototypes**
117	**05200**	**Optical finishing and edge control**
137	**06000**	**Mechanics**
138		Coordination & Reporting
139		Closing report
140	**06100**	**Structural ropes**
146	**06200**	**Composite structural elements**
152	**06300**	**Magnetic levitation**
160	**06400**	**Breadboard friction drive**
166	**08000**	**Enclosure & infrastructure**
167		Coordination & Reporting
168		Closing report
169	**08100**	**Enclosure concepts**
179	**08300**	**Wind studies**
197	**09000**	**Adaptive optics**
198		Coordination & Reporting
199		Closing report
200	**09200**	**1st generation AO & MCAO design for ELT**
211	**09300**	**Large format, high density DMs R&D**
212		**DM-TEC-0**
220		**DM-TEC1**
229		**DM-TEC-2**
237		**Flat 600 mm thin shell**
243		**Convex/concave thin shell**
250	**09400**	**Novel AO concepts**
259	**09500**	**AO & MCAO simulations**
265	**09600**	**Algorithms for reconstruction & control**
273	**10000**	**Observatory & science operations**
280	**11000**	**Instrumentation**
281		WP Management
282	**11300**	**Atmospheric Dispersion Compensation**
288	**11200**	**Other design prospection**
294	**11100**	**Point designs**
301	**12000**	**Site Characterization**
302		WP management
303		**Top Sites Definition**
305		Archieving, Reviewing, Discussion
306		Conclusions
307	**12100**	**Review of site parameters space**
308		Definition of site parameters space
309		Review and update
310		Task closing report
311	**12200**	**Instrumentation, measurements and moc**
312		**Generalized SCIDAR (GS)**
315		**Single Star Scidar (SSS)**
318		**MASS**
321		**Automated mount (AM)**
323		**Differential Image Motion Monitor (DIN**
326		Task closing report
327	**12300**	**Large scale atmospheric properties**
332	**13000**	**System layout, analysis & integrated modellin**
333		WP Management
334	**13100**	**Integrated modelling – development of to**

Figure 2-18. ELT Design Study, overall schedule.

2.13 Scalability

The design of OWL is based to the largest possible extent on serialized production of identical parts. It is therefore to be expected that the results of the studies and the analysis of options presented in this report have an intrinsic scalability to different telescope sizes. What the range of scalability is, how the optical design may evolve as a function of size or how the scientific goals are affected by a smaller or larger diameter than the one considered here need a dedicated study, which will be carried out at the beginning of Phase B.

Here we provide some preliminary considerations and figures.

2.13.1 Science

Annex A of the Science Book looks at the comparative scientific performance of different ELT sizes for the highlight science cases. The results are summarized in Table 2-7 to Table 2-9, showing that the full achievement of the science goals can be met only with a 100-m OWL (although admittedly this is a somewhat circular argument, since the science case was developed for telescope sizes of 50 to 100m to start with).

How a science case scales with size depends not only on the collecting area and the resolution but also on a number of aspects related to the telescope design and to the required technology developments, and how these scale with the diameter. Parameters like field of view (both its size and its coverage: contiguous, sparse etc), limiting magnitude, required angular resolution at a given wavelength, number and type of targets, spectral resolution, sensitivity to polarization, etc, all play a role in determining how a science case scales with diameter. Moreover, some cases may have a “scaling law” that affects only the completeness of their samples, while others may be enabled only above a certain size (an example is the exo-earth science case).

Content of information is also a relevant issue when comparing the scientific capabilities of telescopes of different sizes. For telescopes at the diffraction limit, a given number of pixels cover an angular field proportional to D^{-2}. Assuming that the number of pixels is independent of diameter (in principle it is limited by how many we can afford and by the size of the optics that we can build in the camera containing them), the question of how much information there is in the field of view, or what fraction of pixels contain data on astronomical objects rather than the background, depends very much on the science case and should be carefully analyzed in a study of “science scalability” (does the number of objects increase with increasing sensitivity, does seeing them in better detail offset the fact that there may be fewer of them, etc). This may also lead to different ways of sampling the telescope field of view (as in the multi-IFU vs slit mask approach to multi-object spectroscopy: is there scope for relocatable multi imagers?).

An in-depth analysis of these issues will be carried out at the beginning of Phase B.

20m	- Direct detection of Jovian-mass planets in wide orbits around nearby solar-like stars - Radial velocity search on fainter stars (increasing available volume by a factor of 200)
30m	- Imaging of young (<10Myr) Jovian planets around stars in star-forming regions up to 75pc away - Detection and classification of mature Jovian planets around stars within 10-20pc - Possible detection of one Earth-like planet within ~5pc
100m	- Survey of 1,000 solar-like stars and direct detection of a number of earth-like planets within 30pc - Time-resolved photometry of Earth-like planets (albedo & weather) - Spectroscopy of earth-like planets and search for “Biomarkers” - Study of entire exo-planetary systems

Table 2-7 Summary of exo-planet capability as a function of ELT size

20m	- Resolution of the oldest stellar populations in Magellanic Clouds and Local Group dwarf spheroidals (Sculptor, Fornax, Carina) and the Sagittarius dwarf - Resolution of the brightest giant stars in galaxies in the Virgo cluster - Observations of halo giants in Local Group galaxies (high-resolution spectroscopy)
30m	- Age/metallicity measurements of resolved populations in M31/M32 at ~750kpc (imaging) - Determination of star formation and chemical enrichment histories of galaxies out to Cen A (nearest active galaxy)
100m	- Age/metallicity measurements of resolved populations, reaching the Virgo and Fornax clusters at 16-20Mpc - Detailed study of galaxy formation in a representative sample of the Universe

Table 2-8 Summary of studies of resolved stellar populations as a function of ELT size

20m	- Ly-alpha emission-line spectroscopy from 6<z<10 - Possible detection of z~10 objects (depending on their nature)
30m	- Possible detection of z~10 objects (depending on their nature) - Spectroscopy of “earliest galaxies” found by JWST - IGM studies to z~10 using brightest GRBs as background sources
100m	- Detection of z>10 objects - Spectroscopy of “galaxies” to z~20 (depending on their nature). Such objects may even be resolved with a 100m - IGM studies at z>10 (GRBs, QSOs, PopIII SNe as background)

Table 2-9 Summary of studies of the high-redshift Universe as a function of ELT size

2.13.2 Requirements

Requirements for a telescope depend on the science case, so a proper assessment of how they vary with telescope diameter can be made only after the study mentioned above has been completed. There are however some general scaling considerations: some requirements may remain the same whatever the size of the telescope (e.g. the emissivity) or may vary with the area (e.g. the number of degrees of freedom of AO mirrors). Some may have subtler diameter dependence (e.g. they may disappear if they were set by a science case no longer achievable with a different size). Special cases are the focal ratio, which is set by the viability of different optical designs for different sizes, and the wavelength coverage under adaptive optics correction, where achieving short wavelength AO may be limited to smaller telescopes.

Table 2-10 summarizes our current understanding of the dependence of the requirements on the telescope size.

Requirement	**Dependence on D**	**Comments**
Collecting area	D^2	
Wavelength coverage	D^0	Set by science requirements. Achieving shorter wavelength AO may depend on D
Focal ratio	D^0	But different D’s may allow different designs with different F/ratios
Image quality (opt design)	D^0	e.g. “Diffraction limit over 5 arcmin”
Diffraction limit	D^{-1}	
Emissivity	D^0	Depends on reflectivity and baffling

Requirement	Dependence on D	Comments
Field of View	D^0	Depends on science case.
Transmission	D^0	Equals $\{\Pi_i \eta_i - \ldots\}$ $i=1,N_{mirrors}$
Focal stations	D^0	Larger telescopes may have more room for instruments
Sky coverage	D^0	
Zenith avoidance	D^1	Depends on maximum rotation speed of the structure
Image quality (AO)	D^0	Req depends only on science
Diffraction limit	D^{-1}	
Number of actuators	D^2	
Operational lifetime	D^0	
Technical downtime	D^0	Maintenance may take longer (but not be necessarily more complex) for larger D's
Operating costs	$D^{1.5}$ (?)	Depends mostly on cost law but with a fixed component
ADC residual dispersion	D^{-1}	Constant in terms of pixels

Table 2-10. Dependence of main telescope requirements on diameter D

2.13.3 Concept design

Operational considerations and data management requirements set aside, we can consider an extremely large telescope as a controlled opto-mechanical system. Consequently, the upper size limit is governed by the feasibility and complexity of the optics, of the control systems, structure and kinematics. Feasibility of instrumentation is of course also a limiting factor.

The use of Alt-Az mounts enables very effective ways to improve load transfers and simplify structural design, while at the same time allowing for much smaller (hence much less expensive) enclosures. Closed-loop autoguiding allowed for a relaxation of exacting tolerances on the telescope kinematics. However, casting and polishing large, homogeneous mirrors, and maintaining their shape and alignment in operation imposes strict limits on scalability. Keck, NTT and VLT each addressed these limitations, with spectacular results. Optical segmentation would allow scaling up to the limit of possible industrial production. Active wavefront control would allow optomechanical structures to be controlled up to the limit of affordable control complexity. Such limits are of a very different nature than former ones, and aperture sizes significantly larger than that of OWL should be possible. Control systems rely on fast-evolving metrology and IT technologies, and industrial studies for the production of OWL segments indicate that 3,000 segments would be well within the limit. It should also be noted that the most difficult control system is in adaptive optics, with a number of degrees of freedom comparable or larger than that of the telescope itself combined with a much higher bandwidth.

On the basis of OWL studies and analyses we conclude that beyond ~130-m, adequate structural performance and safety could no longer be guaranteed without extensive use of advanced, composite structural materials with consequent sharp increases in cost.

The difficulty to make monolithic mirrors beyond proven sizes (~8-m) also sets an intermediate range beyond which multiple segmentation becomes inevitable. A 100-m design with a powered, monolithic 8-m class secondary mirror would theoretically be feasible but all such designs explored so far had significant drawbacks in terms of sensitivity to:

- decentres
- vignetting
- availability of suitably located and sized surfaces for adaptive optics
- in the case of a spherical primary mirror, the delivered image quality.

Further design options would have to be explored before proposing any definite conclusion; our judgement is that multiple segmentation becomes a necessary compromise beyond ~70-80 m.

The lower size limit for an Extremely Large Telescope is not a matter of technical feasibility per se, but of overall design and cost (see section 2.13.4). The OWL optical design is quite similar to that of HET and SALT. Extrapolating upwards from more classical solutions, one should note that scaled-up versions of existing designs (basically a larger Keck with VLT flavour in control systems) must also overcome significant, specific technical hurdles. Large secondary mirrors point towards Gregorian solutions, with correspondingly longer structures or a shorter primary mirror focal ratio, limited field of view and high sensitivity to decentres. All current 30 to 50-m class designs allow for a limited number of reflections, at the cost of large, aspheric adaptive secondary mirrors comparable to that proposed for OWL second generation adaptive optics.

In general, we expect that overall design choices made for OWL would hold within a downscaling to ~60-m, with comparable functionality, similar hierarchical distribution of functions, perhaps with a significantly different optical design and, at the lower limit, single segmentation. The situation is far less clear in the 20-50 m range. It is worth recalling that all studies made for 30- to 50-m telescopes opted for more conventional design solutions. It is plausible that below 60-m, the compromises underlying the OWL design would have to be re-balanced, leading to a leaner, but far less cost-effective, design.

2.13.4 Cost and schedule

The schedule and cost-effectiveness of the OWL design are mainly due to

- design tradeoffs (e.g. open air operation, spherical primary mirror, large lightweight structural design, low-cost kinematics),
- low fabrication and supply risks,
- and above all, reliance on standard parts or serial production.

Design tradeoffs - HET and SALT are spectacular examples of how far design compromises may impact costs. Arguably the largest optical telescopes, they have been built at a cost lower than the 3-4-m class telescopes commissioned in the 1970s and 1980s. HET and SALT designs also incorporated low supply risks (spherical, 1-m class segments) and low cost enclosures. They may have benefited from serialized production of segments and structural elements, but to a far more limited extent than OWL. On the other hand, with its alt-az kinematics, OWL does not go as far as HET and SALT in design compromises, which henceforth would play a more limited role in terms of cost reduction.

Open air operation and relaxed requirements on the enclosure (no air conditioning), however, leads to very significant cost savings. Enclosures for 3- to 4-m class telescopes of the second half of the 20th century represented more than 50% of the total project investment. With NTT and VLT this figure has been brought down to 20-30% and the trend is due to hold.

Lightweight structural design - Although the cost per unit mass of structural, passive mechanics is very low, the OWL design, with a volumic mass about 60 times lower than that of the VLT, allows for notable cost savings. A downscaled version of the current structural design to 60-m leads to a factor two reduction in moving mass (see section 9.6.4) hence, in first approximation, to the same factor two on the telescope structure. This is probably optimistic as the mass ratio between high cost functional (drives, actuators) and low-cost structural (passive) mechanics increases with decreasing telescope size.

OWL friction drives come at a cost comparable to that of the VLT's hydraulic pads and tracks. We do not expect that dimensional tolerances for hydraulic pads and tracks could be met with apertures significantly larger than that of the VLT. No detailed assessment of the cost of friction drives for a 60-m class telescope has been made; we expect, however, such cost to be roughly proportional to moving mass i.e. a factor 2 lower.

Standardization - With the current OWL design, approximately 82% of the total mass (excluding foundations, enclosure and infrastructure) of the telescope is made of standard steel elements, and approximately 17 % of serially produced[30] parts (structural nodes, drives, segments, actuators, etc). Only 1% of the total mass corresponds to custom-made units (8-m mirror units, adaptive units, etc). Figure 2-19, taken from a leading optical manufacturer, shows the relation between unit cost and total quantity. The model applies to conceptually simple items, which can however be the result of a complex process (optical parts being a typical example). Parts or units themselves made of standard components would follow a less favourable law.

Still, capital investment in production facilities is a significant fraction (~30-50%) of supply costs, at least for the segments (see e.g. RD6 to RD12). It is in the area of structural mechanics, not optics, that cost benefits induced by standardization are maximal.

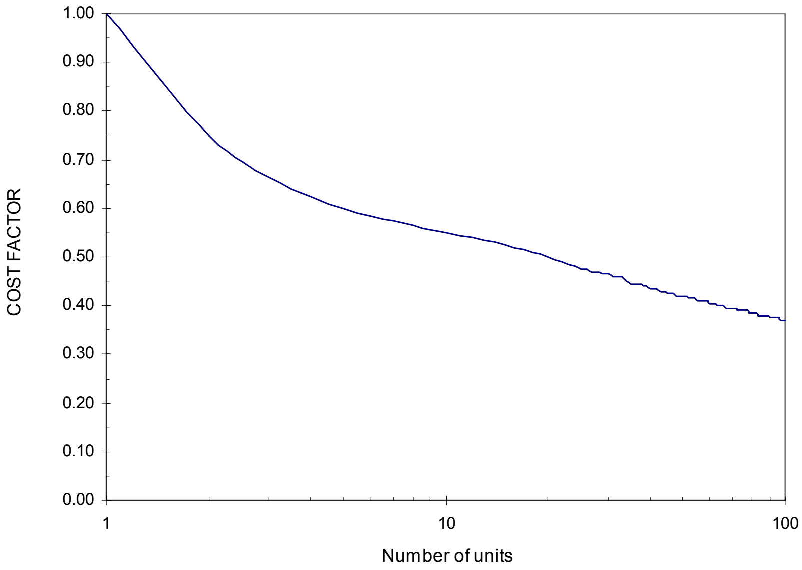


Figure 2-19. Unit cost vs. quantity (industrial data).

As for schedule, scaling the aperture would affect the construction but not the design phase, which is only weakly design dependent (provided, of course, that the design phase capitalizes on the effort already put into the conceptual design phase).

With the current OWL design the schedule to first light is essentially set by the production of the 8-m mirrors and of the first generation adaptive unit. Downscaling to ~60-m is likely to lead to a redesign of the optics but active mirrors in the 4- to 8-m and adaptive ones in the 2-3 m range would still be required. As a result, downscaling would not lead to a very significant reduction of schedule. We anticipate that a 60-m telescope designed and built on the principles underlying OWL would see first light about one year earlier than the current design.

2.14 Risk areas

Any project has associated risks, and one as complex as OWL will need appropriate risk management. A Risk Review is planned early after the start of Phase B.

This section describes the risks identified in the course of the conceptual design, and indicates plausible mitigating actions. We separate the risks areas in two main categories: environmental risks, e.g. natural phenomena that may affect the safety of the observatory or atmospheric

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[30] At least a few hundred units.

effects on science performance, and system risks, e.g. critical technological developments or manufacturing difficulties.

We describe the processes and the underlying philosophy of risk management that ESO has in place for its projects, as applicable to the OWL design and development.

2.14.1 Environmental risks

OWL has to be able to cope with a variety of environmental conditions, from atmospheric effects on the structure or on the optical quality that affect observations, to extreme natural phenomena like earthquakes or storms that may jeopardize its integrity.

The conceptual design presented here addresses most of these risks by setting level one requirements that account for them and by exploring design solutions that allow mitigating or minimizing them.

Table 2-11 summarizes some of the most important environmental risks, and possible mitigating solutions and/or areas where further development is needed. It should be noted that not all the possible solutions have been studied (dedicated studies are planned in Phase B). Of those already considered, not all have been analyzed with the same level of detail as some can only be addressed properly after the design iteration at the beginning of Phase B and/or once a site has been selected. However, awareness of the risks and their possible consequences will be a driving input in the site selection.

Problem	**Effect**	**Possible solution(s)** **(non mutually exclusive)**
Wind buffeting	Tracking errors, phasing errors	• High mechanical stiffness • Control loops optimized for perturbation rejection • Lightweight segments • Accelerometer feed forward/feedback • Embedded wind screen / mesh • Lower the altitude axis of 12.8 m. To be crosschecked with thermal turbulence compatibility. • Prevailing direction wind screen • Site selection criterion (low ground wind speed required for adaptive optics as well)
Differential refraction	Position of stars in "large" field of view varies differentially as zenithal distance changes (up to > 2 mas/hour at 1 arc minute distance)	• Observe at ± 1 hour from meridian • Post processing (requires background limited short exposures ~ 0.1 PSF/rate and extremely low RON in optical) • Smaller field of view at wavelengths shorter than I-band (< 2 arc minute) • Variable curvature cylindrical optics
Atmospheric turbulence	Seeing, scintillation	Adaptive optics. Requires: • Good site (long $\tau0$ i.e. low ground and jet stream wind speeds) • High order correction (> 10,000 dof) • Very fast computers • Gradual approach (IR SCAO first) • R&D on large deformable mirrors
Atmospheric dispersion	Source light dispersed by atmosphere	• Atmospheric dispersion compensator • Needs to correct to ~ 0.2 pix • More than one glass (?) • Active dispersion correction • At instrument/sensor level

Problem	Effect	Possible solution(s) (non mutually exclusive)
		• Partial correction to use atmosphere as dispersive element in an instrument (?)
Earthquake	Potentially devastating	• Structural stiffness, damping, higher steel grade. • Composite materials for highly seismic site. • Telescope low mass • Smooth transmission of loads. • Foundation tailored to ground geo-mechanical characteristics. • Site selection criteria (low level of earthquake, stiff local soil conditions) • Self deploying safety devices (e.g. mirror clamps, airbags etc) • Kinetic energy absorbers • Energy absorption on the x-y plane due to azimuth wheel and track friction. • Energy absorption on the z direction using the bogies hydraulic whiffle tree needle valve. • Hierarchical acceptable damage strategy (human safety paramount)
Exceptional precipitations, snow, ice, storms, fire	Potentially devastating	• Design requirements, safety margins • Redundant, self-powered “closing” mechanisms • Early warning (off-site real time monitors) • Shelters (human safety), evacuation procedures • Fire fighting facilities / equipment • Lightening strikes protection facilities and embedded in the concept (Faraday cage) • Site selection
Pollution, contrails, dust, light contamination	Decrease of performance, downtime, possible reliability issues (dust contamination of electromechanical assemblies)	• Slight overpressure in enclosure (dust) • Increase preventive maintenance (dust) • Dust deposition rejecting concept of the telescope structure. • Telescope tracks protection and cleaning system. • Local dust and thermal protection of critical subsystems and components (Optics, electronics, etc.) • Site selection • Several opportunities for baffling (stray light)

Table 2-11. Summary of environmental risks (a few comments still to be incorporated).

2.14.2 System risks

The main system risks are listed in Table 2-12. The risk management methodology is outlined in section 2.14.3. In the following we address each of them very briefly.

	Area	Risk	
1.	**System size & complexity**		
1.1.	Design, AIV	Traceability, project processes, number of interfaces	Performance Cost Schedule
1.2.	Maintenance	Permanent and intensive maintenance	Cost Performance
2.	**Adaptive optics**		
2.1.	Adaptive mirror unit		
2.1.1.	Number of degrees of freedom	Complexity, reliability	Performance Cost Schedule
2.1.2.	Mirror shell	Production, interface glass/actuator	Performance Cost Schedule
2.1.3.	Safety	Handling, mirror integrity	Performance
2.1.4.	Field stabilization	Failure to meet accuracy / dynamic range requirements	Performance
2.1.5.	Vibrations	Failure to meet image quality requirements	Performance
2.2.	Real-Time computer	Number of degrees of freedom	Performance
2.3.	Detector, wavefront sensor	Readout noise, frequency, size	Performance
2.4.	MCAO	Not yet proven on-sky	Performance
2.5.	XAO	Requires new corrector technology (MOEMs)	Performance, Cost
3.	**Laser Guide Stars**		
3.1.	Laser	Laser technology, reliability	Performance Cost
3.2.	Wavefront sensing	Aberrated reference, enormous defocus	Performance
4.	**Phasing**		
4.1.	Calibrations	2 mirrors to phase (on-sky calibration)	Performance Cost
4.2.	On-sky metrology	Accuracy, capture range	Performance
4.3.	Reliability	Number of actuators, sensors	Performance
5.	**Wind (open air)**		
5.1.	Tracking	Image quality, downtime	Performance
5.2.	Mirrors deflections	Image quality, downtime	Performance
6.	**Integrated wavefront control**		
6.1.	Complexity	Nesting / overlap / cross-talk; reliability	Performance
7.	**Optical fabrication**		
7.1.	Segments	Production	Cost, schedule
7.2.	Segments	Edge misfigure (turned-down edges)	Performance

	Area	Risk	
			Cost Schedule
7.3.	Aspheric mirrors	M4 figuring and testing.	Performance Cost
8.	**Telescope structure & kinematics**		
8.1.	Construction	Production, integration	Schedule
8.2.	Kinematics	Friction	Performance
8.3.	Open air integration	Must withstand environmental conditions during integration	Cost Schedule
9.	**Enclosure, infrastructure**	Enclosure size, wind load	Cost

Table 2-12. System risks

1. System size and complexity

1.1. Design, AIV

The overall system complexity and the implied number of interfaces call for strong System Engineering, configuration and interfaces management. Although the number of degrees of freedom is substantially larger with OWL than with VLTI, the overall number of possible configurations is somewhat lower and the overall number of independent functions comparable.

1.2. Integration, maintenance

Integration and maintenance processes need some form of “Industrialization”. Process flow studies by expert consultant are foreseen in the design phase. De-localisation, off-line maintenance and outsourcing will be studied in the design phase.

High standardization and the availability of spares as a maintenance buffer (e.g. segments assemblies) are favourable factors.

System robustness / partial or progressive loss of performance associated to maintenance failure is a design criterion. Multiple maintenance lines allowing parallel processing of individual assemblies vs. single line processing several assemblies in a single run will be evaluated in the design phase.

2. Adaptive Optics

2.1. Adaptive mirror units

Concept design studies and analysis are currently being contracted out (2 competitive studies) to industry. A complete re-assessment of risks shall be undertaken in the design phase.

2.1.1. Number of degrees of freedom

Reliability will depend on actuator technology and may have significant cost impact. The performance impact of single actuator failure should be marginal -in particular with force actuators (LBT technology). Prototyping and extensive testing is foreseen in the design phase. Adaptive mirror units shall make maximum possible use of Line-Replaceable Units (electronics, actuators) and allow rapid replacement in case of failure. Extensive diagnostics shall be incorporated in the design of the units.

2.1.2. Mirror shell

According to suppliers, the production of a thin (~1mm) two metre-class shell suitable for M6 does not seem to be a major challenge. The flat shape of the mirror is an essential factor and may allow cost-effective production. Samples of low-cost LCD screen and Borofloat® sheets have been tested for optical quality and the results are very encouraging. Such sheets are available up to 2.3-m width at a cost of about € 1,000.- a piece. Several thicknesses, starting with 0.7-mm are available in standard production. According to the first test results (20 × 20 cm² samples), only minor post-polishing would be required –if any.

The same does not apply to the M5 unit (3.4 to 3.9-m, depending on allowable vignetting on the wavefront sensors). Longer development time is allocated to this unit.

Interface to actuators and lateral support systems are areas of concern. Prototyping and extensive qualification of the interfaces is foreseen in the design phase.

Temporary, non-adaptive M5 and M6 subunits are included in the plan to allow for engineering runs prior to the integration of the first adaptive subunit (M6). Single conjugate, ground layer and extreme AO do not depend on the availability of the adaptive M5.

2.1.3. Safety

Handling equipment and procedures shall be defined in the design phase. It should be noted that handling of thousands of large glass shells is routine operation in the glass industry.

2.1.4. Field stabilization

The large pupil compression factor on M6 (~1:40) implies large (1:20) angular magnification between on-sky and mirror angles (i.e. 1 arc second on-sky corresponds to ~20 arc seconds mirror tilt). This most probably will require a two-stage tip-tilt compensation, the fine stage being provided by the adaptive shell itself.

2.1.5. Vibrations

Active vibration damping will be evaluated in the design phase. Maximum reaction forces at interfaces are included in the specifications for the conceptual design studies.

2.2. Real-time computer

The number of degrees of freedom and the bandwidth of the control system imply demanding requirements. According to our analysis, however, the requirements for OWL first generation adaptive optics could be met with already existing technology (see section 8.2.1.2.4).

2.3. Detectors, wavefront sensors

Extensive detector development is foreseen in the design phase. According to our analysis, the requirements for OWL first generation adaptive optics could be met with already existing technology (see section 8.2.1.2).

2.4. MCAO

MCAO is not yet fully proven on-sky. Recently the Multi-conjugate Adaptive optics Demonstrator (MAD) had MCAO first light in laboratory. On-sky results are expected by 2006.

2.5. XAO

Extreme Adaptive Optics most probably implies an entirely different mirror technology, MOEMs being the most likely one. The availability of first stage, large amplitude correction with M6 is a positive factor as it relaxes amplitude requirements on the high order corrector. Provisions have been made for substantial R&D well into the construction phase.

3. Laser guide stars

In the current plans, Laser Guide Stars AO is foreseen as third generation adaptive optics so as to allow for maximum development time. This is not an irreversible decision and the implementation would be accelerated if allowed by the progress of concepts and related technologies.

3.1. Laser technology, reliability

With the VLT Laser Guide Star Facility ESO and its partners are gaining experience in the laser technologies. With a number of new generation of Sodium LGS systems entering into operation worldwide, we expect significant development in this area (see also section 8.4.6).

3.2. Wavefront sensing

Spot elongation, defocus and aberrated LGS conjugation may lead to prohibitively complex implementation and limited performance. Complex and active relay optics may be required (see RD1). There are, however, hopeful developments towards entirely different ways to do wavefront sensing on Laser Guide Stars (see section 8.4.4).

4. Phasing

4.1. Double segmentation

The need to calibrate both primary and secondary mirrors metrologies (position sensors) independently is an added complexity. Current efforts in filtering techniques and pattern recognition to disentangle the primary and secondary mirrors phasing errors are giving encouraging results.

It should be noted that one focal station (No 6) is reserved for a permanently mounted technical instrument, with ample design space for on-sky metrology systems.

As a backup, M2 position sensors specifications could be tightened (higher stability) to allow in-situ recalibration with an independent metrology[31] at a manageable time interval. A major cost increase of the position sensors for the secondary mirror would not have a strong impact on the overall project costs[32].

4.2. On-sky metrology (calibrations)

According to Chanan [6], the Keck on-sky calibration technique can be implemented up to ~4,000 segments. Alternatives are under development, all successfully tested in the laboratory, and a pyramid wavefront sensor has recently been tested on-sky (on WHT with segmented AO mirror).

The Active Phasing Experiment (APE) will allow a rigorous comparison of performance of at least three techniques. Further experiments are foreseen on GTC.

4.3. Reliability

With about twice as many sensors as strictly required, the system is over-determined. The performance impact of phasing failures (a few segments) has been analyzed and found to be negligible (see RD21). Local vs. global control and error propagation shall be evaluated in the design phase.

5. Wind (open air)

Substantial effort is being invested in simulations, wind tunnel testing, and measurements on Jodrell Bank radio telescope. This effort will be pursued in the design phase and in the ELT Design Study, in particular with the Wind Evaluation Breadboard (see appendix A-1.2).

5.1. Tracking

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[31] One option would be to fit dual wavelength interferometers (such as that used in APE, see appendix A-1.2) in the M2 covers to allow daytime calibration. Assuming that position sensors would meet drift specifications over 20 days, 12 segments (2 per interferometer) would have to be re-calibrated every day. The estimated cost of this additional equipment is about M€ 3.6, including translation mechanisms inside the M2 covers.

[32] A factor 10 increase compared to the sensors of the primary mirror would lead to a total cost overshoot of about 12 M€.

According to first analysis (see section 7.2.1) wind rejection would not be a major issue. The relatively stiff structure and the insensitivity of the optical design to lateral decentres are favourable factors.

5.2. Mirror deflections

According to first analysis (see section 7.5.5), high spatial and temporal frequency intersegment motion under wind excitation can be controlled to negligible amplitudes.

Preliminary simulations show that residual phasing errors can be significantly reduced by adaptive optics (see section 8.3.2.4).

There is, in addition, room for improvement in the design: local stiffness (segments supports), feed forward on the basis of accelerometers signal. Silicon Carbide would be an advantage (bandwidth of the control system).

Wind screens embedded into the azimuth structure would protect M1 until z~30 degrees. Studies of this option have been cautiously included in the plans.

Finally, it should be noted that sites with low ground wind speed will be favoured for adaptive optics as well.

6. Integrated wavefront control

Integrating all wavefront control loops into transparent and reliable operation is perhaps the most serious challenge for any Extremely Large Telescope. Extensive integrated modelling is foreseen in the design phase. Defining, evaluating and optimizing control schemes in representative conditions is one of the major objectives of the Active Phasing Experiment (see appendix A-1.2).

7. Optical fabrication

7.1. Segments production

The cost and schedule risk for the segments production is critical but probability of occurrence is deemed moderate to low by expert manufacturers (see RD6 to RD12). The spherical shape of the segments is a major advantage.

Cost estimates by different optical manufacturers (polishing) are in very good agreement. Cost estimates for the substrates are rather disparate, owing to the very different underlying technologies (silicon carbide or conventional glass-ceramic).

According to current plans there is a 14 month buffer time between the delivery of the first segments and the start of their integration into the telescope. This buffer could be extended at the cost of a smaller equivalent diameter at first light.

7.2. Edge misfigure

Edge misfigure might lead to significant loss of performance, in particular for high contrast imaging.

Controlling edge misfigure to tight specifications (spatial extension, amplitude) could be a major difficulty, with significant cost and/or schedule impacts. The technique used for GTC segments was to mount wasters on the segments edges. This allowed the segments to be polished to tight specifications up to their edges.

According to suppliers the spherical shape of OWL segments is a favourable factor in that it allows using mostly large, stiff polishing tools. Tests will be made in the framework of the ELT Design Study to polish silicon carbide with minimal edge misfigure and without wasters.

Coronagraphic techniques (see RD22) may alleviate the problem and allow for tolerance relaxation.

7.3. Aspheric mirrors

Figuring and above all testing of the most aspheric mirror (M4) is a major challenge. Owing to the angular magnification (~6) between sky angle and mirror slope the specifications for surface slope errors can be significantly relaxed compared to the VLT

[9]. In addition, a substantial fraction (40%) of the VLT primary mirror active force range was used for the conversion between Nasmyth and Cassegrain. This allocation could be transferred to the correction of residual figuring errors.

It should be noted that the equivalent mirror in the SALT corrector has a similar slope deviation[33] from best fitting sphere. We are not aware that this led to particular difficulties.

The highest risk is with M4 test set-up. A setup has been identified but implementation is extremely challenging (see section 6.5.2). This set-up relies on large (~1.6-m for the largest) spherical, glassy Zerodur lenses. Using computer-generated holograms combined with lenses should alleviate the difficulty to some extent.

In order to account for lengthy test procedures in the final stages of polishing, the time allocation for the polishing of M4 is about 2.4 times longer than the time it took to figure the last VLT primary mirror.

8. Telescope structure & kinematics

8.1. Construction

The telescope structure & kinematics being on the sub-critical path, delays would likely affect the schedule to first light.

The modular design and very high standardization are favourable in allowing parallel supply lines.

According to plans final design would start at the earliest possible date following site selection.

8.2. Kinematics

OWL kinematics cannot realistically rely on classical hydraulic pads / tracks solutions, with their exacting dimensional tolerances. According to our analysis (see section 9.4.5.1.3) friction can be compensated to acceptable levels. Measurements and tests will be performed in the framework of the ELT Design Study (breadboard friction drive, see appendix A-1.4). Magnetic levitation is also to be studied in the same context.

8.3. Open air integration

According to current plans the telescope structure and kinematics (without corrector) would be exposed to natural environment during erection. This may have cost and schedule impacts, depending on the site meteorological conditions. A complete evaluation is foreseen in the design phase.

9. Enclosure

Wind drag is a potential issue. With relatively conventional solutions (sliding enclosure) this leads to a total cost higher than initially anticipated.

The total cost estimate presented in this document takes this issue into account.

Alternative enclosure concepts and technologies (see RD40) may allow major cost reduction.

The enclosure is close to sub critical path; according to plans final design would start at the earliest possible date following site selection.

2.14.3 Risk management

The purpose of this section is to outline the methodology ESO intends to use to guarantee sound planning as part of the execution of the OWL project, in order to anticipate potential obstacles to timely and cost-effective performance, and that processes are in place to mitigate and/or minimise the risks. The OWL project plan is detailed in the Integrated Master Schedule.

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[33] which, as far as polishing difficulty is concerned, is more indicative than aspheric departure.

The first element of this process will be to conduct a Risk Review soon after starting Phase B. This Review will focus on risk identification and on improving the following:

- Concise Risk Descriptions. Descriptions must contain Cause and Effect definitions. Named Risk Owners must clearly define the Probability of occurrence and the Impact if the risk should materialise against the prescribed 3 impact areas of Quality, Cost and Schedule.
- Risk Mitigations Actions. Individual Risk Mitigations must be targeted at specific risk impacts (for example, to add more resources to an activity is aimed at reducing schedule impact. The aim of the mitigations must be clear and must be prepared by the risk owner.
- Risk Contingency Plans. These define alternatives only to be taken if a risk occurs or a mitigation plan has failed to have the intended effect.

Following this review the OWL project office will carry out quarterly programme reviews with all the parties involved to share and discuss the top risks. A ‘snapshot’ of the current risk status will always be available in the Project Risk Register.

Risk Management is Project Management *in action* and generally fosters effective communication between the key areas of the project. To establish and effectively implement mitigation or contingency plans, each action must be: specific, measurable, achievable, realistic and time bound.

The risk impact will be determined using the criteria listed in Table 2-13.

Cost	Quality	Schedule	Impact / Value SEVERITY
Cost increase to OWL Project > XX MEuro	Failure to deliver a major product to an acceptable standard	Delay of > 6 months of a Top Event from the IMS	CRITICAL
Cost increase to OWL Project between CC and XX MEuro	Failure to meet key criteria against OWL specification and no work around currently identified	Delay of 2 – 6 months of a Top Event or 4 – 6 months of a major event from the IMS	HIGH
Cost increase to OWL Project between BB and CC MEuro	Failure to meet key criteria against OWL specification but work around identified	Delay of 0 – 2 months of a Top Event or 2 – 4 months of a major event from the IMS	MEDIUM
Cost increase to OWL Project between AA and BB MEuro	Failure to a criteria against OWL specification that does not significantly affect overall performance	Delay of 0 – 2 months of a major event from the IMS	LOW

Table 2-13. Areas of Risk Impact.

Probability of occurrence of the Risk will be categorised into 1 of 4 criteria:

- Very High. Risk will materialise almost certainly.
- High. Risk would not materialise under optimistic assumptions only.
- Medium. Risk may or may not materialise under normal circumstances. No clear evidence found to support either possibility.
- Low. Risk would materialise under pessimistic assumptions only.

A combination of the Risk Severity and Risk Probability provides a ranking of risks that the Management Team can then address with appropriate attention.

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