Report presented by the

ELT Telescope Design Working Group

(WG4)

May 4th

Issue 3

Preamble

The Working Group on telescope design was appointed by the ESO Director General and included the following people:

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A first meeting was held on January 18th and an additional meeting on February 20th/21st led to the finalization of the present report. In the meantime several sub-groups performed the analysis of optical designs selected as the most representative of the various design families. The work presented in this report is by no means definitive but represents possible starting points for further design and optimization. It is to a large extent based on work done previously at ESO and in the community.
Following the terms of reference of the working group, the report attempts to define the pros and cons of every design and gives a summary of the main design features in order to facilitate the discussion with other working groups and hopefully reach a consensus.
For the sake of simplicity, an aperture of 42 m (geometric average area between 30 and 60m) has been selected on the ground that any 42m concept could also be up or down scaled for any size between 30 and 60m.

1 Introduction

A priori a large number of designs are possible for telescopes of the 30 – 60 m class. The telescope design has to consider requirements set by the users and, more specifically by instrumentation constraints. In addition, the design has to take into account technological constraints imposed by its subsystems, for example the feasibility to manufacture large mirrors and to operate adaptive optics systems. Trade-offs will have to be done in order to accommodate demanding and sometimes incompatible requirements, to contain the cost and finally to make the telescope reliable and maintenance friendly.
To be able to compare the different designs in an easy way a standard template has been used for describing the various optical concepts. A global summary table attempts to put together in an easy way the key parameters of the various concepts investigated.
Both the mechanical structure and the enclosure need to be designed according to the selected optical design. However, for the purpose of this crude analysis it may be assumed that both the mechanical structure and the enclosure are independent from the optical concept to the extent that for a given primary mirror size all designs have, to first order, rather similar dimensions and requirements. There are therefore separate sections dealing with mechanical design and enclosure issues.

The report contains the following sections:

- Section 2 : Requirements from instrumentation and adaptive optics.
- Section 3: Ritchey-Chrétien design
- Section 4 : Gregorian design
- Section 5 : Optical design incorporating three adaptive mirrors
- Section 6 : Optical design with a spherical primary mirror
- Section 7 : Five mirror design with an aspherical primary mirror
- Section 8 : Status and perspectives of mirror segments technology
- Section 9 : Issues for the mechanical structure design
- Section 10 : Issues for an enclosure design
- Section 11 : Conclusions

Reference documents:
A number of documents have been produced in the frame of this working group. These documents are too large to be inserted in this report but they can be consulted on the ESO internal BSCW site created for the working groups. The access to this site is provisionally limited to the members of the various working groups.

- Minutes of first meeting (18th January 2006)
- OWL concept design report-Phase A design review-Oct 2005
- Review of spherical mirror telescope designs (P.Dierickx)
- Identification of design options for Gregorian/Ritchey-Chrétien telescopes (T.Andersen and al)
- Power point presentation “ELT designs for a 42m Nasmyth telescope (B.Delabre)“

- Note on Adaptive secondary mirrors (P.Salinari)
- Note on ELT 5-mirror option with M1 paraboloid (G.Lemaître)
- Main mechanical parameters to be considered for the mechanical design (E.Brunetto, F. Koch, R. Tamai)
- Summary of alternatives for the design of the building (M. Schneermann)
- Atmospheric dispersion correction, Final report, European Extremely Large Telescope design, European Community’s Framework Programme 6

2 Requirements and technological constraints

At the time of writing this document, because of the simultaneous work of the other working groups, a number of requirements are not precisely defined and will probably necessitate some further iterative interaction. In the following we indicate the requirements which have been considered by the working group based on either previous experience and input from instrument and adaptive optics groups and those that will need to be defined at a later stage.

2.1 Instruments

The following requirements have been considered for this study

- Telescope final focal ratio: between 10 and 20, 15 close to optimal.
- Unvignetted FOV: 10 arcminutes (including science and telescope metrology)
- Linear field size preferably less than ~2m
- Image quality : Diffraction limited over about 4 arcminutes FOV in K band
- Mechanical back-focal distance : ≥ 0.5 m
- Field curvature: if possible flat, strong field curvature to be avoided
- Several instrument stations and fast switching
- Possibility of a gravity stable instrument station
- Low background emission from the telescope
- Low straylight from the telescope; possibility for efficient baffling

Some parameters will have a strong impact on the telescope design and will have to be defined:

- Type of instrument attachment, adapter/rotator or fixed on platform
- Maximum mass/size of rotating and non-rotating instruments
- Wavelength range
- Need for a coudé focus versus a well isolated instrument room located on the telescope structure
- Tolerances for errors not correctable by adaptive optics, in particular for high contrast imaging

2.2 Adaptive optics

The following list indicates major requirements provided by the adaptive optics group.

- One adaptive mirror corresponding to ground layer (conjugated to altitude of 0 – 200 m) to be integrated in the telescope. Mirror preferably flat or with low curvature.
- For MCAO, additional deformable mirrors can be post focal although such mirrors can be extremely large and pose a real problem with respect to the space available.

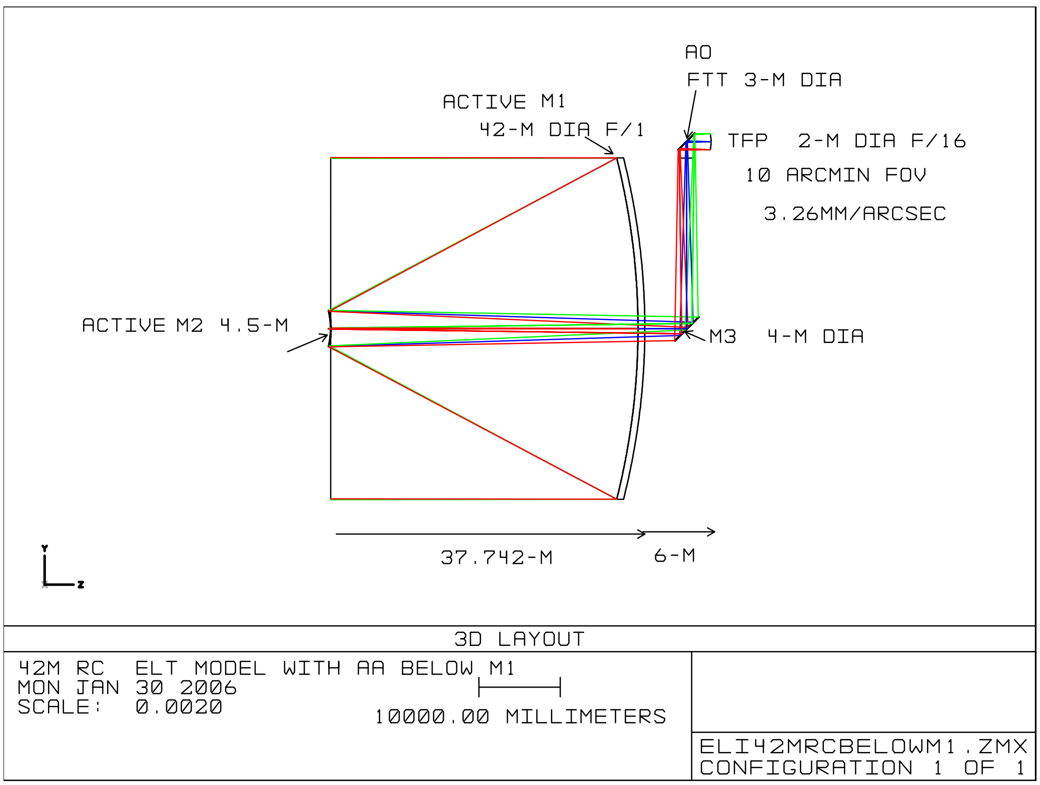
- For extreme AO at about 90% Strehl ratio in H-band, the telescope optical quality should be better than 10/20 nm rms for spatial frequencies > 1/0.4m
- DM cannot perform fast and large tip/tilts correction. This function should be off loaded to a separate field stabilization mirror or gimbal mount.
- Diameter of DM1: Presently, deformable mirrors are available in the 1 m class. Feasibility of larger mirrors has not been demonstrated. Deformable mirrors in the 2-3 m class seems however a reasonable goal.
- Availability of an internal calibration source for testing the DM highly desirable

A number of issues related to the use of adaptive optics and in particular of laser guide stars will need further investigation. This is in particular the case for parameters such as the optical quality required, image and pupil distortion, conjugations between layers, deformable mirrors and sensors.

3 Ritchey-Chretien design

A) Description of telescope architecture

The optical design model is a classical RC 2-mirror telescope with an f/1 primary mirror that is aspheric (almost paraboloid), segmented and has a 42 m clear aperture diameter. The secondary mirror is convex and hyperboloid. This system was optimised for 10 arcmin fov and has a concave focal surface (pointing towards the sky and a radius of curvature of 4.64 m). It can also be working in a seeing limited mode at a field of 20'. The optical layout is shown below.
In the baseline configuration the M2 is an adaptive mirror and M3 can be used for field stabilisation, albeit not in a pupil. M4 is an optional additional flat that can flip the beam downward to a gravity stable instrument.



The characteristics of the mirrors are:
M1: R1=84.2242 m; K1=-1.000926; D1=42 m
M2: R2=9.32367 m; K2=-1.296144; D2= 4.5 m

B) Telescope main characteristics (for every available focus)

- Focus type : 2 Nasmyth foci
  1 Cass focus
  1 possible Coude focus

- F-Number : F/16
- Plate scale: 1 arc sec = 3.26 mm
- Angular and linear FOV 10 arc min - 2 m
- Diffraction limited FOV (2.2 µm) >2.5 ‘
- Image Quality at 45” and 2’ off axis

Field of view (radius)	RMS Wavefront Error (nm)	Strehl ratio at 500 nm	Strehl ratio at 2200 nm
Axis	0	1.00	1.00
1 arc min	53	0.65	1.00
2 arc min	209	-	0.70

The image quality for fields above 5 arcmin is shown in the detailed report as well as spot diagrams. This shows that the 2 mirror optical system gives diffraction limited images for fields up to 4’ diameter and seeing limited performance (100% eed within 0.1”) for fields up to 10’ diameter.
To achieve diffraction limited imaging for fields of 10’ a field corrector is necessary. Since an ADC design is required to achieve this high level of performance, the field corrector may be integrated into the ADC.

- Sensitivity

This telescope has only 2 powered mirrors. The following table shows the sensitivity of M2 for tilt and decentering with respect to M1:

		Dec. 1mm	Tilt 1 arc sec	Z position 1 mm
M2	Rms WFE (µm)	3.4	0.074	256 mm defocusing
	Pointing err. (mm)	14.96	0.68	

The sensitivity to Z position of M2 will be reduced if we choose an f/11 RC (1mm will defocus the f/11 image by 121 mm)

- Central obstruction and baffling

The central obscuration is very low (1% area) which will provide an excellent PSF and a very low emissivity. As all the existing telescopes (VLT , Gemini..), the mirror M2 will have a sky baffle and a field stop next to the final F/16 image at the Nasmyth platform. The sky baffle is likely to increase the obstruction.

- LGS friendliness (optical quality of the image of the LGS for different heights)

The RMS WFE of the LGS varies from 0.2 to 2.15 µm for a LGS placed at 100 km and on-axis and at 5’ off axis. The defocus of the LGS is 5 m relative to the sky image. The only possibility to reduce this defocus is to reduce the f/n of the optical system. An f/11 RC optical system has been studied (see detailed report) given 2.7 m defocus.

- Instrument available space

The only limitation is the size of the Nasmyth platform

- Gravity invariant instrument space

Possible using mirror M4.

C) Wavefront control

- Active control of the primary mirror is common to all concepts. It is delicate but well understood and reliable solutions already exist.
- The alignment tolerance s for M2 are very tight because of the fast primary mirror. All wavefront control functions except phasing are concentrated on M2

D) Advantages and Disadvantages

Advantages

- The Cassegrain configuration consists of only 2 aspheric mirrors,
- The Nasmyth configuration will have 3 mirrors (4 for gravity invariant instruments).
- Short tube, would decrease the size of enclosure
- Small obscuration (1% area). Low emissivity and high throughput
- Possibility to extend the optical design beyond 10’ FOV and up to 20’

Disadvantages

- Aspherical primary mirror
- Large convex adaptive secondary mirror
- No baffling in telescope
- All wavefront control functions except phasing concentrated on M2
- Large field curvature (5m concave towards sky)

F) Risk areas and risk reduction measures

Risk area	Level	Risk reduction measures
Manufacturing and cost of aspheric segments	Low for a moderate ashericity	R&D for performance improvement
Manufacture, reliability and control of large convex deformable mirrors (M2)	High	Substantial R&D effort Provisional back-up: solid M2 and AO shifted to instrument with 2 mirrors relay optics
Tip-Tilt function on M2	Medium	R&D effort
Sensitivity of adaptive M2 to wind load	Unknown	Test on existing telescopes-Simulation

G) Perspectives for design improvement and simplification

Several mechanical design options can have a cost saving potentials which are related to design simplification or technology developments. These options are common to all the optical designs and they allow a high degree of flexibility, thus maximising trade-offs among performance, cost and schedule.

4 Gregorian design

This design belongs to the family of Gregorian designs to which the Californian TMT belongs to. The main difference is that in this particular design, there is the possibility to have a Cassegrain focus and one or two Nasmyth foci using a two-mirrors relay system. The basic feature of Gregorian designs is the concave secondary mirror which makes its manufacturing considerably easier at the expense of a longer tube length.

A) Description of telescope architecture

Many variants of Gregorian or Ritchey-Chrétien “two-mirror” designs exist. We here present one possibility but it may well be possible that others are found more attractive after further studies.

An optical layout is shown in Figure 1. The configuration combines Gregorian foci under the primary mirror with gravity stable foci on the Nasmyth platforms. The design is here shown with a concave, Gregorian secondary, but may also be used with a convex, Ritchey-Chrétien secondary.

A Gregorian focus with SCAO may be established with only two reflections and will therefore provide a high throughput, a large field, good IR performance, alignment on one single element, and low polarization. If a folding flat is added, more Gregorian observing stations can be obtained.

On one Nasmyth platform, a gravity stable observing station with vertical de-rotation axis may be established with totally 6 reflections. The exit field is perpendicular to the exit optical axis for field rotation. Calculations suggest that, with a deformable secondary, it is possible to establish a Nasmyth observing station on the other platform without a powered relay system, simply by using one or two folding flats, re-focusing the secondary, and adjusting the aspherical form of the primary and the secondary. Adjustment of the primary mirror form can be done using the segment alignment system and low-order active control systems for each of the segments. The form of the secondary must also be adjusted, either using active optics or a deformable mirror. With that approach, an additional Nasmyth station with only three reflective mirrors can be obtained. For a rigid secondary, a relay system must be used also for the second Nasmyth platform, requiring totally 5 or 6 reflections in total.

The secondary mirror can be either deformable or active. With a deformable secondary, GLAO, SCAO and seeing limited observations in the Gregorian focus and the Nasmyth focus are possible, whereas DCAO (dual-conjugate adaptive optics) is possible in a Nasmyth focus. With a rigid secondary (although active), SCAO and GLAO on one Nasmyth platform is possible. One of the relay mirrors is then deformable and has a diameter of 2.4 m.

The K-band diffraction limited field in Nasmyth focus 1 is 1.9’ which is sufficient for both SCAO and DCAO.

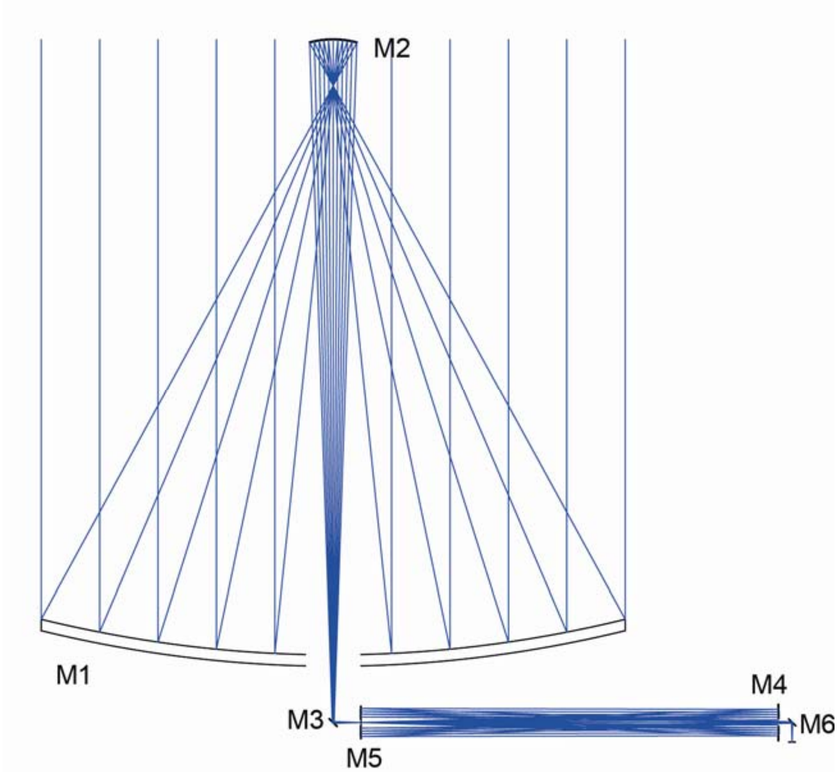


Figure 1. Optical layout of the Gregorian/Nasmyth 1 design.

The optics scheme is listed in the table below:

Surface	Radius	Thickness	Diameter	Form	Def. Const.
M1	-84 m	45.4 m	42 m	Ellipt.	-0.999356
M2=DM1	6.386 m	52.4 m	3.4 m	Ellipt.	-0.777912
Greg Foc	3.36 m	30 m	0.28 m	Sph.	0
M4	64 m	30 m	2.8 m	Hyp.	-1.362129
M5=DM2	61 m	35.3 m	2.4 m	Ellipt.	-0.722396
Nasmyth foc.	3.34 m		0.29 m	Sph.	0

B) Telescope main characteristics (for every available focus)

Gregorian Focus

- F-number: 15.4
- Distance M1 – M2: 45.4 m
- Plate scale: 0.318 "/mm (3.14 mm/arcsec)
- Linear fov: 1889 mm
- Angular fov: 10'
- Diffraction limited fov (K) 2.9 arcmin
- Image quality, 45", W_{rms}= 0.085 µm

- Image quality, 5’, W_{rms} = 1.9 µm
- Linear central obstruction ratio: 0.081
- RMS LGS:

90 km: Axis W_{rms} = 0.088 µm, 5’ W_{rms} = 3.3 µm
180 km: Axis W_{rms} = 0.35 µm, 5’ W_{rms} = 2.35 µm

Nasmyth Focus (DCAO Focus)

- F-number: 15.7
- Plate scale: 0.313 ”/mm (3.19 mm/arcsec)
- Angular fov: 2.4 arcmin
- Linear fov: 460 mm
- Diffraction limited fov (K): 1.9 arcmin
- Image quality at 45”: W_{rms} = 0.11 µm

C) Wavefront control

- Active control of the primary mirror is common to all concepts. It is delicate but well understood and reliable solutions already exist.
- The control of the secondary mirror is more specific:
  - Option A: Active optics M2
    - Position control system of complete secondary mirror unit, for instance using inertial sensors
    - Slow tip/tilt control of (light-weighted) secondary (bandwidth 1-5 Hz)
  - Option B: Deformable M2
    - Deformable mirror control system including high bandwidth/low stroke tip/tilt control
    - Low bandwidth/high stroke tip/tilt control (bandwidth about 5 Hz)
    - Position control system of complete secondary mirror unit, for instance using inertial sensors
- Adaptive optics
  - NGS wavefront sensors in Greg and Nasmyth foci
  - LGS wavefront sensors in Greg focus
  - LGS launcher above top unit
  - Alignment system of LGS launcher to field
  - Perspective elongation compensator
  - Virtual wavefront sensing (i.e. injection of a test source in Greg focus and detection of aberrations in final focus using the source)

This system is basically simpler than other systems with more mirrors but there is one difference: The need for virtual wavefront sensing is a complication although it does provide the advantage of separate monitoring of the two deformable mirrors in a DCAO system with negligible cross-talk.

E) Advantages and disadvantages

Advantages:

- Small obscuration (1% area). Low emissivity and high throughput.
- Provides a Cassegrain/Gregorian focus with only two-mirror reflections
- Equally usable with a deformable or an active, stiff secondary
- Can be implemented with a concave or convex secondary (RC or Gregorian)
- Several observing stations can in principle be implemented
- Infrared and polarization friendly at Cassegrain/Gregorian focus
- A Gregorian design is advantageous because of the conjugation height of the secondary (a few hundred meters above ground) and the possibility to calibrate a deformable secondary in-situ. A shorter telescope tube can be obtained with a convex Cassegrain mirror but there is risk involved in polishing and testing of a large convex mirror.

Disadvantages:

- Aspherical primary mirror
- A field of maximally 2.4' minutes at Nasmyth focus. It is larger than the field that SCAO or DCAO can deliver due to sky limitations.
- The Nasmyth field is in most cases too small for laser guide stars. Wavefront sensing at the intermediate Cassegrain/Gregorian focus overcomes the problem.
- A Gregorian has a longer tube than a Cassegrain, so the enclosure for a Gregorian is larger than for a Cassegrain. The present optical concept can be adapted for both configurations.

F) Risk areas and risk reduction measures

Risk area	Level	Risk reduction measures
Manufacturing and cost of aspheric segments	Low for a moderate asphericity	R&D for performance improvement
Manufacture, reliability and control of large concave deformable mirrors (M2)	High	Substantial R&D effort despite it is easier than a convex mirror Provisional back-up: use M5 as deformable mirror
Tip-Tilt function on M2	Medium	R&D effort
Sensitivity of adaptive M2 to wind load	Unknown	Test on existing telescopes-Simulation

G) Perspectives for design improvement and simplification

Several Gregorian and Ritchey-Chrétien designs exist and can be studied according to instrument requirements.

5 Optical design with three adaptive mirrors

A) Description of telescope architecture

The optical design for a fully adaptive telescope (3 DMs) is a 5-mirror system based on a genuine f/8.1 RC configuration. The 'fast' primary mirror (f/0.8) is a hyperboloid (almost paraboloid), segmented and has a 42-m clear diameter. The small f/number is required to conjugate, in a configuration with the altitude axis below the primary mirror, the mirrors M4 and M5 to useful altitudes of 7.2km and 12.4km. The secondary mirror is a convex hyperboloid. The image given by these two mirrors is relayed with a flat folding mirror and a two-mirror relay system (with an intermediate image) to a Nasmyth platform. This optical system was optimised for 8 arcmin full field of view. The characteristics of the 5-mirrors system is given in the figure below:

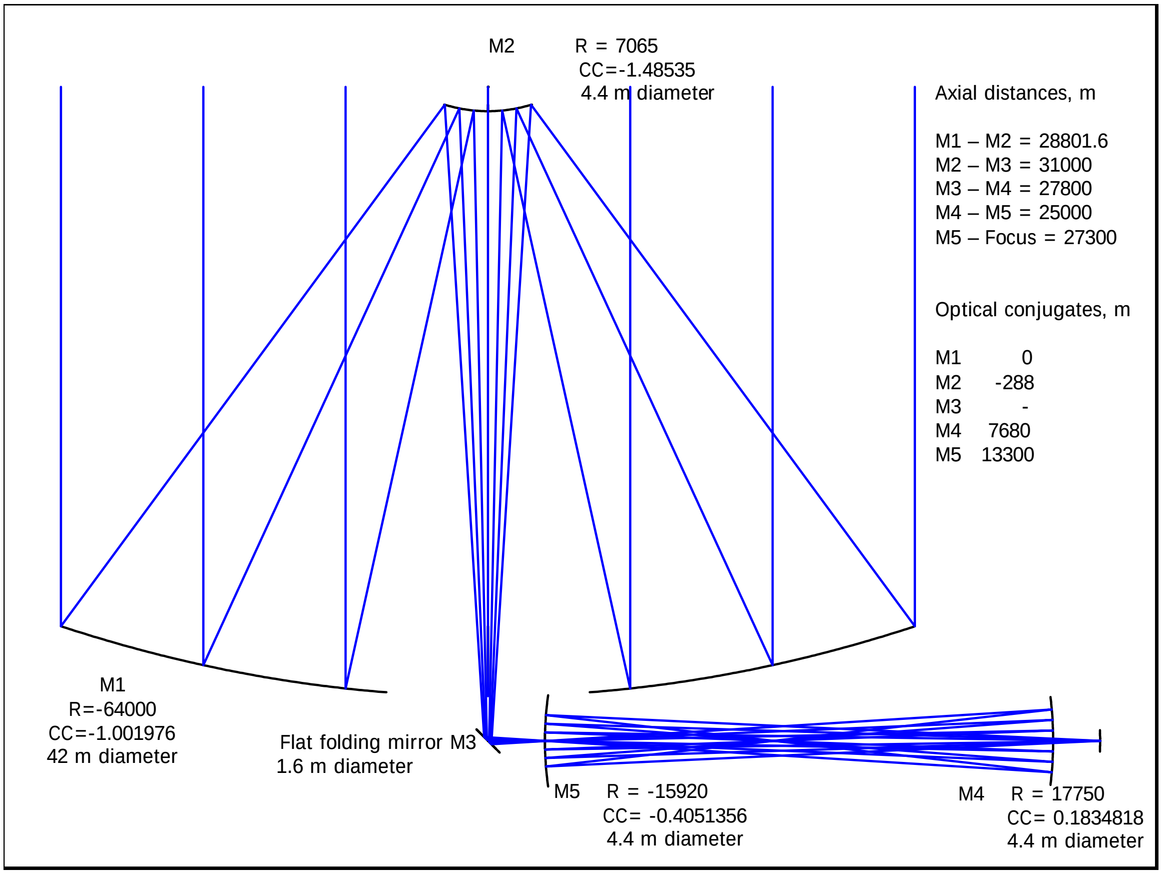


Figure 2. Optical layout of the fully adaptive 5- mirror f/10.8 telescope design.

B) Telescope main characteristics (for every available focus)

	2 surfaces (intermediate focus)	5 surfaces
1. Focus type	Cassegrain	Nasmyth
2. F-Number	8.1	10.8
3. Plate scale	1.65 mm/arc sec	2.2 mm/arc sec
4. Linear and angular FOV	1980 mm, 20 arc minutes	1056 mm, 8 arc minutes
5. Diffaction limited FOV (2.2 μm)	2.4 arc minutes	8 arc minutes
6. Image Quality at 45" and 4' off axis (see table below)	45" diffraction-limited (at 0.55 μm) at 4' : < 1.7 μm wavefront rms	45" diffraction-limited (at 0.55 μm) at 4' : < 0.07 μm wavefront rms
7. Sensitivity matrix RMS wavefront error	Major effects : Axial decenter of 1 mm: M2 → 50μm coefficient defocus M4 → 1.8μm coefficient defocus M5 → 0.3μm coefficient defocus Lateral decenter of 1 mm: M2 → 7.4μm (7.6μm for Cass) M4 → 0.13μm M5 → 0.17μm	
8. Central obstruction and baffling	~10% area, conventional baffling	~10% area, excellent baffling
9. LGS friendliness (optical quality of the LGS images for 90 km height, see Figure 2)	~2.7 μm wavefront RMS at at 4' off-axis (after 1.3 m refocusing)	~3.4 μm wavefront RMS at 4' off-axis (after 3 m refocusing)
10. Instrument available space	Cassegrain type, cylindrical volume ~8m diam., 10m L	Nasmyth, larger design space
11. Gravity invariant instrument space (possibility for)	No	Yes, requires a field de-rotator

12: Image Quality at 45" and 4' off axis at Nasmyth focus

Field of view (radius)	RMS Wavefront Error (nm)	Strehl ratio at 500 nm	Strehl ratio at 2200 nm
axis	0	0.978	0.999
1 arc min	13	0.973	0.999
2 arc min	22	0.925	0.996
3 arc min	37	0.908	0.989
4 arc min	67	0.502	0.964

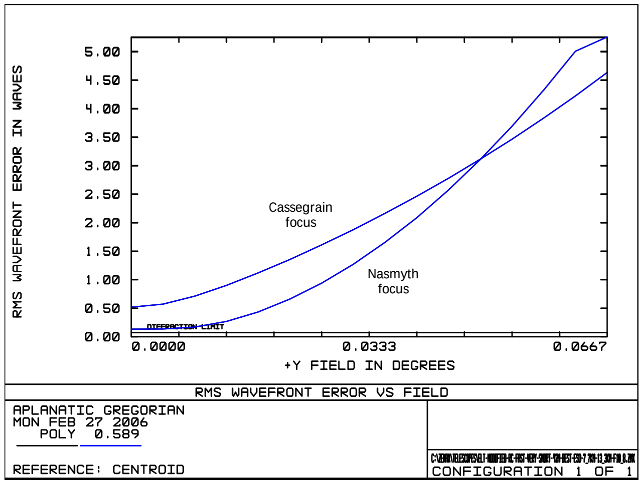


Image quality of LGSs (90km height) at Cassegrain and Nasmyth foci.

C) Wavefront control

Required control loops

- Phasing
- Pre-alignment
- Active optics (M2)
- Field stabilization with M2 (diam 4.4 m)
- Adaptive optics with M2, M4 and M5 (M2 for ground layer, M4 7.2 km and 12.4 km,),

D) Mechanical structure main characteristics

See common design by T. Andersen for AG and RC configurations with elevation axis located behind the primary mirror cell.

E) Advantages and Disadvantages

Advantages

- Excellent image quality both at the Cassegrain and Nasmyth foci.
- Conventional baffling for the RC and good baffling for Nasmyth focus (2 intermediate foci – one of which is of good quality).
- Rapid switching between a relatively large number of focal stations possible in the Cassegrain focus over 20 arcmin field using a small folding flat mirror.
- Ability to use two or three deformable mirrors integrated into telescope design (fully adaptive telescope)
- Fold-back solution with a dual-conjugate system (Figure 3) if M2 can be only made as an active mirror
- LGS friendly, refocusing and compensation of LGS-specific aberrations might be possible at the intermediate image (virtual wavefront sensing at Cassegrain focus)
- Alignment is simpler in two-mirror RC systems than in multi-mirror systems
- Moderate sensitive of the relay system to misalignment

- Two Nasmyth platforms with different relay systems
- Short telescope structure (30m)

- **Disadvantages**
- Number of surfaces (5) for Nasmyth focus
- Vignetting outside 4 arc minutes (variable central obscuration)
- Large adaptive mirrors (3 x 4-m class)
- 30% linear central obscuration (10% light loss)

F) Risk areas and risk reduction measures

Risk area	Level	Risk reduction measures
Manufacturing of aspheric segments	Low	R&D for performance improvement
Tip-Tilt function on convex M2 (4.4m)	Medium	R&D effort
Manufacture, reliability and control of large deformable mirrors (M2, M4, M5)	High for M2 Medium for M4-M5	Substantial R&D effort Provisional back-up: solid or low order deformable mirror
Sensitivity of adaptive M2 to wind load	Unknown	Test on existing telescopes-Simulation

G) Perspectives for design improvement and simplification

- Separation of adaptive and field stabilization functions on M2 by adopting dual-conjugate system with M5 being conjugate near 2.4 km, see Figure 3
- Exploration for additional foci and re-imaging system solutions
- Optimisation of the telescope f-ratio, central obscuration and field of view

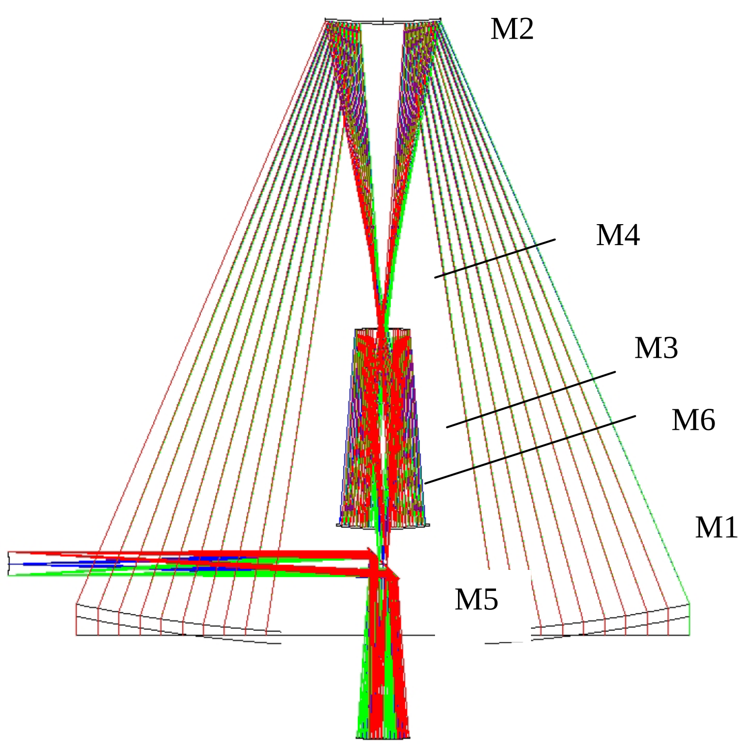
Optical design with a spherical primary mirror

A) Description of telescope architecture

The optical design is a 6-mirrors combination consisting essentially of the two main mirrors (M1, M2), of a 2 mirrors corrector (M3, M4) and of a relay system made of 2 mirrors that send the beam to the Nasmyth focus.
The intermediate focus after the corrector has an f/ratio of about f/5.
M4 can be a deformable mirror conjugated with the ground layer while M5 can be a second deformable mirror conjugated at an altitude of 5-6km

The primary mirror has an F/ratio of f/1.25. The design can be optimized to provide suitable image quality at the intermediate f/4-f/5 focus. Active deformations of M2 and/or M3 might allow to enhance optical quality when switching between the intermediate f/5 and the final focus.
The diameters of the mirrors are

M1	42m
M2	8m
M3	6.4m
M4	3.7m
M5	3.7m
M6	2x2.8m



B) Telescope main characteristics

	Intermediate focus	Nasmyth focus
Number of mirrors	4	6
Focus type	Cassegrain	Nasmyth
F-Number	<5	>10
M1-M2 distance	42m	42m
Plate scale	> 0.8 mm/arc sec	> 2mm/arc sec
Linear and angular FOV	> 500 mm, 10 arc minutes	> 1200 mm, 10 arc minutes
Diffraction limited FOV at 2.2 microns (diameter)	> 8 arc minutes	> 10 arc minutes
Image Quality	45” diffraction-limited (vis.) 5’ : < 1.0 μm wavefront rms	45” diffraction-limited (vis.) 5’ : < 0.2 μm wavefront rms
Sensitivity matrix	Major effects : Axial decenter of 1 mm : M1 → 40μm coefficient defocus M2 → 50μm coefficient defocus M3 → 13μm coefficient defocus Lateral decenter of 1 mm : M2 → 11μm coefficient coma M3 → 42μm coefficient coma M4 → 33μm coefficient coma NB : M3 and M4 decenters tend to compensate each other if they are of the same sign –which should be the case under gravity load.	
Central obstruction and baffling	~30%, good baffling As the system includes an additional image and pupil, no sky baffles will be required near M2	~30%, good baffling As the system includes an additional image and pupil, no sky baffles will be required near M2
LGS friendliness (optical quality at 5 arcminutes off axis)	~1-2 μm wavefront RMS	~1-2 μm wavefront RMS
Instrument available space	Cassegrain type, cylindrical volume ~12m dia., 15m L	Nasmyth, large/very large design space
Gravity invariant instrument space (possibility for)	No	Yes, requires 1 more reflection

C) Wavefront control

- Active control of the primary mirror is common to all concepts. It is delicate but well understood and reliable solutions already exist.
- The large number of mirrors implies the use of several wavefront sensors and control loops but also allows better control of overall prescription.

- The alignment tolerances for M2 are very tight because of the fast primary mirror. However tolerances on M2 can be relaxed and corrections be shifted to mirrors further down in the optical train at more stable locations

E) Advantages and Disadvantages

Advantages

- Spherical primary mirror (fabrication, number of spare segments, alignment, maintenance)
- Excellent image quality, diffraction-limited over the whole AO patrol field.
- Excellent baffling opportunities (2 pupil images, 2 intermediate foci – one of which is of good quality).
- Separation of adaptive and field stabilization functions, both in pupil images
- Relaxed alignment tolerances on M2. Corrections can be shifted to mirrors further down in the optical train at more stable locations and with a lower accuracy.
- Possibility to refocus LGS at intermediate focus (shorter course due to longitudinal magnification)
- Alignment (conceptually) simpler than with aspherical primary mirror (to be checked against tolerances);
- Possibility to perform phasing at center of curvature
- Possibility to use the intermediate focus for small IR instrument

Disadvantages

- 6 mirrors
- Large mirrors (one 8-m , one 6.5 m, and two 3.5m), one of which a strong asphere (M4)
- AO with strongly aspherical mirror unless AO and field stabilization merged on M6 (2-m class, flat)
- Some vignetting outside 3-5 arc minutes (variable central obscuration),
- Relatively large central obstruction (10% area)
- Delicate access to M3 and M4, and also to M6 if elevation axis above the primary mirror

F) Risk areas and risk reduction measures

Risk area	Level	Risk reduction measures
Manufacturing, testing and handling of very large M2	High	Substantial R&D effort Very large test mirror (~10m, spherical) necessary but testing could also be done by zones with a smaller mirror.
M4 Adaptive mirror is concave and strongly aspheric	High	Substantial R& D effort Provisional back-up: solid mirror or low order deformable mirror
Manufacture, reliability and	Low	R& D effort

control of large tip-tilt mirror		

G) Perspectives for design improvement and simplification

- Design optimisation could reduce size of M2
- Spherical M2 or spherical M5 possible without dramatic loss of image quality.
- Image quality at the intermediate focus could be improved should this appear necessary for implementing specific instruments
- M5 could become a second adaptive mirror for MCAO
- The intermediate focus can be used for an IR instrument if this focal station is equipped with the appropriate telescope control features. A 2-3 arc minutes FOV requirement would allow for a conveniently small, cryogenic corrector, thereby allowing no more than 2 warm surfaces (M1 and M2).

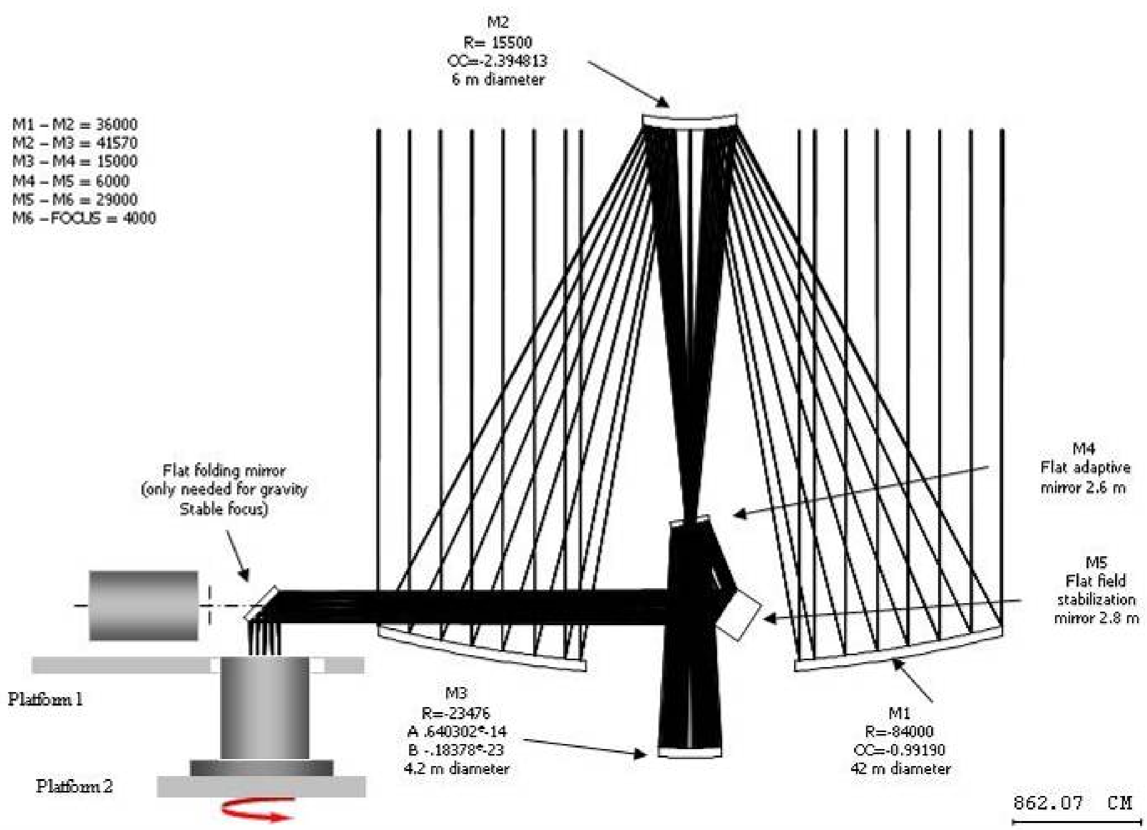
6 –Five-mirror design with an aspherical primary mirror

A) Description of telescope architecture

The optical design is a 5-mirrors combination consisting of the two main mirrors of a conventional telescope and of a relay system made of 3 mirrors which accommodate a flat deformable mirror and a flat tip-tilt mirror for field stabilization. These two mirrors cannot be simultaneously placed in a pupil but the out-of-pupil effect is limited.
A sixth mirror can possibly be added to send the beam downward for a gravity stable instrument.

The 'fast' primary mirror (f/1) is aspheric (almost parabolic), segmented and has a 42-m clear aperture diameter. The secondary mirror is convex and hyperboloid. The image given by these two mirrors are relayed by a 3rd concave near spherical mirror and two flat mirrors to the Nasmyth platform. This optical system was optimised for 10 arcmin field of view and has a flat focal surface.

The characteristics of the mirrors are indicated in the figure below:



B) Telescope main characteristics

- Focal stations: 2 Nasmyth foci
- F-Number : F/15.9
- Plate scale : 1 arc sec = 3.24 mm
- Diffraction limited FOV (2.2 μm) 10 arc min
- Linear and angular FOV: 10 arc min/1944 mm (limited by M4)
- Image Quality

Field of view (radius)	RMS Wavefront Error (nm)	Strehl ratio at 500 nm	Strehl ratio at 2200 nm
Axis	0	1.00	1.00
1 arc min	3	1.00	1.00
2 arc min	7	0.99	1.00
3 arc min	13	0.97	1.00
4 arc min	22	0.93	1.00
5 arc min	33	0.83	0.99

- Sensitivity of adjustments

This telescope has only 3 non flat mirrors. The following tables shows the sensitivity of M2 and M3 for tilt and decentering with respect to M1 at 500 nm

		Dec. 1mm	Tilt 1 arc sec	Z position 1 mm
M2	Rms WFE	3.5 μm	0.11 μm	250 mm defocusing
	Pointing err.	15,9 mm	0.93 mm	
M3	Rms WFE	0.05 μm	0.003 μm	14 mm defocusing
	Pointing err.	3,6 mm	0.52 mm	

- Central obstruction and baffling 10 % (area)
  As the system includes an additional image and pupil, no sky baffles will be required near M2
- LGS friendliness
  Optical quality of the image of the LGS:
  160 nm RMS at 90 km
  90 nm RMS at 160 km
- Instrument available space
  Limited by the size of the Nasmyth platform
- Gravity invariant instrument space : possible adding a flat near the Nasmyth

C) Wavefront control

- Active control of the primary mirror is common to all concepts. It is delicate but well understood and reliable solutions already exist.
- The large number of mirrors implies the use of several wavefront sensors and control loops.
- The alignment tolerance s for M2 are normally very tight because of the fast primary mirror. This is common to all designs. However the adjustment of M2

can be much relaxed because the corrections can be shifted to mirrors further down in the optical train at more stable locations and with a lower accuracy.

E) Advantages and Disadvantages

The following tables show the pros and cons of the design:

Advantages

- Diffraction limited all over the field at all wavelengths. No field curvature
- Excellent baffling possibility due to intermediate focus and pupil
- Separation of adaptive and field stabilization functions. The fast tip/tilt is done with a dedicated 2.5m lightweight mirror located at the center of gravity of the telescope.
- Relaxed alignment tolerances on M2. Corrections can be shifted to mirrors further down in the optical train at more stable locations and with a lower accuracy.
- The A.O. mirror is flat and has a convenient size for foreseeable technology.
- Good image quality for LGS.
- Possible use of intermediate focus
- Possibility to refocus LGS at intermediate focus (shorter course due to longitudinal magnification)
- Short tube, would decrease the size of enclosure
- The M3/M4/M5 makes a separate unit that can be tested independently in a laboratory and relatively protected from the environment .

Disadvantages

- Aspherical primary mirror
- Large convex secondary mirror with delicate manufacturing and testing
- Two additional mirrors with respect to a conventional Nasmyth solution:
- Adaptive Optics mirror tilted by 11.5°
- Relatively large central obscuration (10% area)
- Delicate access to M3-M4 if elevation axis is above the primary mirror

F) Risk areas and risk reduction measures

Risk area	Level	Risk reduction measures
Manufacturing of aspheric segments	Low	R&D for performance improvement
Manufacturing, testing and handling of M2	medium	Very large test mirror (~10m, spherical) necessary but testing could also be done by zones with a smaller mirror.
Manufacture, reliability and control of a large deformable mirror (2.5 m)	Medium	R& D effort Provisional back-up: solid or low order deformable mirror
Manufacture, reliability and control of large tip-tilt mirror	Low	R& D effort

(2.7 m diameter)		

G) Perspectives for design improvement and simplification

- The intermediate focus can be used for an IR instrument if this focal station is equipped with the appropriate telescope control features.
- It has been verified that a moderate active correction of the primary mirror segments and an exchange of the secondary mirror could transform the 5 mirrors design into a true RC telescope with Nasmyth and Cassegrain foci. However, one would loose the advantage of independent and easy telescope adjustment and control, all functions would have to be concentrated on the secondary mirror (adaptive, tip-tilt, collimation).
- M3 could become a second adaptive mirror. M3 is conjugated to 5 km for the altitude axis below M1 and to 3.6 km for the altitude axis above M1.

7 Status and perspectives of segments technology

Segment material candidates are essentially Zerodur and Silicon Carbide although some ceramic material could also prove to be interesting if their development can be made compatible with the time schedule. The question of material is to a large extent common to all telescope concepts.
Glass is available while SiC has to be further developed. Use of SiC would have a favorable impact on the mass hence on mechanical performance and segments control bandwidth.

The question of polishing, in particular for aspheric segments is more delicate.
Several telescopes use aspheric segmented mirrors in particular the 10m Kecks and the GTC. The SALT uses a spherical segmented mirror and rather detailed studies done in the frame of OWL by ESO provide interesting information.
Several approaches have been used for the polishing of aspherical segments and the feasibility of both spherical and aspherical segments is therefore well established. The consequences in terms of cost and performance of an extrapolation to a much larger number of mirrors are nevertheless much open to speculation.
The most recent aspheric segments are those of the GTC. An average optical quality of about 27nm rms WFE has been obtained, with 19nm rms WFE after eliminating low frequency errors. Significant errors appears in some of the edges (~1/3 of them), being the rest of good quality. Some improvements are still necessary to achieve good quality regularly in all the edges, and to approach the goal set for adaptive optics (10-20nm for high spatial frequencies)"

At the present time we only have limited information concerning the cost of the primary mirror.

- The OWL study estimated the cost of spherical segments to be about 13000 €/m2 (for a very large quantity). Non committing statements by manufacturing firms indicate that the extra cost for polishing aspheric segments could be 40% more than for spherical segments although other sources indicate a much larger factor. (The GTC mirrors are a factor of 5 above that figure, see below).
- The cost for polishing the SALT spherical segments scaled to a 42m diameter has been reported to be about 20 M€, very consistent with the OWL estimate
- The cost for the polishing of the GTC mirror has been reported to be about 60000€/m2 to which a few tens of thousands Euros of development and investment should be added.

The lowest quoted figure for aspheric segments being 40% above that of spherical, the lowest cost for aspheric segments would be about 30 M€ while an upper figure extrapolated from the GTC would be 80 M€ for recurrent costs only. Bearing in mind that the GTC had only 36 segments and that an ELT will require much larger quantities it is reasonable to expect that technology improvements will both improve the performance and reduce the unit cost. Development and investment may be in the range of a few tens of millions Euros.

Though there are many unknowns in particular about the development and investment necessary to achieve the necessary quality and a production rate compatible with the time schedule, it is clear that the risk on polishing cost, while important, should not have a dramatic impact on the overall telescope budget.

The optimal shape of the segments is yet unclear; against potential fabrication issues there is indication that near-square (petal) shaped segments could have significant performance advantages. In the case of an aspherical primary, this could also restrict the number of segments families. The analysis of the pros and cons of the two possible shapes shall be part of the detailed study.

8 Issues for the mechanical structure design

Although the optical and mechanical designs are closely linked, most of the major decisions to be taken for the mechanical design are largely independent of the optical design. The main issues relative to the mechanics of the telescope are as follows
.

- Altitude axis above or below the primary mirror.
  An axis below M1 would be favourable for the balancing of the telescope structure, but a 20 m light path through the primary cell structure must be established.
- Light or heavy altitude structure above the primary mirror.
  A light structure could reduce emissivity and straylight, but would reduce the eigenfrequencies of the structure and therefore complicate the control of M2.
- Space for instruments or additional optics inside the M1 support structure.
  Additional space could be used for Cassegrain-type instruments, but would weaken the telescope structure.
- Type of drives for azimuth and altitude axes.
  Three main options are gear, friction, and direct drives.
- Bearings for azimuth and altitude support.
  Some of the options are frictionless bearings like hydrostatic bearings or magnetic levitation and roller bearings.
- Material for special parts of the telescope structure.
  Most of the telescope structure will be made of steel. However, special parts may require the use of lighter and stiffer materials.
- Use of cables to stiffen the structure.
  Stressed cables represent an elegant way to stiffen the structure and improve the mechanical characteristics. However the impact on the image (diffraction) and on the emissivity needs to be assessed.
- Type of foundation.
  The options are a structure which is embedded in the foundation or sitting on a pier-like foundation.
- Primary mirror mass (SiC or solid glass/ceramic)

9 Issues for an enclosure design

The type of enclosure which will be chosen depends on the requirements defined by the telescope design and on the site. There is a wide spectrum of options for the design of an enclosure ranging from a co-rotating dome supplying air conditioning, ventilation, and the equipment for the telescope maintenance on the one hand to a simple retractable shelter on the other hand. These choices are related to a few important issues.

- Open air operation or permanent protection.
  Open air operation may provide smoother conditions with respect to wind flow and will not generate additional seeing. However, especially the primary mirror will be exposed to stronger average wind speeds. A flexible enclosure design permitting both open air and sheltered operations could be ideal.
- Air-conditioning required during the day.
  Without efficient ventilation the telescope may have to be cooled to the expected night time temperature.
- Lifting equipment incorporated into the dome design.
  This is the logical path if a heavy enclosure is foreseen. It may however be cheaper to use a light dome and supply extra handling equipment.

A detailed list of options for the enclosure is available in the report ‘Summary of the alternatives for the design of a building’.

10 Conclusions

The table in annex summarizes the main characteristics of the concept families analysed in the report.

The scope for this working group was not to converge toward a particular design. Therefore various designs were proposed and analyzed by the group. Very fruitful discussions took place during the various meetings and cross fertilization brought up a number of interesting ideas that will need to be assessed in the detailed design phase. Besides the solution based on a spherical primary, it was realized that the 2 main concepts using an aspheric primary mirror, one issued from the EURO50 study and the other from the ESO project office had some commonalities. In fact the ESO 5 mirrors solution could be seen as a quasi-conventional Ritchey-Chrétien solution with a Cassegrain focus (the intermediate focus) followed by a 3 mirrors Nasmyth adaptive module. Should an adaptive secondary mirror be realistically feasible it would be possible to remove the 3 mirrors module and transform the 5 mirrors solution in a conventional 2/3 mirrors Cassegrain/Nasmyth telescope, thus merging the two main solutions presented in this report.

For a final definition of the basic telescope architecture, quite a number of issues will have to be considered. Some key issues are briefly outlined below.

Primary mirror segments
Though the feasibility of aspheric segments is well established there is a large uncertainty on their cost and potential performance in extreme AO mode. However the relative impact of this uncertainty on the overall telescope cost should be relatively modest. Nevertheless this is an area where ESO should concentrate appropriate means to carry out adequate studies so that contracts could be launched as soon as possible after the project approval. Main technical issues concerning the segments are the optical quality, substrate material and segment shape (hexagonal, 4 sided circular petal).

Adaptive secondary mirror
From a theoretical point of view, the secondary mirror may be seen as the optimum location for a deformable mirror correcting the ground layer turbulence. However, the ELT secondary mirror is very large and the realization of an adaptive M2 of a few meters diameter will be extremely challenging. Moreover, because of its size and location high above the primary and subjected to high wind that mirror must be highly reliable both from the functional and survival points of view. Another issue is the concentration of highly demanding functions on the same physical unit (deformable mirror, tip-tilt, collimation). Serious doubts have been expressed by several members of the group concerning the availability of such a mirror in the time frame of the ELT construction. The alternative to an adaptive secondary mirror is either to move adaptive optics entirely to a post focus location or to introduce extra mirrors to re-image the pupil on to an adaptive mirror of reasonable size.

Mechanical structure and position of elevation axis

Several conceptual ideas exist for the mechanical structure and they can be adapted to any optical design after some optimization. The type of structure is therefore not a major issue at the present stage. However a critical feature for the conceptual design of the structure is the position of the elevation axis that can be above or below the primary mirror surface (radio telescope or conventional optical telescope solution).
This is an important issue that will affect the space available for instrumentation as well as access and maintenance to some critical parts.
An elevation axis below the primary mirror will avoid complex structural parts to stay above the mirror and will probably make maintenance operation on M1 easier and safer. It will have the disadvantage to increase the size of the enclosure and to make the secondary mirror structure lighter but more flexible.
An elevation axis above the primary mirror will make the telescope more compact but attachment and handling of optical elements above the mirror will be more difficult and possibly more risky. The telescope balancing will also be difficult.
In any case the position of the elevation axis will have an impact on the telescope maintenance and operation as well as on access and space for instrumentation. A final decision shall be taken in close collaboration with instrument developers and on the basis of conceptual designs to be prepared soon by the ESO project office.

ADC

The type and location of ADCs has not been much discussed by the working group as it is mainly linked to the instruments requirements. Unless integrated with the instrument, an ADC could be set near the focal plane but might be extremely large if it covers a large portion of the field of view. Where possible an ADC could also be located at a fast intermediate focus where the linear field is smaller.

Coudé focus

A conventional coudé focus using a train of mirrors like in the VLT would be costly and have a strong impact on the mechanical structure design. Using a fiber optics would indeed be preferable and a mixed solution in which long distances are covered with a couple of mirrors followed by a fiber may also be envisaged.

Site selection

A review of several types of enclosure is given in a reference document. The selection of the enclosure is much dependent of the site characteristics. The site, in particular its wind pattern, may also have quite an impact on the mechanical structure and the compatibility of an adaptive secondary mirror with a windy site could be an issue.
The consideration of some exotic sites like Antarctica, while scientifically outstanding, would indeed necessitate a complete rethinking of the development strategy.

ANNEX: Summary table

	Ritchey-Chretien Cass/Nasmyth	**Ritchey-Chretien full adaptive Nasmyth focus**	**Gregorian-I Cass/Nasmyth**	**Spherical primary Nasmyth focus**	**5 mirrors Nasmyth focus**
Concept	• 2 mirrors Ritchey Chretien • Flat folding for Nasmyth	• 2 mirrors Gregorian • Flat folding mirror • 2 concave mirrors relay to nasmyth	• 2 mirrors Gregorian • Flat folding mirror • 2 concave mirrors relay to Nasmyth	• Spherical primary+ Convex secondary • corrector : 2 concave mirrors • relay optics to Nasmyth : 1 concave+1 flat	• 2 mirrors Ritchey Chretien • relay optics to Nasmyth : 1 concave and 2 quasi-flats
M1 diameter	42m	42m	42m	42m	42m
M1 F/Number	F/1	F/0.8	F/1	F/1,25	F/1
Secondary mirror	4.5m Convex	4.4m/Concave	3.4m/Concave	8m/Convex	6m/convex
Other mirrors	• M3 : Flat/4m	• M3 : 1.6m • M4 : 4.4m • M5 : 4.4m	• M3 : • M4 : 2.8m • M5 : 2.4m	• M3 :Cv-6.4m/ • M4 :Cv/3.7m • M5 :Cv/3.7m • M6 :Flat/2x2.8m	• M3:Cv/4.2m • M4:Flat/2.6m • M5:Flat/2.8m
Nasmyth F/Number	16	10.8	15.4	>10	15,9
Plate scale at Nasmyth	3.26 mm/arcsec	2.2 mm/arcsec	3.14 mm/arcsec	2mm/arcsec	3.24 mm/arcsec
Intermediate focus F/Number		8.1		4 - 5	4.5
angular /Linear FOV	10 arcmin/2m	8 arcmin/1.06m	2.4 arcmin/1.9m	10 arcmin/1.2m	10 arcmin/1.944m
Diffraction limited FOV (2.2 mic)	2.5 arcmin	8 arcmin	2.9 arcmin	5 arcmin	10 arcmin
Obstruction (area) Baffling	1% No baffling	10% Baffling in relay optics-	6.5% Baffling in relay optics-	10% Baffling in relay optics	10% Baffling in relay optics
Ground conjugate AO mirror	M2	M2	M2	M4	M4
Altitude conjugated AO mirrors	None	M4: 7.2km M5: 12.4km	None	M5: 5-7km	M3: 4-5 km
Field stabilization mirror	M2	M2	M2	M6	M5

Main specific difficulties/risks	• Aspheric segments M2: convex + deformable + tip/tilt;	• Aspheric segments • M2: convex+deformable + tip/tilt;	• Aspheric segments • M2: deformable + tip/tilt;	• Large & convex M2 • M4 large aspherisation	• Large & convex M2 • Aspheric segments
Main advantages	• High throughput: 3 mirrors at Nasmyth • Cassegrain focus	• Concave M2 • Cassegrain focus	• Cassegrain focus	• M1: lower cost & better performance • Decoupling of control functions; Collimation on low sensitivity mirror • Intermediate focus	• Decoupling of control functions; Collimation on low sensitivity mirror • Intermediate focus • Can be transformed in conventional RC
Main disadvantages	• M2: high sensitivity;	• M2: high sensitivity;	• M2: high sensitivity;	• 6 mirrors, long tube,	• 5 mirrors