Gran Telescopio CANARIAS

TITULO

Gran Telescopio CANARIAS
Conceptual Design

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ABBREVIATIONS AND ACRONYMS USED

A&G	Acquisition and guiding
ADU	A to D unit
AE	Additional extinction
AGN	Active galactic nucleus
AO	Adaptive optics
ATM	Asynchronous transfer mode
AU	Astronomical unit
AWS	Automatic weather station
BBN	Big Bang nucleosynthesis
CAMC	Carlsberg Automatic Meridian Circle
CCD	Charge coupled device
CMB	Cosmic microwave background
CORBA	Common Object Request Broker Architecture
CTE	Coefficient of thermal expansion
DIMM	Differential image motion monitor
ENO	European Northern Observatory
EPICS	Experimental Physics and Industrial Control System
FOV	Field of view
FWHM	Full width at half maximum
GPS	Global positioning system
GRANTECAN	Gran Telescopio Canarias, S.A.
GTC	Gran Telescopio Canarias
HOAO	High-order adaptive optics
HST	*Hubble Space Telescope*
IAC	Instituto de Astrofísica de Canarias
IAU	International Astronomical Union
IDL	Interface Definition Language
IIOP	Internet Inter-ORB Protocol
ILS	Integrated logistic support
InSb	Indium antimonide

IR	Infrared
IUE	*International Ultraviolet Explorer*
LCU	Local control unit
LGS	Laser guide star
MSL	Mean Sea Level
NLR	Narrow-line region
NOT	Nordic Optical Telescope
OMA	Object Management Architecture
OMG	Object Management Group
ORB	Object Request Broker
ORM	Roque de los Muchachos Observatory
OT	Teide Observatory
PAH	Polyaromatic hydrocarbon
ppb	Parts per billion
PSF	Point spread function
PVD	Physical vapour deposition
QE	Quantum efficiency
QoS	Quality of service
QSO	Quasi-stellar object
rms	root mean square
S/N	Signal to noise
SCI	Scalable Coherent Interface
SR	Strehl ratio
TCS	Carlos Sánchez Telescope
TNG	Telescopio Nazionale Galileo
UKIRT	United Kingdom Infrared Telescope
UML	Unified Modeling Language
ULIRG	Ultraluminous infrared galaxy
USAF	United States Air Force
VLT	Very Large Telescope
WBS	Work breakdown structure

WHT	William Herschel Telescope

1. INTRODUCTION

This conceptual design for the Gran Telescopio Canarias (GTC) contains the essential information on the planned instrument and constitutes a working baseline. These pages describe the basic requirements to be met and the proposed solutions. They analyse the main subsystems and technological problems and present different solutions or viable alternatives, both technical and financial. This document aims to be a summary of all the information available concerning the specific tasks to be performed (these are dealt with in each of the corresponding chapters and fuller information is available from the Project Office for the reader interested in the details). This study provides a firm basis for a realistic discussion of the goals of the project and its execution. Final approval is necessary before initiating the next stages of the project.

A ‘Feasibility Study’, completed in 1995 and approved by the Governing Council of the Instituto de Astrofísica de Canarias (IAC) on 7 February 1996 explains in detail the strategic, scientific, technological, industrial and cultural reasons for the project.

1.1 GRANTECAN, S. A.

In order to expedite the project, the IAC set up a limited company called Gran Telescopio Canarias, S. A. (GRANTECAN), whose sole objective is to direct the building and installation of the telescope. GRANTECAN is a formally constituted non-profit Spanish trading company, open to participation by other countries. There is a Project Office, created by GRANTECAN, to make technical studies devoted to the development of the first stages of the project. The particular site for the telescope has now been chosen in the magnificent Roque de los Muchachos Observatory (ORM) on La Palma.

1.2 Historical background

This project was not born overnight. The IAC has been actively planning the construction of a large telescope for the ORM since the mid-eighties, and the first important steps were taken in collaboration with the Royal Greenwich Observatory that resulted in a proposal for an 8-m telescope which was to have been built jointly by Spain and the United Kingdom. Finally, after a close vote, the British authorities opted instead for a collaboration with the USA in the GEMINI project.

The initial design of the telescope had an 8-m monolithic primary mirror, very much in line with many similar projects started at the end of the eighties. However a project review by the leading experts in the field concluded that a better approach would be a segmented primary mirror. This decision is justified in the ‘Feasibility Study’.

1.3 Reasons for Spain to undertake this project

It would be appropriate to list, albeit briefly, the reasons for which Spain decided to initiate this big science project.

While reading this document please bear in mind that it was written when none of the countries or institutions in the GTC project had made a formal declaration of their intention to join it. It is natural, therefore, that the point of view expressed here should be primarily a Spanish one. Nonetheless, most of the interests stated here will coincide with those of prospective partners in the project, whose particular interests will in any case be readily accommodated in the GTC participation agreement. These new partners will complement and augment the scientific, technological and financial needs of the project.

Astrophysics is a science whose history in Spain is brief, but whose growth has been quite spectacular. A mere 20 to 25 years ago where was very little, but more than ten groups have now burgeoned throughout the country. There are now over 200 Spanish members of the International Astronomical Union (IAU), and the rate of scientific production of Spanish astronomers is comparable to that of the most advanced countries.

This shining success, dating from the seventies onwards, is due to the Canarian skies, a genuine natural resource that Spanish astronomers have exploited scientifically. Spain has provided in the Canary Islands the necessary infrastructure for the observatories and has protected its excellent astronomical quality by law. Several other European countries have installed advanced astrophysical installations at the observatories in the Canaries.

This rapid growth of astrophysics in Spain has led to an ever-increasing demand for access to ground-based telescopes, and the rate of oversubscription (the ratio of demand to availability of observing time) of the Canarian telescopes is equal to or greater than that in the owner countries of the installations.

Of course, technology advances rapidly and it is now possible to build larger telescopes than those of the present observatories. None of these telescopes will be built in Spanish territory, however, and Spain will not be participating in their construction. Spanish astronomers will therefore not have guaranteed access to observing time on these large facilities.

The GTC project was created to satisfy the needs of Spanish astronomers for more telescope time and larger telescopes. The GTC project also has great technological appeal to national industry, which is always eager to participate in this kind of stimulating project. Not only does developing scientific instrumentation mean being at the forefront of new areas of research, it also provides opportunities for industry to innovate and sharpen its competitive edge.

The project will spearhead collaboration between research centres and companies, thereby generating transfer of technology. Furthermore, multidisciplinary projects like this require the participation of specialist groups in different fields, research centres and industries from different countries working side by side, creating synergy.

This project, in its various aspects, fits in perfectly with the latest European, national and regional R&D goals.

1.4 An international opportunity

Most European astronomers urgently need observing time on large telescope in the northern hemisphere. This project offers the astronomical community, especially in Europe, the chance of building latest-generation instruments to be installed in the Canary Islands and continues the return on the substantial investments already made.

A truly outstanding and thriving observing site is vital for the progress of astrophysics and will also attract investment from large scientific bodies. For these reasons it is a much prized lodestone for scientific and technical development. The financial interests at stake are therefore quite considerable, both regionally and nationally.

Strategically, these are very strong reasons for the construction of the GTC, which would secure a future in the vanguard of astrophysics for the ORM and guarantee the consolidation of the status of the Canary Islands as the European Northern Observatory (ENO), at the same time as boosting Europe’s observing capacity in the northern hemisphere.

The GTC project does more than simply increment the list of so-called ‘8–10 metre class’ telescopes. Its requirement for higher specifications differentiates it from other telescopes of its generation. The GTC will combine a large collecting surface with excellent image quality and a suitably optimized observing range in both the visible and the infrared (IR). These guarantee maximum scientific return.

The Gran Telescopio Canarias is a state-of-the-art instrument, tailored to meet the scientific challenge of the next millennium.

2. REQUIREMENTS

2.1 Introduction

The requirements for a major scientific undertaking such as outlined in this design document must be driven by the intended science. In the last two or three decades astronomy has shown an unprecedented growth, due mainly to the availability of increasingly powerful observational facilities. The aim of this project is to produce a world-class observational facility and thereby foster the continued development of the Spanish astronomical community. It is difficult in a few pages even to outline a representative selection of the science that will be made possible with the 10-m telescope. There are a number of conference proceedings on just this topic. Therefore, in the following section a small selection is offered of the projects that between them provide pointers to the top-level science requirements for the GTC. These top-level science requirements are, fundamentally, increased limiting magnitude over 4-m class telescopes and high image quality. Following this, the detailed requirements for the GTC are developed.

The useful time available on the GTC will be finite, with far more scientific projects being proposed than can be carried out in practice. Hence, the remaining top-level science requirements seek to maximize scientific return. This in particular requires implementing new modes of operation, which are not normally employed at present on ground-based visible/IR telescopes.

2.2 Summary of science programmes

2.2.1 Extrasolar planets and faint stellar sources

There are high expectations of finding Earth-like planets; such a discovery would be important not only from a scientific point of view, but also because of the wide public appeal of this topic.

It is envisaged that ground-based facilities will discover such planets, although their physical characterization will require infrared space observatories. However, the recent discoveries of Jupiter-like planets orbiting main-sequence stars show that the present theories of planetary formation and evolution need to be thoroughly revised.

The search for brown dwarfs is also of great interest, especially if statistical analysis can be carried out on the distribution of brown dwarfs and the implications of this for the total baryonic density of the Universe. Likewise, spectroscopic studies of cool (5000 K) white dwarfs as faint as V=20 mag will provide valuable information on the origin and evolution of the halo and disc of the Galaxy, particularly on their ages. These objects have extremely thin atmospheres and are therefore ideal laboratories for the study of physical processes in stellar atmospheres.

Observationally, these projects require:

- A large collecting surface for faint-object detection and high spatial resolution.
- Adaptive optics (AO) in the near IR.
- Excellent image quality to allow the use of coronagraphic devices for blocking out the light from the bright central object.
- Medium-resolution spectroscopic capabilities down to R=24 mag.
- High-resolution spectroscopic capabilities which can measure radial velocities of objects at several astronomical units (AUs) to within a few m s^{-1}.

2.2.2 Protostellar objects and star formation

The physics of star formation is becoming well understood except on very small scales, where protostellar objects develop jets, discs and other features. The mechanisms producing and collimating these jets, however, are still unknown. Moreover, new stars are formed deep inside dense molecular clouds where tens of magnitudes of extinction are frequent, and the very youngest photospheres are still basically undetected.

From an observational point of view pursuing these lines of research demands:

- A large collecting area.
- Excellent image quality, both in the visible and the IR.
- Adaptive optics in the near IR for imaging the inner regions of protostellar discs and jets.
- Visible and IR spectroscopic capabilities, to study the dynamics of jets and discs, and the physical conditions in the parent dark nebulae.
- Medium- and high-resolution IR spectroscopy to study the very youngest photospheres and their formation.

2.2.3 Compact objects and black holes

The ubiquity of these high-energy objects is nowadays well established after the discoveries using X- and γ-ray satellites. While optical identifications are readily made with 4-m class telescopes, the determination of the compact central mass is only possible dynamically through the study of radial-velocity curves.

Observationally we require:

- A large collecting area to extend the search range to compact objects near the Galactic centre.
- Medium- to high-resolution spectroscopic capabilities for producing radial-velocity curves, and most importantly the determination of the rotational broadening of the lines of the compact objects.

2.2.4 Stellar populations of external galaxies

The study of the stellar populations of external galaxies is a difficult task, and successful observations have been made for just a few of the nearest galaxies of the Local Group. Moreover, chemical abundances of the galaxies in our Local Group are unknown, not to mention those of galaxies further away. Another important topic in astronomy is the determination of the distance scale, which, in spite of the substantial extension by *Hipparcos* of the range over which distances can be determined trigonometrically and kinematically, still lies well within our local neighbourhood inside the Galaxy.

Further links in the distance chain are based on observations of standard candles, e.g. Cepheids and Type I supernovae in external galaxies.

Relevant advances in these and other related fields can be made only if stellar parameters such as effective temperature, surface gravity and chemical composition can be determined for stars in galaxies at the distance of the Virgo Cluster and beyond. A gain in spectroscopy of 2–3 magnitudes over 4-m class telescopes is therefore necessary.

Accordingly, these projects require:

- A large collecting area.
- Excellent image quality to allow the use of 0.1-arcsec slits.
- Spectroscopic capabilities at low and medium resolution.

2.2.5 Active, starburst and primeval galaxies

The study of active galactic nuclei (AGNs) is still plagued with a number of fundamental problems, in particular those relating to the thermal or non-thermal origin of the huge amounts of energy radiated by these objects.

Starburst galaxies, and especially the so-called ultraluminous infrared galaxies (ULIRGs), are peculiar objects, radiating most of their energy in the far IR. These have space densities as great as or greater than those of quasars and are undergoing an intense burst of star formation in which the entire galaxy is participating. Current models suggest an evolutionary link between ULIRGs and AGNs. Furthermore, the unification models for AGNs are gaining momentum in the explanation of the different classes of active objects as being due to purely geometric effects, a suggestion that can readily be tested with polarimetric techniques.

It is not clear though whether all ULIRGs host an active nucleus, or what the spatial extent is of the star-forming processes in these extreme objects.

Finally, galaxies are being discovered that show star-formation activity at ages that are only a small fraction of the age of the Universe.

To make significant contributions in this field, the requirements are again:

- A large collecting area to observe the faintest objects in the early Universe.
- Excellent image quality for spatially resolving the narrow-line regions (NLRs) in AGNs and the circumnuclear star-forming regions in both AGNs and ULIRGs.
- Visible and IR imaging capabilities, including AO, that will allow diffraction-limited imaging at $\lambda > 2$ μm.
- Optical and IR spectropolarimetric capabilities.

2.2.6 Cosmology

One of the most difficult problems in present-day astrophysics is the determination of chemical abundances immediately following the Big Bang. In particular, the determination of the primordial helium abundance is of fundamental importance, given its central role in providing a crucial test of standard Big Bang nucleosynthesis (BBN) theory. This is done through the observation of extremely low metallicity HII regions located in dwarf galaxies. Unfortunately, the luminosity-metallicity ratio followed by these galaxies indicates that the lower the metallicity the fainter the galaxy, thereby making it very difficult to obtain the high-quality spectra needed to derive He abundances. The need to obtain spectra of whole galaxies to correct for various effects contaminating the He measurements makes the observational problem even more difficult.

A different approach is provided by the observation of the lithium content of low-metallicity stars in the halo of our Galaxy. Present-day data can only produce reliable estimates of lithium abundances for low-metallicity stars brighter than V=12 mag, although many fainter (V=14–16 mag) extremely metal poor stars are known to exist.

The analysis of the absorption spectra of high-redshift (z) quasi-stellar objects (QSOs) has provided a powerful tool for studying the properties of intergalactic clouds; their spatial clumpiness, metallic content, ionization state and, most importantly, the evolution of these properties with time. To study the evolution of these systems high-resolution, high signal-to-noise (S/N) spectroscopy of very high-z QSO absorption spectra are required. Also, the identification and further study of high-z absorbers, especially those of high metallicity, is of the utmost importance. These absorbers have recently been identified as haloes of spiral galaxies. Observations of normal galaxies at high z will provide important clues in the study of the evolution of the Universe.

The space distribution of QSOs and high-redshift galaxies and the processes that make galaxies form and bind together in clusters are intimately related to the existence of dark matter. The determination of the fractional amount of non-baryonic matter in the Universe is therefore of great interest.

Neutral carbon transitions in high-redshift absorption systems in the intergalactic medium were proposed more than 20 years ago as a way of determining the evolution of the microwave background temperature with the expansion of the Universe. It is well known that this temperature should rise linearly with redshift. Many attempts to confirm this prediction have been carried out with 4-m class telescopes, but have given null results due to the weakness of the CI lines and the need for very high resolution to resolve their fine structure.

These studies demand:

- Large collecting apertures to image the faintest and most distant objects in the Universe.
- Wide-field imaging capabilities to survey the regions around high-*z* QSOs in the search for high-*z* galactic absorbers.
- Wide field capabilities to perform deep surveys of reduced areas of sky to study the large-scale structure of the high-redshift Universe.
- Medium- and high-resolution spectroscopic capabilities.

2.3 Top-level science requirements

Several scientific projects have been briefly outlined above. These are merely a sample of the wide and varied fields of astronomical research currently being carried out in Spain. They are however sufficient to outline the main requirements that the GTC project must meet. A large collecting area and improved image quality are indeed at the heart of every major advance in optical/IR astronomy. Therefore, the principal requirements stemming from the above considerations are:

- A major improvement in limiting magnitude between 0.3 and 15 μm beyond what is currently possible on a 4-m class telescope.
- Excellent image quality over a reasonable field of view (FOV).
- The simultaneous availability of imaging and spectroscopic capabilities over a wide wavelength range (0.3 to 2.5 μm).
- High operational efficiency.
- High reliability.

These top-level requirements represent guidelines with which the GTC project must comply.

Furthermore, the GTC should be located at a high and dry mountain site, enjoying a high number of photometric nights per year.

A detailed top-down description of the above requirements, as summarized below, is given in [2.1] and Appendix A.

2.4 Detailed science requirements

2.4.1 Theoretical limiting magnitudes

Before discussing the actual specifications it would be informative to examine how the limiting magnitude achievable by a telescope varies with different parameters. It will then be possible to identify the most important areas to be optimized for meeting the overall scientific requirements.

The signal-to-noise ratio for point sources in a photovoltaic detector is given by

$$S / N = \frac{S}{\sqrt{S + B + D + N_r^2}}$$

where S = total signal, B = total background signal, D = total dark current, and N_r = read noise. In general, however, one type of noise will dominate (e.g. the thermal background in the mid IR). In terms of the main telescope parameters

r = radius of the primary (assuming a circular mirror)

t = exposure time

N_r = read noise

m_b = background signal in magnitudes per square arcsecond

b = bandpass

Q = proportion of the incoming photons turned into e^- including quantum efficiency

s = diameter of the seeing

three kinds of limiting magnitude may be defined:

Readnoise limited (LM_r): This will be the case for most short exposures in the visible and near IR, in particular for the highest-resolution spectroscopy, with

$$LM_r = 2.5 \log \frac{Qbr^2 t}{N_r} + C_r$$

where C_r is dependent on such factors as the wavelength and other constants.

Detector dark-current limited (LM_d): An example of this could be high-resolution near-IR spectroscopy where the dark currents are typically a few e^- s $^{-1}$:

$$LM_d = 2.5 \log Qbr^2 \sqrt{\frac{t}{D}} + C_d$$

where C_d is dependent on other factors such as wavelength.

Background limited at constant seeing size (LM_{bs}): This is the case for most longer exposures in the visible/near-IR.

$$LM_{bs} = 0.5 m_b + 2.5 \log \frac{r}{s} \sqrt{Qbt} + C_{bs}$$

Alternatively s could be an aperture/slit size when the aperture is larger than the seeing disc.

Background limited at the diffraction limit of the telescope (LM_{bd}): This is the limiting version of the constant seeing and in practice will not be reached. However, it will almost be the case for 10-µm observations and those using AO.

$$LM_{bd} = 0.5 m_b + 2.5 \log r^2 \sqrt{Qbt} + C_{bd}$$

2.4.2 Telescope diameter

The aim of the project is to develop a facility that will provide a significant advance over existing 4-m class telescopes. From the above equations it can be seen that the achievable limiting magnitude goes as 2.5 log r or 2.5 log r^2, depending on the noise regime, so for the telescope to be at least 1 mag more sensitive than a 4-m class telescope, all other parameters being equal, it will need to have a diameter of 10 m. An alternative view of the problem is to examine the time to complete an observation. From the above equations it can be seen that the time required to reach a specific limiting magnitude goes as r^{-2} or r^{-4}. Hence if all other parameters are the same, a 10-m telescope will complete an observation 6.25 to 39 times faster than a 4 metre. Hence observations that would take the equivalent of many nights on a 4-m telescope, and hence not be feasible, could be done in one or two hours on a 10-m telescope.

The fundamental limit to the image quality attainable by a telescope is set by diffraction, which is proportional to r^{-1}. Image quality will be discussed in more detail in the following sections; however, it is clear that, potentially, the larger the telescope the smaller the limit to the image size.

In conclusion, to provide a facility that represents a significant advance (of at least 1 mag) on existing 4-m telescopes requires the entrance pupil of the telescope to have a diameter of at least 10 m.

2.4.3 Estimated limiting magnitudes

The estimated limiting magnitudes versus time for various types of observations with a 10-m class telescope are presented in Figure 2.1. These plots should be taken only as an indication of what is possible, as the real values will depend heavily on the actual instrument and the prevailing weather conditions.

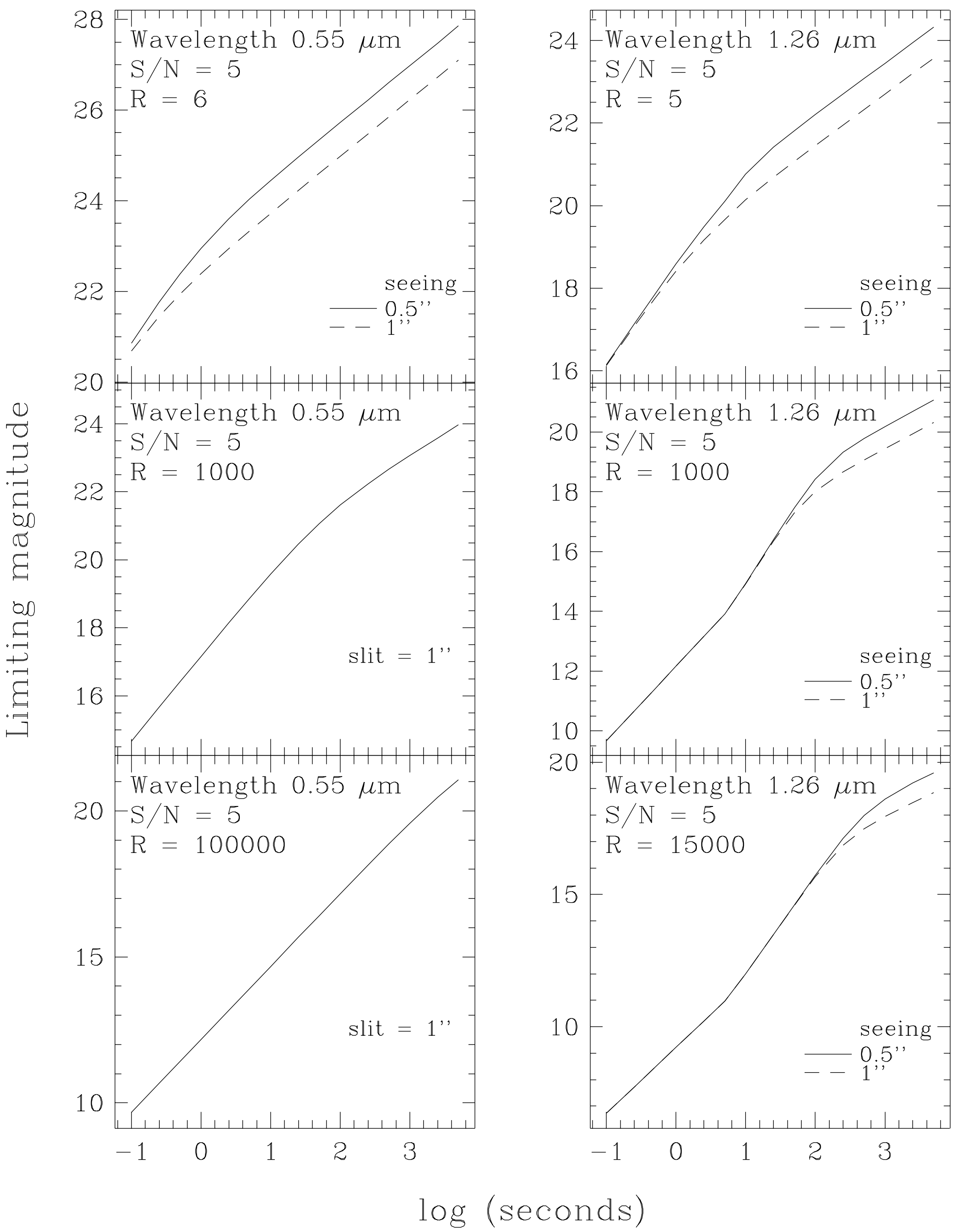

Figure 2.1: Expected limiting magnitudes for a 10-m telescope against time (continued on next page).

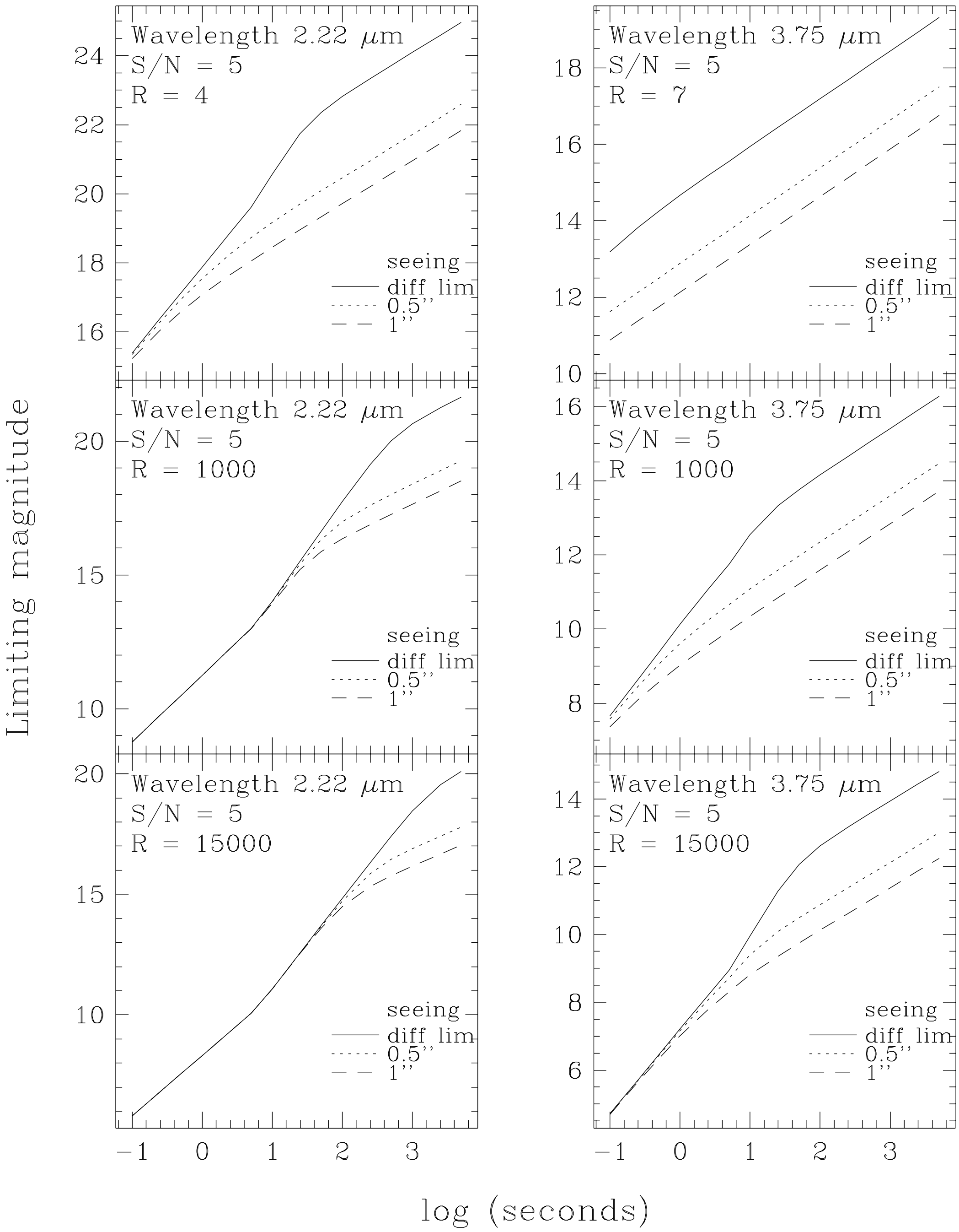

Figure 2.1: Expected limiting magnitudes for a 10-m telescope against time (continued from previous page).

The limiting magnitudes are predicted for imaging (upper plot) and spectroscopy at *V*, *J*, *K* and *L*, as these cover a wide range of backgrounds and will be typical of the observations that are expected to be attempted. The calculations are made for 0.5- and 1-arcsec seeing, and the diffraction-limited case at *K* and *L*. In making these plots a series of assumptions has been made and are listed in Table 2.1.

Filter	Wavelength (μm)	Zero mag. flux (W m^{-2} μm^{-1})	Read noise (e^-)	Background (mag)

V	0.55	375E-10	5	21.5
J	1.28	28.5E-10	50	15.2
K	2.22	3.96E-10	50	12.5
L	3.75	5.07E-11	50	4.0

Table 2.1: Assumptions made in calculating the limiting magnitudes shown in Figure 2.1. The detector read noises are typical for current detectors, and the background magnitudes are based on measured valued.

Other assumptions made in the calculation of the limiting magnitudes were the following:

- For imaging 20% of the photons entering the atmosphere are converted into electrons in the detector, whereas for spectroscopy the total throughput used is 10%.
- A double-correlated sampling readout scheme for IR integrations shorter than 10 s was used, whereas for longer integrations a ramp method was adopted with one-none destructive readout per second.
- The integrations can be indefinite; however, in reality the limit is about 30 min due to cosmic ray strikes.
- The dark currents have been ignored as in general the sky background will dominate, although for spectral resolutions at *J* greater than 15000 or at *V* much greater than 10^5, the dark currents would become significant.
- The plots are made for the quoted seeing at that wavelength, and the pixel scale can be changed to maintain the number of pixels over the image profile. Changing the number of pixels in the profile would alter the point at which the plot changes from being read-noise limited to background limited, the more pixels, the higher the total read noise.
- For the IR spectroscopy an integral field unit based on an image slicer is being used, as this is the most sensitive in the background limited case.

2.4.4 Attainable image quality

There are a number of drivers for high image quality:

- *Limiting magnitude:* In the case of background-limited observations at constant seeing/aperture size it can be seen that halving the image diameter has the same effect as doubling the telescope diameter.
- *High angular resolution:* For example the central regions of active galaxies where the interesting physics is occurring on angular scales under 0.5 arcsec.
- *High dynamic range photometry in crowded fields:* This can greatly increase the effective dynamic range of the telescope, and most probably it will be the fainter objects that will be of interest. A useful example would be finding the luminosity functions of globular clusters.

Ideally the optics for the telescope should be diffraction limited at all wavelengths. However, in practice this would be prohibitively expensive for a very large telescope and at most wavelengths (shorter than 5 μm when not using AO) the free-air seeing will be many times the diffraction limit. Therefore, the requirement on image quality that has been adopted is that free-air seeing in the visible of 0.4 arcsec full width at half maximum (FWHM) should not be degraded to more than 0.44 arcsec. This implies that the combined image degradation from dome seeing, mirror seeing and optics should be under about 0.18 arcsec on axis (FWHM, assuming that it adds in quadrature), or that θ_{80} [1] is 0.84 arcsec.

At wavelengths longer than about 4.8 μm (3.5 μm in very good seeing) image motion (fast tip-tilt) correction alone is sufficient to improve the image quality of a 10-m class telescope significantly. Therefore with a visible seeing of 0.5 arcsec the telescope is required to produce images with a Strehl Ratio[2] (SR) of 0.33 at 4.8 μm on axis.

AO will allow near diffraction-limited imaging at wavelengths of 2.2 μm, or possibly shorter, in very good seeing. As well as giving higher spatial resolution, this potentially provides a major increase in sensitivity. For example, AO will allow slits of 0.1 arcsec to be used with a near-IR spectrometer, which means that the system will be as sensitive for point sources as a seeing-limited 50-m telescope using 0.5-arcsec slits. Hence, it is clear that AO must be considered as an integral part of the telescope design and not an optional extra. The AO systems will significantly reduce any low-order errors in the telescope optics so the requirement adopted is that the combined telescope and AO system should produce diffraction-limited images at 2.2 μm with an SR of 0.8 on axis with visible seeing of 0.5 arcsec.

2.4.5 Foci

There will be three principal foci (Cassegrain and two Nasmyths, see Figure 4.1). There will also be four folded-Cassegrain foci and the possibility of a prime and/or coudé focus.

2.4.5.1 Cassegrain focus

The Cassegrain focus has the minimum number of reflections; it will therefore have the lowest thermal background and the light will be the least polarized. The weight of the instruments and ancillary equipment will have to be carried on the mirror cell and so must be limited in order not to cause distortion; however, if the instruments become too small they will not be capable of the required performance. A suitable compromise is to limit the total weight to 6 tonnes, and the available space at Cassegrain to about 2 m in diameter by 3.5 m in length.

2.4.5.2 Nasmyth foci

The Nasmyth focus requires a third, 45^{o}, mirror in the beam to direct the light through the elevation axis. As the instruments at these foci do not move with the elevation axis they can be significantly heavier than those of the prime, Cassegrain and folded Cassegrain foci. The requirement is that the Nasmyth platforms must support instrument packages weighing as much as 10 tonnes and have a floor area of at least 6×6 m^2. The instruments at Nasmyth can be mounted either directly on the platform or on to a mechanical rotator capable of supporting many tonnes. The Nasmyth flat will be situated on the elevation axis above the vertex of the primary mirror and will be removed from the beam when the Cassegrain focus is being used. From the operational standpoint, the Nasmyth flat must be able to be automatically inserted or removed from the beam in under five minutes.

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[1] θ_{80}: represents 80% of the energy enclosed within this diameter. This is a useful parameter for specifying the energy in the wings of the point spread function (PSF). In this case it has been calculated from the 0.18-arcsec FWHM requirement assuming a typical atmospheric seeing PSF.

[2] This is a comparison of the attained peak intensisty of an image with the diffraction limited case. For a precise definition see Section 4.6.1.

2.4.5.3 Other foci

The telescope will have a set of four folded Cassegrain foci on the elevation ring. These should carry weights of up to 1 tonne and will be particularly useful for carrying any major optical calibration instruments so as not to take up space at the Nasmyth or Cassegrain foci.

Concerning the remaining two possible foci for the telescope, there is currently no science proposed that specifically needs either the prime or coudé focus. However, if possible the telescope should be built such that these can be added at a later stage and advanced instrumentation mounted. In particular an area at least 1.3 m in diameter by 2 m in length should be available for instrument packages at prime focus weighing up to 2 tonnes.

2.4.6 Field of view and image quality

The field of view required very much depends upon the type of observations to be attempted. The following is a representative list of observing techniques which provide the drivers.

2.4.6.1 Visual imaging

Ideally, the seeing-limited performance should be over the largest possible FOV; however, there are limits below which the science becomes restricted. The minimum requirement is a FOV of 8 arcmin without vignetting, although ideally this should extend to 20 arcmin. The image quality off axis should degrade only with the increasing astigmatism inherent in the optical configuration. Clearly, it will be better for the best imaging capability to be available over the largest possible FOV. However, in practice it will be difficult to image over very large areas because of the physical size of the focal plane. Therefore, an unvignetted field of view of 8 arcmin in the visible is required, which will allow most objects to be imaged in a single or few frames.

2.4.6.2 Long-slit visible spectroscopy

The requirement is to be able to mount a 7-arcmin $\times$ 0.5-arcsec slit without image degradation along the slit. In practice most observations will not require slits longer than 4 arcmin, although narrower slits may be needed. It must also be possible to orientate the slit to any angle on the sky.

2.4.6.3 Multi-fibre spectroscopy

Fibres allow objects to be observed over the full FOV of the telescope, including the slightly vignetted part, but with an image quality of around 1 arcsec. A FOV of at least 20 arcmin, and preferably 30 arcmin, is required at either the Nasmyth or the Cassegrain focus.

2.4.6.4 Thermal-IR imaging

Performance at 4.8 μm limited by diffraction and isoplanatic errors over at least 4 arcmin is required and an unvignetted FOV of at least 7 arcmin. Pixel sizes have to remain small (typically 0.06 arcsec) in the thermal IR to avoid saturation problems; even then they have to be read out hundreds of times per second. So it would be problematical to image over more than 1 to 2 arcmin. However, as will be discussed later, it will be necessary to chop. In order to chop on to a completely different field the chopper throw must be equal to the FOV of the instrument (i.e. 2 arcmin), thereby setting the unvignetted FOV.

2.4.6.5 AO imaging/spectroscopy

At 2.2 μm the largest field available with AO imaging will have a radius of at least 60 arcsec. For certain conditions an SR of about 0.2 could be provided by the AO system.

2.4.6.6 Summary of the required FOV

From the above arguments the FOVs required at the individual foci are as summarized in Table 2.2. In each case the full FOV in arcmin is given:

	Minimum	Goal
Cassegrain visible–near IR		
Unvignetted	8	20
Vignetted on mirrors	25	30
Nasmyth visible–near IR		
Unvignetted on tertiary mirror	15	20
Vignetted on tertiary mirror	unvignetted + 5	
Thermal IR		
Unvignetted	7	

Table 2.2: FOV in arcmin required at each focus.

2.4.7 Adaptive optics

High-order adaptive optics (HOAO) will be required in order to maximize the near-IR image quality and hence, as said before, will be considered as an integral part of the GTC design. It is expected that the adaptive mirror will significantly improve the optical performance of the telescope by reducing the low-frequency error; hence the actual requirement is that when using natural guide stars, the telescope and AO system should produce diffraction-limited images at 2.2 μm with an SR of 0.8 on axis and should be limited by the isoplanatic error off axis. The first AO system should be available within two years of Day 1[3].

The sky coverage for AO using natural guide stars is very small. In order to increase the sky coverage a laser guide star (LGS) should be used. The requirement for the AO system when using laser guide stars is that in 0.5-arcsec visible seeing the system should produce images at 2.2 μm with an SR of 0.5 on axis.

There are two possible alternatives for the AO system: either a focal plane system or an adaptive secondary mirror. The technology for the focal-plane system has already been demonstrated on a number of telescopes; however, the adaptive secondary has the advantage of fewer surfaces (hence lower emissivity), and the same mirror can feed all foci. In either case the implementation of the AO system must be consistent with the philosophy of flexible scheduling (see Section 2.5.1); hence, when the AO system is mounted it must not preclude observations not requiring AO.

2.4.8 Background-limited performance

It is clear from the above that minimizing the background signals is crucial. Basically, there are two regimes to consider:

[3] Day 1 is the milestone referring to the start of full GTC scientific operation.

1. At wavelengths shorter than about 2.1 μm the backgrounds are dominated by atmospheric OH emission or nightglow. The telescope itself will not contribute to the background. In order to minimize the background contribution it is important that the detectors only see light in the nominal telescope beam and not the sky directly (at least within the unvignetted FOV). This puts strict constraints on the baffling for both the telescope and the instruments. It is also important that there is good stray-light rejection from, for example, moonlight and very bright sources near the beam. However, it should be noted that the telescope plate-scale will require the scientific instruments to re-image the focal plane. Hence a significant part of the stray-light rejection can be done within the instruments and hence the number of baffles, particularly near the secondary, can be reduced. As a requirement, the background measured on axis at the instrument detector should be at most 10% above the natural background for that position in the sky. In general, the background is stable for at least tens of seconds so that at most only slow nodding of the telescope, and not fast chopping, is required.

2. At wavelengths longer than about 2.1 μm the backgrounds are dominated by thermal emission from both the GTC and the sky. However, as the sky forms a dilute black body which is considerably colder than the GTC it is preferably to see the sky and not the warm optical baffles. The requirement put on the GTC in order to minimize the thermal background is that the emissivity at Cassegrain should be below 5% at 3.8 μm, with a goal of less than 3%. This implies that there will be no optical baffles, and that the mirrors must have coatings with high IR reflectivity. If the background fluxes are to be accurately subtracted it is important that the thermal background from the GTC be stable both in time and over the entire IR focal plane (7 arcmin). Even so, particularly at 10 μm, the background will only be stable for very short periods so sky chopping will be required at a few Hz (see Section 2.4.10).

2.4.9 Throughput

It is crucial that the maximum proportion of the photons entering the optical system arrive at the focal plane. From the previous section it is doubly important that the reflectivity is high in the near IR since not only is light lost but also the background increases rapidly. However, achieving this high reflectivity in the near IR must not preclude observations near 0.3 μm.

Perhaps the biggest potential loss in reflectivity is through the build-up of dust on the upward-facing surfaces. If not removed, this dust could lead to a 30% or more loss of light and can damage the coating. Hence it is crucial that the mirrors are cleaned regularly and measures are taken to prevent dust getting on the mirrors. The requirement is that the emissivity of the optics must not increase by more than 3% above the clean state.

Occasionally the proposed site (see Section 3.9.1) suffers from the presence of Saharan dust for a few days each year. On such nights the atmospheric extinction can rise to over 0.5 magnitude per airmass in the visible, and an unacceptable amount of dust will build up on the mirrors over a few hours. However, the weather conditions are then still usually acceptable for many projects and a method should be found of limiting the build-up of dust whilst allowing some observations, although not necessarily in optimum conditions.

2.4.10 Secondary mirror

From the above discussion, it is clear that visible and IR observations have significantly different requirements. Ideally, the visible requires:

- Unvignetted FOV of 20 arcmin and a Ritchey-Crétien configuration for maximum image quality over the full field.
- Maximum throughput, hence an oversized secondary and coatings which are good to 0.3 μm.

- Good optical baffling to reduce stray light.
- A `reasonable plate-scale. With a large telescope the plate-scales will never be ideal for wide-field images but at least 1.1 arcsec mm^{-1} is required.
- Five-axis motion for alignment.

The requirements for the IR are:

- An unvignetted FOV of 7 arcmin.
- An undersized secondary and no optical baffles in order to minimize the thermal backgrounds.
- The ability to chop at 2.5 Hz up to ± 1 arcmin and at 10 Hz up to ± 7.5 arcsec, with a duty cycle of 80%.
- The ability to chop between any number of positions within the ± 1-arcmin maximum chopper throw.
- The repeatability of the chop should be <0.03 arcsec.
- Fast image motion and possibly focus correction at up to 40 Hz, over 3 arcsec and with a precision of <0.01 arcsec rms.
- Five-axis motion for alignment.
- A focal ratio sufficiently close to the visible such that the best image quality over the full FOV can be obtained.
- IR-optimized coatings.

2.4.10.1 Number of secondary mirrors

While it is clear that all the ideal requirements for the secondary mirrors cannot be met by a single mirror, there are very strong arguments for adopting a single-mirror option, which is the adopted baseline. In this form:

- All of the mounted instrumentation will be available in optimum conditions, and flexible scheduling can be adopted.
- Fast image-motion correction will be available for all wavelengths. As well as chopping, the thermal-IR secondary mirror should be capable of fast image-motion correction, which will certainly improve the image quality at 4.8 μm. In principle, there should be little advantage in fast tip-tilt capability at visible wavelengths. However, in moderate wind conditions having fast tip-tilt will reduce the image smear caused by windshake, and it is probable that if the image requirements are to be met with winds of up to 10 m s^{-1} then fast image-motion correction in the optical will be required.
- Down-time for secondary changes is avoided.

Thus a compromise has to be reached between the visible and IR requirements, the most important of which are the following:

- An undersized secondary with 8-arcmin minimum unvignetted FOV at Cassegrain.
- A plate-scale of more than 1.1 arcsec mm^{-1}.

- Deployable baffles to allow either visible or IR optimization.
- IR-optimized coating but with reasonable reflectivity to 0.3 μm.
- Fast image-motion correction and chopping with the above-mentioned requirements.

2.4.11 Pointing and tracking

The principal requirements for pointing and tracking are:

- To be able to point to any position with an elevation angle between –1° and 91°, whereas for normal observations the elevation angle will be between 15° and 89.5°. The extra range is required for maintenance and security purposes.
- The telescope drive system must continuously track any object moving at up to 1 arcsec per second relative to the sidereal rate, when the object has an elevation angle greater than 15°. The zenith blind spot should be at most 1°. The control system should be able to track on any object moving with a predictable path and within the limits of the drive and encoder system to allow Solar System objects to be observed. As a goal the telescope should be able to track any object with an elevation angle above 0°, although the observations will be vignetted on the dome.
- In order to meet the preceding requirement there is a minimum necessary angle of rotation in azimuth (453° [2.2]). However, to improve the efficiency of the telescope and minimize the number of azimuth slews greater than 180° the minimum angle must be increased. The optimum would be to allow 720° of motion but this would cause a number of mechanical problems. Hence, the requirement is that the rotation in azimuth must be at least 60° more than the minimum, with 540° of total motion as the goal.

The basic requirements for pointing and tracking are given in Table 2.3:

	Requirement	Goal
Pointing accuracy (arcsec rms)		
5° < zenith angle < 60°	2	<1
zenith angle ≥ 60°	3	<1
Elevation range (°)	-1 to 91	
Offsetting accuracy (arcsec rms)		
30 arcmin	0.1	
60 arcmin	0.3	
Time to point/offset and start tracking (s)		
5 arcsec	1	
5 arcmin	10	5
10°	30	20
to any position in sky	300	180
Elevation tracking limit (°)	15	0
Open-loop tracking accuracy, sidereal rate (arcsec rms)		
in 10 min	0.1	
in 1 hour	0.5	
Diameter of zenith blind spot (°)	1	
Maximum closed-loop guiding jitter (arcsec rms) without image motion correction averaged over 5 to 10 s	0.038	

Table 2.3: Pointing and tracking requirements.

Note that the pointing and tracking accuracy is for elevation angles up to 85°. Close to the zenith blind spot the azimuth velocity increase significantly and it is probable that the accuracy will decrease slightly.

In general, the above requirements for pointing and slewing speed are for maximizing the efficiency of the telescope. Slightly poorer absolute pointing would only slow down the time to acquire objects. However, the offsetting accuracy is important if objects are to be placed accurately on to 0.1-arcsec slits.

The telescope will usually operate with closed-loop guiding, however there will be occasions when open-loop tracking is required (for example, immediately after pointing to an object, or in very high background conditions), hence the importance of precision in open-loop tracking.

2.4.12 Instrumentation

Provision must be made to supply and support a few high-performance instruments for imaging, spectroscopy, and polarimetry between 0.3 and 15 μm. The instruments will be built by outside consortia, the Project Office being ultimately responsible. The detailed requirements for instruments are discussed in Chapter 7.

As there will be only a few facility instruments they will in general have multiple configurations. It is expected that the workhorse instruments will be an intermediate-dispersion visible imager/spectrometer and a 1–5 μm camera/spectrometer. In normal operation these should always be available.

2.4.13 Data reduction and archiving

In general the initial steps in data reduction are standard, e.g. removing the bias and flatfielding. For each facility instrument there should be a process to reduce the images automatically using the best calibration data available, so that the user can see the reduced images within minutes of the observation having been completed. During the day the process should be re-run using all of the calibration data for the previous night to produce reduced images.

Experience with various data archives, such as those from the *Hubble Space Telescope* (*HST*) or the *International Ultraviolet Explorer* (*IUE*), has shown that these can be valuable tools in their own right. There will be two data archives:

1. The calibration archive.

2. The data archive, which will store the raw data (primarily as a safeguard), and the reduced data.

The data will have a proprietary period; once this has lapsed the data will be made available to the general community. The calibration data will have no proprietary period.

2.4.14 Acquisition and guiding

An important part of the philosophy of the acquisition and guiding (A&G) system is that it will be designed to point the aperture of the science instrument, rather than the telescope itself, at the object of interest, since in practice the user wants to put the source at the centre of the aperture on the science instrument, the position of which will vary in relation to the position of the telescope tube, or even the optical axis, due to flexure.

There are two basic A&G systems required by the telescope:

1. *Off-axis A&G system:* This will have frame rates of a few Hz and will be designed to maintain the position of the telescope mount (slow guiding).

2. *On-axis A&G system:* With IR instrumentation, a dichroic can be placed in the beam to divert the visible light, which can then be used for guiding. For wavelengths longer than 4.8 μm (or

3.5 μm in very good conditions) image-motion correction (fast guiding) alone will be sufficient to provide images with a high SR if there is a guide star within the isokinetic patch[4] (typically 1–2 arcmin). This will require a camera with frame rates of about 200 Hz. Long-slit spectrometers can have slit-viewing cameras, and the images from this can be used for the acquisition and guiding.

Some of the on-axis A&G systems will have to be built into the individual instruments, particularly the slit-viewing camera. However, in all cases the A&G sensors will be the responsibility of the telescope and not of the instrument. At least initially no A&G systems will be provided at the prime or folded Cassegrain foci.

The requirements for the telescope A&G are:

- To be able to position the camera FOV anywhere within the FOV of the telescope (including into the vignetted area).
- FOV > 1 arcmin for acquisition (possibly smaller for guiding).
- Frame rates from 10 Hz to 0.01 Hz for the slow guiding system and 200 Hz for the image-motion correction system.
- A tolerance in the position of the camera with respect to the aperture of the science instrument of 0.015 arcsec.
- Ability to accommodate filters (neutral-density filters for bright stars and colour filters for identification).

2.4.15 Telescope enclosure

The fundamental requirements for the enclosure are that it must:

- Provide a clear aperture on the sky which moves with the telescope for elevation angles greater than 15°. The aperture size must allow a 1° FOV and motion of the telescope through 2° in azimuth without moving the dome.
- Have minimal impact on the seeing.
- Protect the GTC when not in use against rain, snow, dust, high winds, etc.
- Protect the telescope from the wind when in use.
- Provide support for the running of the telescope, easy change of equipment, etc.
- Prevent the build-up of dust.

The enclosure will provide maintenance and storage facilities as well as a suitable working environment for staff and visiting scientists. Additionally, for safety reasons the dome must be able to shut in under 3 minutes.

2.4.16 Control system

[4] By 'isokinetic patch' is meant that field within which the image motion originating from the atmosphere may be considered as constant.

The fundamental requirement for the control system is that it provide the most efficient operation possible of the GTC so as to maximize the scientific return. The control system should allow the instrumentation and telescope to operate as a single unit with a clear display of the current system status and any errors. In normal operation the system should require minimal user intervention with provision for automatic scheduling of an observing list, automatic setting of the autoguiders, etc.

2.5 Operational and support requirements

The operational and support requirements will be taken into account in the design of the GTC, with the aim of minimizing the running costs, simplifying the maintenance and guaranteeing safety [2.3]. An integrated logistic support (ILS) approach will be adopted, which will also ensure that the necessary support equipment is provided (see Section 9.2.5.7). Therefore, both the high- and low-level operational and support requirements have to be clearly identified along with the potential users and the expected operating conditions.

2.5.1 Operational requirements

One of the top-level science requirements of the GTC is a high operational efficiency to maximize the scientific return. Whilst this is a difficult parameter to quantify there are some basic guidelines:

- The GTC must remain scientifically competitive, so that its results, not being within the reach of smaller apertures, match those obtained with the best telescopes.
- Multiple use of the scientific data by the development and the exploitation of the data archive.
- Priority will be given to maximizing the quality of results. It is necessary to guarantee the success of those observing proposals that have the highest scientific interest, especially those that require the best observing conditions.

The factor that produces the largest variation in attainable image quality is the prevailing weather conditions. For many observations (e.g. background-limited observations of point sources) when the seeing doubles, the time to reach a specific limiting magnitude increases by a factor of four, while there are other observations (e.g. surface-brightness measurements of extended objects) where the observing time is basically independent of seeing. Hence, there will be many projects that are only feasible with excellent seeing whereas others can proceed in poorer conditions. Similarly there are observations which require low water vapour, photometric conditions, etc., if they are to produce the required results. Using the classical technique, whereby observing slots are scheduled months ahead, means that the actual observing conditions are purely a matter of luck. Hence, those observations requiring the very best conditions are unlikely to be successful and their completion rate will be low. Therefore, in order to maximize the scientific return from the telescope, a mode of observation is required which will allow access to the best observing conditions for those observations requiring them. This can be achieved only if the observations are scheduled immediately prior to their execution, when the observing conditions are known to be suitable.

2.5.1.1 Modes of operation

Currently it is envisaged that there will be three general modes of operation of the GTC, two for scientific observations and one for engineering. The fundamental differences between the modes are the level of interaction possible with the telescope and who is responsible for the operation of the telescope during the assigned period:

1. *Queued service observing*:

   In queued service observing, periods are allocated for use in this mode but the actual observations to be undertaken are not determined until immediately before the observations take place. Therefore, the conditions (e.g. seeing or humidity) are known and those observations that require the best conditions have access to them.

   For queued service observing to be successful there are a number of prerequisites:

   - The simultaneous availability of observing programmes which cover the full range of expected observing conditions. The programmes must consist of observing blocks that unambiguously define the required measurements and the observing conditions required. There must also be a scientific priority rating assigned by the time allocation committee.
   - The simultaneous availability of instruments to provide a wide range of observing options. The time to switch between instruments must be low.
   - Software to guide the astronomers in the preparation of observing programmes.
   - Software to schedule and perform the observations.
   - Operational staff (see next section) with sufficient experience to oversee the observations.
   - A significant proportion of the available telescope time scheduled for queued service observing so that there is a sufficient number of excellent nights available.

   The advantage of queued service observing is the high flexibility in scheduling; however, this is at a cost of a loss of immediate interaction with the astronomer. In principle this interaction could be at two levels:

   - None at all, the astronomer being informed on the following day that the data have been taken.
   - Listening in. The astronomer would be informed that his observations are likely to be scheduled that night. By remotely logging in from his home institute the astronomer can see the data remotely as they come off the telescope and where necessary modify those observations still to be performed. However, the astronomer would have no control over the observations as they are carried out.

2. *Classically scheduled observing*:

   It is recognized that there will be many observations that are not suited to service-mode observing (e.g. groups using their own instrumentation), and that these will have to be scheduled classically, i.e. with the astronomer being allotted a specific period (this may be whole nights or parts of nights) and being responsible for operating the telescope during this time. There are two forms of classically scheduled observations and both will be available with the astronomer physically present at the telescope or logged in remotely:

   - *Assisted observation:* Here the astronomer would break the observing programme into the same observation blocks as used in the queued service mode, and the scheduler then would order them for maximum efficiency. The observation would then proceed as in the queued service mode, except that only the one observing programme would be active, and that the astronomer would have full control over the queue.

- *Detailed observation:* The astronomer would enter each command individually into the telescope control system and each command would be acted upon as it arrives. For system safety it would be helpful for the commands to be entered into a command sequencer so that high-level checking could be performed.

3. *Engineering*:

   In engineering mode the primary goal of the time usage is not science, and the operations are performed by maintenance staff or development personnel. The sorts of operations included are:

   - Development and commissioning of any new subsystems or instruments.
   - Calibration of the telescope.
   - Scheduled maintenance tasks.

   Some of these operations may be carried out using the same procedures as the scientific observations (e.g. constructing the telescope pointing model); however, in other cases direct access to the subsystems will often be required. Access must be provided for remote operation because if a problem occurs, it is crucial that an expert can quickly look at the problem so that the time lost is minimized. This expert could be a member of the GTC staff who is not on site or an instrument engineer who could be anywhere in the world, hence it is important that there is a low-level interface to the control subsystems that operates over the external networks.

2.5.1.2 Users of the GTC

Potential users of the GTC fall into four categories:

1. *Visiting astronomers*: These are the end users of the GTC. Their level of interaction with the GTC will depend heavily on their scientific programme. Those using facility instrumentation will be primarily concerned with verifying the quality of the data, whilst those with their own instrumentation will also have to have more control over the actual operations.

2. *Support staff:* This category includes the support astronomers and night assistants of the GTC, all with experience in its operation. In classically scheduled observing, the duties of the support staff will help the visiting astronomer. In queued service observing, the support staff will supervise the operation of the GTC.

   An important responsibility of the support staff will be to improve the operation of the GTC. Since they will be in continuous contact with the telescope, they will be in a good position to suggest new operating procedures, changes to subsystems etc., and thereby improve the scientific return from the telescope.

   The support staff will be ultimately responsible for safety of the GTC during astronomical operation.

3. *Maintenance staff:* This group will be responsible for maintaining the GTC in perfect working order.

4. *Development personnel:* This group will be in charge of implementing and installing improvements and new developments in the GTC (see Section 9.4).

The tasks of the support and maintenance staff (GTC staff) will be defined in the operation and maintenance plan.

2.5.1.3 Low-level operational guidelines

To maximize of the operational efficiency of the GTC, the following guidelines will be employed:

- Minimize the time required for engineering while maintaining the correct operation of the GTC.
- Ensure that the operation of the GTC is clear and simple.
- Employ specialized support staff.
- Have adequate training, simulation tools, and documentation for both visiting astronomers and support staff.
- Plan the observations in detail before carrying them out to maximize their efficiency. As well as assistance from the GTC staff, tools will be provided to help astronomers prepare their programmes.
- Have available tools that rapidly inform the user of the quality of the observations.
- Automatic start-up/shut-down of subsystems. Time to run up the GTC from a cold start should be less than 5 minutes and to close down less than 1 minute (assuming the telescope to be already parked and the dome closed).
- To promote continuous improvement in the service provided to the astronomical community. A mechanism for efficiently attending to their comments will need to be set up.

2.5.1.4 Safety during GTC operation

The safety priorities, in descending order, are as follows:

1. Protection of persons.
2. Safeguarding the integrity of the GTC.
3. Protection of scientific data.

The criteria guaranteeing safety are the following:

- When it comes into operation, the GTC must comply with current European Union safety regulations.
- All maintenance and operational procedures will be submitted to validation from the point of view of safety. Development and maintenance operations of the GTC will be authorized by the operational staff manager.
- Where possible, hardware and software limits will be established for the operation of the GTC.
- To avoid potential risks, measures will be taken to prevent the use of the GTC when the environmental conditions are outside the operational range (see Section 3.6.1).
- The GTC will be protected from unauthorized access, particularly over the external networks. Access privileges will be established in accordance with the requirements of the users.

- The operational and maintenance procedures will provide maximum protection against accidental loss of scientific data. Similarly, the confidentiality of data during the proprietary period will be guaranteed.

2.5.1.5 Meteorological limits on telescope operation

The GTC will be required to operate in a wide range of weather conditions. On the basis of the expected conditions at the site (see Section 3.6.1) the following requirements for the operation of the GTC have been determined:

- With wind speeds from 0 to 10 m s^{-1}, the GTC will operate with no appreciable loss of performance.
- The telescope will operate in wind speeds from 10 to 22 m s^{-1}, albeit with lower image quality. There will a number of nights with high wind speeds, and although the GTC cannot be expected to operate at peak performance there will be useful science that can be obtained.
- With wind speeds above 22 m s^{-1}, the telescope dome will be closed. There will be relatively few nights with such high wind speeds so the loss of science will be negligible.
- Shutdown for the GTC should occur when the relative humidity reaches 90% or when water starts to condense. Most current telescopes tend to operate above the ambient temperature so condensation is unlikely. However it is proposed to operate the GTC as close as possible to ambient temperature, so care must be taken not to allow dewing of the optics.
- All components must operate correctly over the expected operational temperature range (see Section 3.6.1) and in particular the electronic components must reliably boot from a cold start over the full temperature range.

2.5.2 Support requirements

High reliability is one of the top-level requirements of the GTC. This is established in terms of the maximum percentage of down-time due to failures, which must not exceed 2% of the useful time. Also, the estimated percentages of time dedicated to maintenance tasks and other support operations of the GTC are given in Appendix B.

The following guidelines need to be taken into account:

- The updates and modifications of the GTC must be implemented with the minimum impact on availability and cost.
- As far as possible, the same components will be used in different subsystems in order to keep maintenance simple and minimize cost. Where possible, standard commercial components which have proven performance and servicing will be used.
- The GTC will have self-diagnostic tools, which will warn of the occurrence of faults.
- Facilities for carrying out many of the maintenance operations remotely should be provided.
- The maintenance of each subsystem will be independent of the rest of the GTC. Maintenance tasks must be simplified, this will require the implementation of good monitoring and diagnostic capacities. All maintenance activities, whether corrective, predictive, or preventive, must be registered in the database, which will be accessible by maintenance staff. This particularly includes results of the periodic checks on the performance of the GTC, as well as the replacement of elements, including software.

- As far as possible, each subsystem will have a stand-alone capability so that in the event of a failure in one subsystem the rest of the GTC will continue to operate. Information relating to failures will be recorded in a database for future consultation by the maintenance staff and provide statistic on the reliability of the system.
- The operations carried out by the GTC and the conditions in which they are undertaken must be recorded. This is invaluable for analysing problems that have arisen.
- The required lifetime of the GTC is at least 50 years.

2.5.3 Electromagnetic compatibility requirements

All elements of the GTC will have to comply with the electromagnetic compatibility regulations of the European Union in force at the time of its installation. This applies chiefly to:

- *Electromagnetic disturbance:* Both radiated and conducted electromagnetic disturbance generated by electrical and electronic equipment will be kept as low as possible.
- *Electromagnetic susceptibility:* Measures will be taken to minimize unwanted coupling of signals.
- *Electrical discharges:* It is necessary to take into account the environmental conditions at the Observatory. There are extended periods with very low humidity which lead to problems with static electricity. Attention must be given to the protection of personnel and equipment to prevent electrostatic discharge. Poor earths on the mountain mean that lightning strikes on the facility are probable during electrical storms. In such circumstances, particular care must be taken to protect personnel and sensitive electronic equipment.

References

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3. THE GTC SITE

3.1 Introduction

The GTC must be situated on an excellent site. This means not only at an excellent observatory but also at the best available location within that observatory. Chief areas of concern are that:

- For good image quality the GTC must be located at a site with the best possible natural free air seeing. It should be remembered that adaptive optics works well only in excellent seeing conditions.

- The site must have a very high percentage of usable nights, since weather will cause by far the largest loss of observing time. However in order to obtain the best science it is crucial that within the usable time there should be a high number of excellent nights for observing (i.e. photometric, with good seeing and/or low water vapour).

- For the lowest possible background it is essential that the site should have as little artificial light pollution as possible.

- The site should be well above the local inversion layer. The inversion layer will tend to trap the water vapour making the site dry and hence suitable for IR measurements. It will also block out light pollution from sea level.

- The site must have good atmospheric transmission in the poorer parts of the atmospheric windows as well as in the better parts. It is particularly important that the precipitable water vapour above the site be low as this will allow observations well into the wings of the IR windows.

- The temperature at the site should be low. It can be shown that the background in the thermal IR goes as

$$Thermal \quad background = \frac{\varepsilon}{\lambda^5\left(e^{\frac{hc}{\lambda kT}} - 1\right)} d\lambda$$

  where ε is the emissivity of the telescope. Hence between 2.1 and 5 μm the background flux is very sensitive to temperature and doubles for each increment of 10 ^{o}C.

- The temperature should vary slowly and predictably during the time. Since various parts of the telescope will cool at different rates, fast changes in temperature would distort the structure and cause alignment and pointing errors.

In what follows, the conditions for astronomical observations at the ORM are reviewed. This revision includes seeing and meteorological campaigns, geological sounding tests as well as water-vapour measurements. A study on the effects of Saharan dust on astronomical observations is also included. Regarding the IR properties of the ORM a study is presented that uses both old data from the Teide Observatory (OT) as well as data from the recent, although brief, water vapour campaign carried out at the ORM. It will be shown that the ORM qualifies as an excellent observatory for the GTC.

3.2 Roque de Los Muchachos Observatory

The Canary Islands, at 28° N and 17° W, enjoy a special climate that has been the subject of a number of studies [3.1] [3.2]. The main characteristic that makes the Canaries an excellent site for astronomical observations is the stability of the inversion layer, which varies in height between 800 and 1500 m MSL (mean sea level; unless indicated otherwise, all height given here are above MSL), for 90% of the year. The Observatory is situated at a height between 2100 and 2400 m just beneath the rim of an extinct volcanic caldera, well above the inversion layer, with the result that the atmosphere is normally dry, stable and transparent [3.3] [3.4]. Light contamination is virtually nil since urban development is well removed from the Observatory, besides which public lighting on the whole island is legally controlled ('Real Decreto 243/1992', *Boletín Oficial del Estado*, 20 April 1992) in accordance with Law 31/1988 on the protection of the astronomical quality of the IAC observatories.

The ORM forms part of the IAC, whose headquarters are in La Laguna on the island of Tenerife, and which is also responsible for the OT on the same island. The ORM is part of the municipality of Garafía, on the island of La Palma and its surface area is 189 hectares. Since it adjoins the Taburiente National Park, the Observatory site is classified as an area of ecological sensitivity and is highly sensitive to modifications in its landscape. To minimize any possible adverse impact on the landscape, the restriction has been imposed on all buildings or installations on the site that they must not be visible from either the Cumbrecita or the Mirador del Lomo de las Chozas viewpoints, both of which are situated in the National Park.

The orography of the Observatory is irregular, with strong changes of gradient alternating progressively northwards between rugged terrain and smooth and continuous slopes. Since the last century, there have been numerous studies made of the astronomical quality of the Canarian skies, both at the OT and the ORM. Murdin [3.4] gives a full review of this work up to 1985. The different studies of site quality conclude that 60% of the nights are photometric[5] and 70% are spectroscopic[6].

3.2.1 Environmental conditions at the ORM

The environmental conditions of the ORM (described in detail in [3.5]) are the following:

- Air temperature: between –8 and 25 °C (at 6 m above ground level)
- Relative humidity: between 1 and 100%, lying between 10 and 50% most of the time. This leads to high static electricity.
- Barometric pressure: 720–800 mbar.
- Wind speed: up to 55 m s^{-1} with gusts up to 67 m s^{-1}.
- Sporadic incidence of nights with high level of dust in suspension.
- Maximum rainfall over 24 hours: 200 mm.

[5] In this case, a photometric hour is defined as a night hour during which the relative humidity is less than 90%, the average wind speed is less than 15 m s^{-1}, the zenithal extinction in V is less than 0.3 mag, and cloud cover is less than 5% for elevation angles greater than 30° and less than 15% for elevation angles above 10°.

[6] A spectroscopic hour is defined as a night hour which is within the above-mentioned limits for relative humidity and wind speed, but with a zenithal extinction less than 0.5 mag and cloud cover less than 50% above 30°.

- Maximum rainfall over 1 hour: 80 mm.
- Thickness of snow cover: 1 to 1.5 m (fresh) and 300 mm (compact).
- Thickness of ice layer: 150 mm.
- Occasional electrical storms.
- Seismic activity: the ORM is located in a degree 7 zone (seismic resistance regulation NCSE 94), which corresponds to a horizontal acceleration of 0.08*g*.

Figure 3.1: Aerial view of the ORM.

3.3 Site options

The choice of site for the GTC is a delicate matter that has required several years' study. From 1995 two sites have been examined as possible locations for the telescope. The two locations, hereafter called Site 1 and Site 2, are on the western side of the Observatory. The sites are about 500 m apart, but due to the irregular orography of the zone they differ substantially from each other. An aerial view of the Observatory is presented in Figure 3.1. General views of Sites 1 and 2 are shown in Figure 3.2 and Figure 3.3, respectively.

Figure 3.2: Site 1.

Figure 3.3: Site 2.

In accordance with the official classification of the Observatory grounds, the two sites are graded as Class 1, which implies that the ground can be developed for astronomical purposes. The area needed for laying the foundations of the GTC installation, at either of the sites, would be of the order of 4000 m^2.

3.3.1 Site 1

Site 1 is in a zone with a steep average gradient and is located in the highest part of the mountain, known as La Cruz del Fraile. The installation would be situated on the 2350-m contour between the Nordic Optical Telescope (NOT) and the Telescopio Nazionale Galileo, (TNG), at a distance of about 400 m from the TNG and almost 300 m from the NOT. The ground level of the installation would be 71 m below the ‘Roque de los Muchachos’ geodesic marker and more than 200 m from the rim of the caldera, which means that it would not affect the landscape of the National Park in any way.

3.3.2 Site 2

The second site under consideration for the GTC installation is in a zone known as Lomo del Llano de Las Lajitas. The ground level of the installation for this site is on the 2250-m contour, 171 m below the ‘Roque de los Muchachos’ geodesic marker and more than 500 m from the caldera rim, which would place it beyond all possibility of affecting the National Park landscape. Site 2 is quite flat with a milder average gradient than Site 1 and is about 450 m away from the TNG.

3.4 Geotechnical campaign

During the summer of 1995 preliminary soundings were taken to analyse the geological and geotechnical characteristics of the two candidate sites for the GTC.

At Site 1 there is a red top layer of loose basaltic pyroclasts (unsuitable material for laying concrete, but capable of improvement) composed of scoria, lapilli and ash of poor mechanical properties, and a layer of highly weathered, extremely fragile and brittle volcanic tuff at a depth of 10 m which has a mean resistance to compression of 47.7 kPa cm^{-2}.

At Site 2 there are sedimentary deposits made up of layers of basalt embedded in a loose matrix of sand and soil. There are also outcrops of basaltic lava (which are also found below the sedimentary deposits in the sample cores, as well as thin intercalated layers of pyroclasts). At a depth of 12 m there is a basaltic mantle that would be very suitable for foundations except for its depth; however, it is of irregular strength and distribution. This compact basalt offers a mean resistance to compression of 1000 kPa cm^{-2}.

3.4.1 Conclusion

The results of the campaign demonstrate that construction of the GTC installations is feasible on both sites, although the laying of foundations would be easier at Site 2. Also, less earth removal and containing works would be necessary, which means that the cost of construction would be slightly less than at Site 1.

3.5 Seeing campaign

A key parameter for determining the quality of an astronomical site is image quality expressed in terms of seeing (see [3.6] and [3.7] and references therein). At the beginning of the 1990s an intensive site-testing campaign was carried out at the ORM by the IAC in collaborations with the Astrophysics Department of the University of Nice. This campaign followed the classical scheme of simultaneous integrated optical measurements and meteorological soundings, also with exclusive use of the NOT for several days [3.8] [3.9]. The relative contribution of the turbulence in different layers of the atmosphere was quantified, and it was found that the contribution of the surface layer above 6 m was negligible. This is obviously of great importance for the design of telescopes located at the ORM.

The results for a year’s continuous seeing measurements at the two preselected sites are presented here. Further details of the campaign can be found in [3.10]. At each site a 5-m tower, designed by the TNG group at the ORM [3.11], was built for the differential image motion monitor (DIMM), or seeing monitor. The working routine adopted during the campaign was to take a fixed programme of measurements on 3 or 4 nights at the beginning of each week in order to increase the statistical significance of the sample. The temporal resolution of the seeing monitors is below half a minute. At Site 1, high relative humidity accounted for 25% of the time lost, followed by clouds (8%), wind speeds greater than 15 m s^{-1} (6%) and technical problems (3%). At Site 2, the main cause of losses was again high relative humidity (30% of the time), followed by cloud cover (7%), high winds (5%) and technical problems (2%). The percentages of hours observed at both sites are well below those obtained during other long-term campaigns at the ORM. Measurements carried out at the Carlsberg Automatic Meridian Circle (CAMC) and compiled by Sarazin ([3.12]) give the proportion of the useful hours for observations as 79% of those available.

The image-quality data for each site are discussed separately in order to make a comparison of the two. The statistics always refer to monthly blocks. The mean and median seeing values (see Figure 3.4) are normally better at Site 2, with differences of up to 0.26 arcsec being reached between the two sites (as occurred in May 1995, the most discrepant month). In general, the better the seeing the closer together the values measured at both sites, the difference in August 1996, for example, being nil.

It should be stressed that the median seeing measured each month at both sites varies, in general, between 0.5 and 0.76 arcsec, which means that both are excellent astronomical locations as far as image quality is concerned. However, the abnormally high number of hours lost during the winter months (November 1995 to February 1996) and a very atypical May should be noted.

The best (lowest) seeing values of the monthly statistics at each site are shown in Figure 3.4. The minimum values are practically identical for both sites with a possible difference of the order of 0.1 arcsec, the minima being independent of site. In general, minimum values below 0.3 arcsec can be reached at any time of the year at both sites. Figure 3.5 shows the cumulative frequency of the seeing (along the abscissa) for both sites. Superimposed is the distribution obtained in other ORM campaigns, in particular at the TNG (taken from [3.14]).

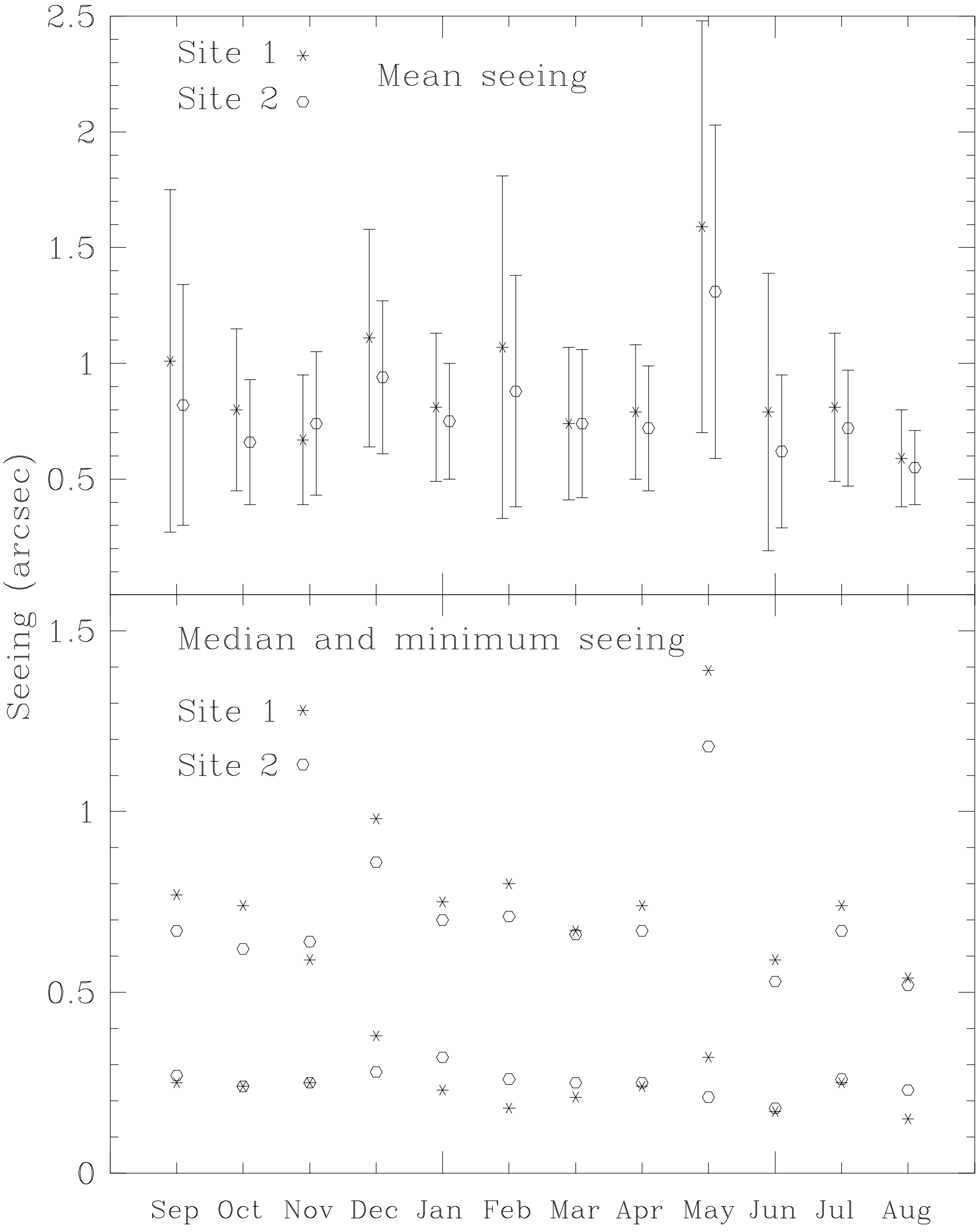

Figure 3.4: The upper plot shows the mean seeing for Site 1 and Site 2 with the error bars showing the standard deviations and the monthly statistics. The lower plot shows the median and minimum seeing for each month.

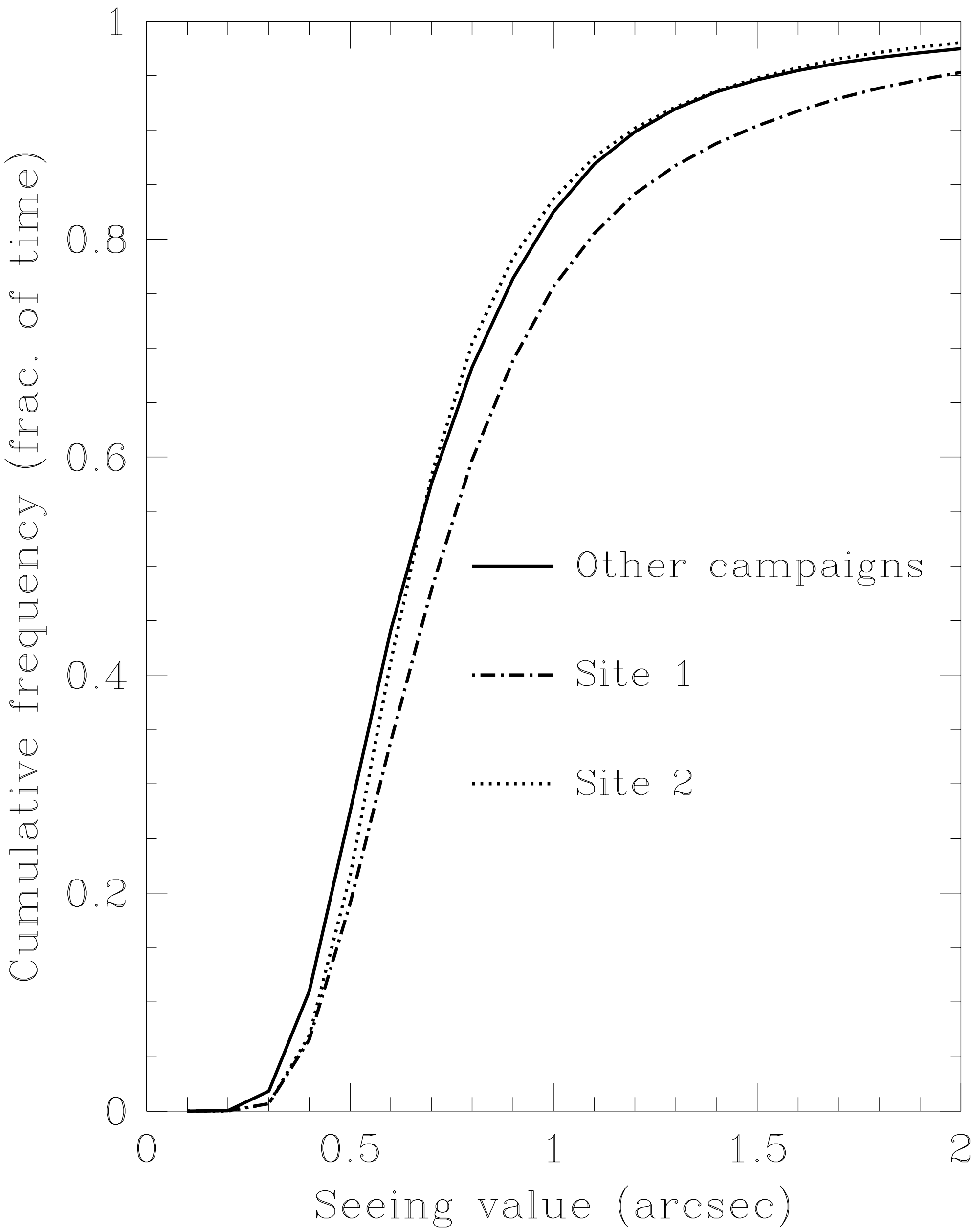

Figure 3.5: Cumulative seeing probability distribution.

Seeing values better than 0.5 arcsec are reached in 22% of cases at Site 2 and in 19% of cases at Site 1. These percentages are similar to those obtained in previous campaigns (see [3.14]). Seeing values above 2 arcsec were measured for 5% and 2% of cases in Sites 1 and 2, respectively. 76% of the seeing measurements at Site 1 gave values less than 1 arcsec, compared to 84% at Site 2. The median seeing for the complete campaign in Sites 1 and 2 was 0.72 and 0.65 arcsec, respectively.

The percentage of seeing values better than 0.5, 1.0 and 2.0 arcsec, as well as the statistics (minimum, mean, median and typical standard deviation) calculated for all the data of the campaign at both sites are shown in Table 3.1 (taken from the accumulated distribution function in Figure 3.5). For comparison, values corresponding to other ORM campaigns have also been included.

	Site 1	Site 2	Other campaigns
No. of points	160119	87978	86385
Min.(arcsec)	0.15	0.18	0.17
Mean (arcsec)	0.72	0.75	0.76
Std (arcsec)	0.55	0.40	0.47
Median (arcsec)	0.72	0.65	0.64
<0.5 arcsec	19%	22%	28%
<1 arcsec	76%	84%	82%
>2 arcsec	5%	2%	3%

Table 3.1: Percentage of seeing measurements better than 0.5, 1.0, and 2.0 arcsec at both sites and statistics (minimum, mean, median and standard deviation) calculated using all the data of the campaign at each site. Results from other ORM campaigns also included.

3.6 Meteorological campaign

For the study of meteorological parameters, data have been taken with automatic weather stations (AWSs [3.15]). In this study an analysis has been made of soil and subsoil temperatures, rainfall, air temperature at 2 m, relative humidity, surface wetness, barometric pressure, insolation (also at 2 m), and wind speed, gust and direction (at 12 m) [3.10].

Before analysis, a 3-point median filter is passed through the raw data to remove possible spurious peaks that occasionally occur, especially at Site 1. The data were separated in separate day and night blocks, and the statistics (minimum, maximum, mean, median and standard deviation) were calculated on a monthly basis. Nighttime was defined in terms of insolation (it was assumed to be night when the solarimeters marked < 50 W m^{-2}). The statistics were done on a monthly basis. Due to technical and weather problems there are months for which the database is not complete. In particular, there was a great loss of data at Site 1 associated with severe lightning damage to the wind sensors and mast. This has resulted in only 3 months' simultaneous data being available for both sites.

The minimum values for nighttime air temperature, measured at 2 m, are given for each month in Figure 3.6 for both sites. It can be seen that the results are similar for both sites during all the months for which there are data from both sites available, with the exception of October 1995, when a lower minimum was reached at Site 1. As was to be expected, the air temperature exhibits a seasonal behaviour throughout the year, with progressively lower minimum, maximum, mean and median values from September to November and rising again during the summer months. The absolute minimum of –5.4 °C was registered in March 1995. The maximum value, 25.1 °C, was recorded in August 1996.

The deviation in nighttime air temperature, also represented in Figure 3.6, is typically about 3 °C, the difference between maximum and minimum being less than 5 °C each night. The typical standard deviation does not differ by more than a few tenths of a degree between both sites, which is within the combined errors of the two temperature sensors. This implies that the stability of the air temperature is practically identical for both sites.

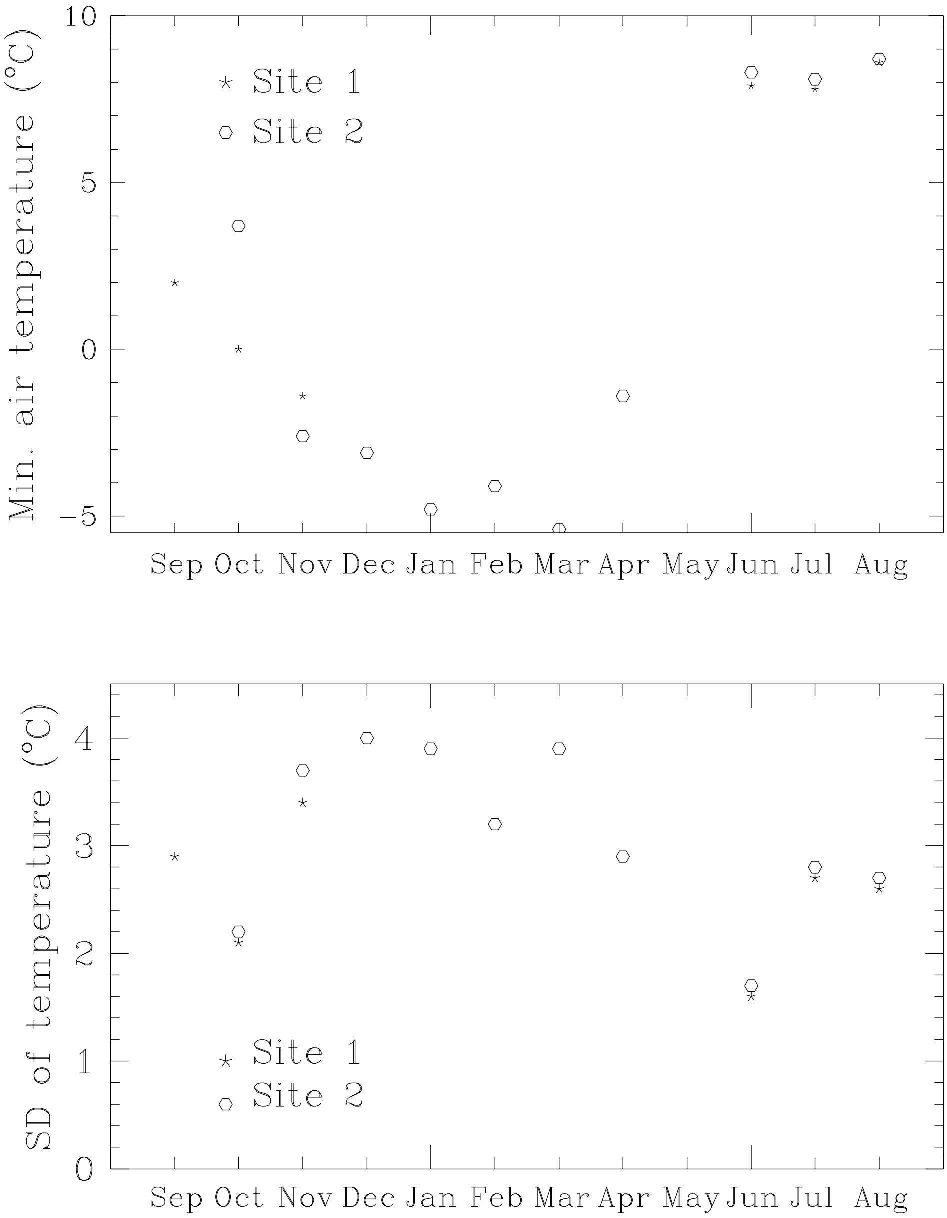

Figure 3.6: Monthly minima and typical standard deviations of nighttime air temperature measured with sensors at 2 m above ground level at Sites 1 and 2.

Combined mean values of relative humidity during the night are given in Figure 3.7. During the summer months the mean values of relative humidity are identical at both sites, and in the months of October and November these values are 4 to 7% lower at Site 1. Occasionally, when the inversion layer is unstable clouds reach Site 2 with greater frequency, but it can also happen that overspill of clouds from the Caldera affects Site 1 adversely.

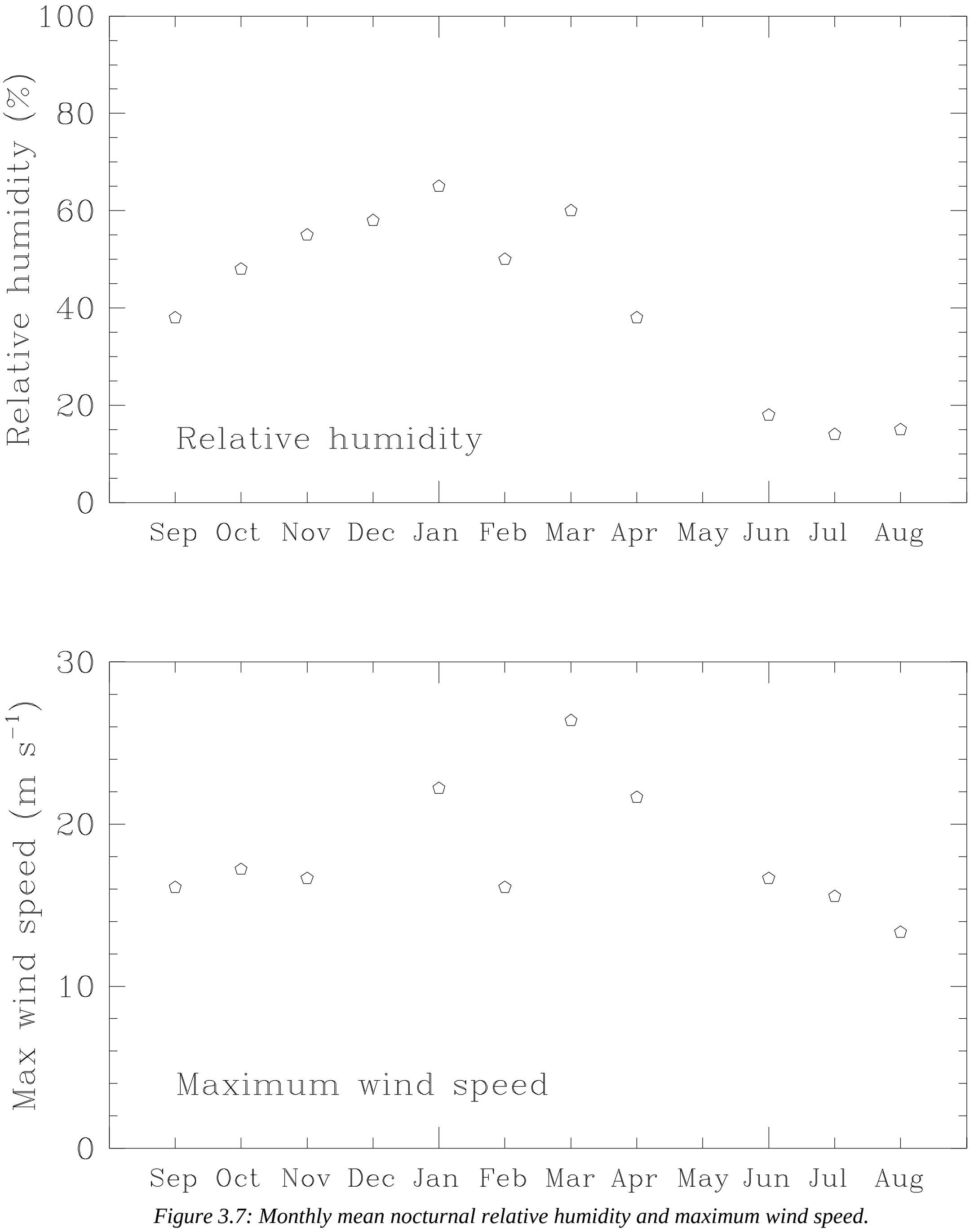

Figure 3.7: Monthly mean nocturnal relative humidity and maximum wind speed.

During the campaign wind speeds in excess of 27 m s^{-1} were not measured (Figure 3.7), but this is to be expected since in conditions of very strong freezing wind (as in a cold front) the cup anemometer and windvane froze to a halt. The mean wind speed each month only varied 1 to 2 m s^{-1} at both sites.

Due to the problems already mentioned concerning Site 1, there are insufficient data on wind speed and direction for this site to carry out a reliable statistical comparison with Site 2. As for the months during which data for the two sites are available, there are no major differences.

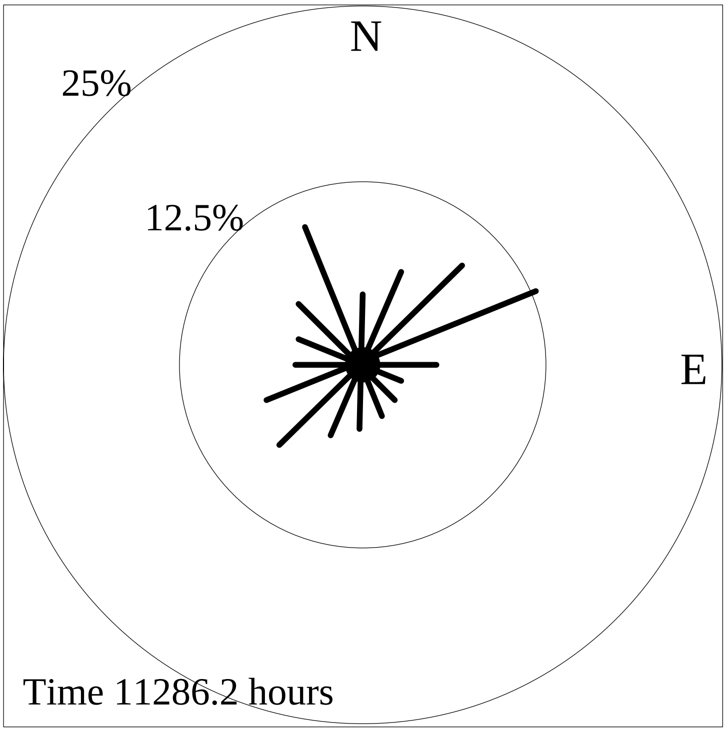

Figure 3.8: Composite windrose for Site 2.

From a composite windrose for the period February 1995 to May 1996 at Site 2 (Figure 3.8), it is possible to distinguish three wind regimes accordingly as the wind is predominantly from the north sector, from the south sector or from no predominant direction:

- North wind regime: examples of this occurred in February, June and July 1996, when the wind was clearly predominantly from the NE. During the summer months this regime is clearly related to the trade winds. During August the wind direction was predominantly northwesterly, although with important contribution from other sectors.

- South wind regime: the wind roses for December 1995 and May 1996 show wind predominantly from the SW.

- No prevailing wind: examples of this ‘mixed’ wind regime occurred in October 1995 and April 1996.

The percentage wind frequency (in terms of hours’ measurement) in the three regimes defined above are shown in Table 3.2.

Wind regime	Percentage of hours measured
North	39
South	37
‘Mixed’	17
Discarded	7

Table 3.2: Prevailing monthly wind as a percentage of hours measured.

The wind regimes shown differ considerably from the 20 years of weather statistics for Izaña (Tenerife) compiled by Sánchez [3.13], which showed a clear 60% wind predominance from the NE. There is no comparable meteorological database for the ORM, but both the results reported by Sánchez for Izaña and by Muñoz-Tuñón, Varela & Mahoney [3.10] for Site 2 agree well with the wind rose published by Brandt and Righini [3.16] for Izaña and the ORM. This indicates that there is a possible difference between the observatories in terms of prevailing wind directions in the northern sector, with a presence of northeasterly winds at the ORM which is almost entirely absent from the wind regimes at Izaña. The wind roses of Site 1 for the September to November 1995 show little difference between the sites in terms of wind direction, but data need to be taken over a much longer period for this result to be confirmed.

3.6.1 Conclusions

From these results it can be concluded that there is no systematic statistical meteorological difference between the two sites which would affect the useful observing time. It has also been possible to establish from these results the expected range of meteorological conditions for the GTC (Table 3.3).

	Nominal conditions	Range of operation	Limit of operation[7]	Survival
Air temperature	$-2°$ to $+19°$ C	$-8°$ to $+25°$ C	N/A	$-15°$ to $+35°$ C
Relative humidity	2 to 87%	1 to 90%	90%(or dew point)	100%
Atmospheric pressure	770 to 790 mbar	720 to 800 mbar	N/A	N/A
Wind speed				
Averaged over 15 min looking into the wind[8]	0 to 10 m s^{-1} [9]	0 to 16 m s^{-1}	16 m s^{-1}	55 m s^{-1}
Averaged over 15 min looking away from the wind	0 to 13 m s^{-1} [10]	0 to 22 m s^{-1} [11]	22 m s^{-1}	55 m s^{-1}
Gusts	N/A	0 to 27 m s^{-1}	27 m s^{-1}	67 m s^{-1}
Earthquakes (horizontal acceleration)	N/A	N/A	N/A	0.1 *g*

Table 3.3: Environmental specifications for the GTC. Nominal conditions are those that prevail during 98% of the time in which the operation of the telescope is not impeded by weather conditions [3.17]. (N/A: not applicable).

3.7 Conditions for IR observations at the IAC observatories

Here several observational results are reported that help in determining the IR quality of the IAC observatories. The data used below have been principally acquired at the Teide Observatory, which is at the same height (about 2300 m) and enjoys very similar weather conditions as the ORM. Data from the Teide Observatory have been used as there is a lack of IR data obtained at the ORM. The ORM has traditionally been devoted to optical astronomy. As both observatories are located on adjacent islands and are subject to very similar weather patterns, in most instances the conditions in one observatory are transportable to the other.

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[7] Conditions above which the dome must be closed.

[8] The telescope pointing within ±45° of the wind direction.

[9] Wind speed between 0 and 10 m s^{-1} for 92% of the useful time.

[10] Wind speed between 0 and 13 m s^{-1} for 98% of the useful time.

[11] Wind speed between 0 and 22 m s^{-1} for 100% of the useful time.

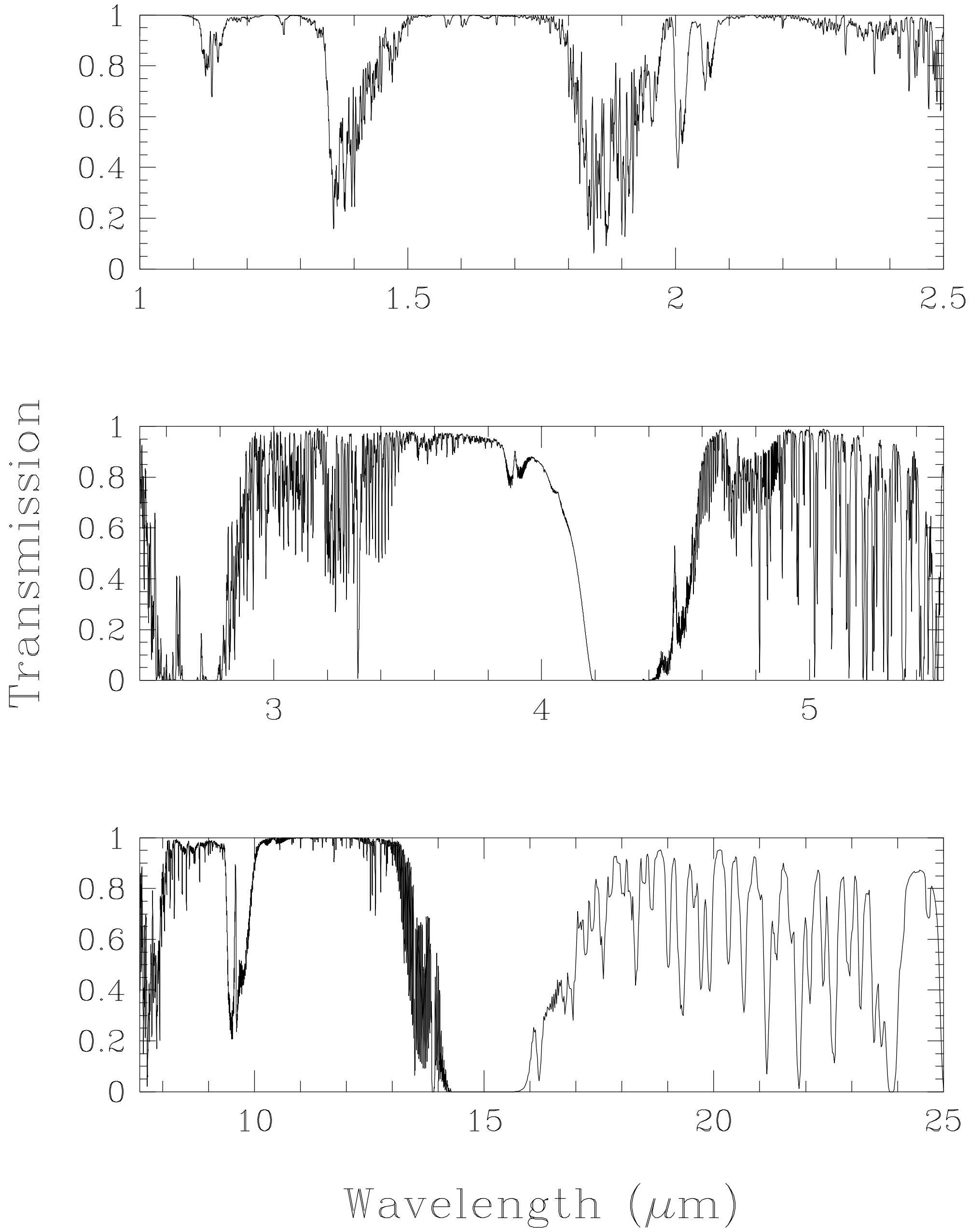

Figure 3.9: Atmospheric transmission windows for an excellent site.

Water-vapour lines cover the whole of the IR spectral range, and whilst in general the absorption is small there are large areas where the atmosphere is effectively opaque. Figure 3.9 shows a model of the terrestrial atmospheric transmission between 1 and 25 µm. As can be seen, the wavelength range breaks up into windows.

3.7.1 Model atmospheric transmission for a very good site

The best parts of the atmospheric windows are almost independent of the amount of water vapour, and observations can be made at sea level. Conversely the worst parts of the atmospheric windows will be opaque even from the highest mountain sites and observations in these wavelength ranges are only possible from space. However, as can be seen there is an intermediate region where the possibility of observing is strongly dependent on the amount of water vapour, and this will affect both photometry and spectroscopy.

In order to maximize signal-to-noise ratio the broad-band filters extend into the wings of the IR windows. On lower sites the windows become narrower, but more importantly the amount of water vapour can vary significantly during the night. This will change not only the airmass extinction coefficients but may well significantly change the effective system bandpass hence reducing the accuracy of the photometry.

There are regions, such as 2.8 to 3.4 μm, 5 to 5.5 μm or the edges of the windows where spectroscopy is realistically possible only from high dry observing sites. However, these wavelength ranges include many of the most interesting features. Water vapour itself, polyaromatic hydrocarbons (PAHs), ice bands, Carbon, etc.

Clearly any 10-m class telescope, where the IR is an important consideration in the science to be attempted, has to be placed on an extremely dry site which will allow the full range of IR observations to be attempted in optimum conditions.

3.7.2 Constituents of an IR spectrum

A raw infrared spectrum is basically the multiplication of three factors:

1. The spectrum of the object.
2. The instrumental response, i.e. the detector quantum efficiency (QE), filter profile and grating efficiency. However apart from at the very edge of the filter profile these vary slowly with wavelength.
3. The atmospheric transmission.

Hence IR spectra with sufficient resolution can be used to examine the quality of an astronomical site.

3.7.3 Wavelength range for making the test

One method for the determination of the quality of an astronomical site is to look in the poorer parts of the usable atmospheric windows. From this a direct determination of the effect of the water vapour can be made. One of the best wavelength ranges for this is in the *L* window (2.8 to 4.05 μm). The range between 3.5 and 4 μm is basically clear of lines and in regions the total transmission can be above 95%. However, between 2.8 and 3.4 μm the atmospheric transmission spectrum is full of strong water vapour bands and on all but exceptional sites this part of the window is effectively closed. At 3.31 μm there is a CH_4 line which is opaque from any earth-based observatory. Hence one method for determining the quality of the site is to compare the relative strengths of the CH_4 line with the water-vapour bands at close wavelengths. Another is to examine the relative shape of the spectrum; where there is significant water vapour in comparison with those where there is little.

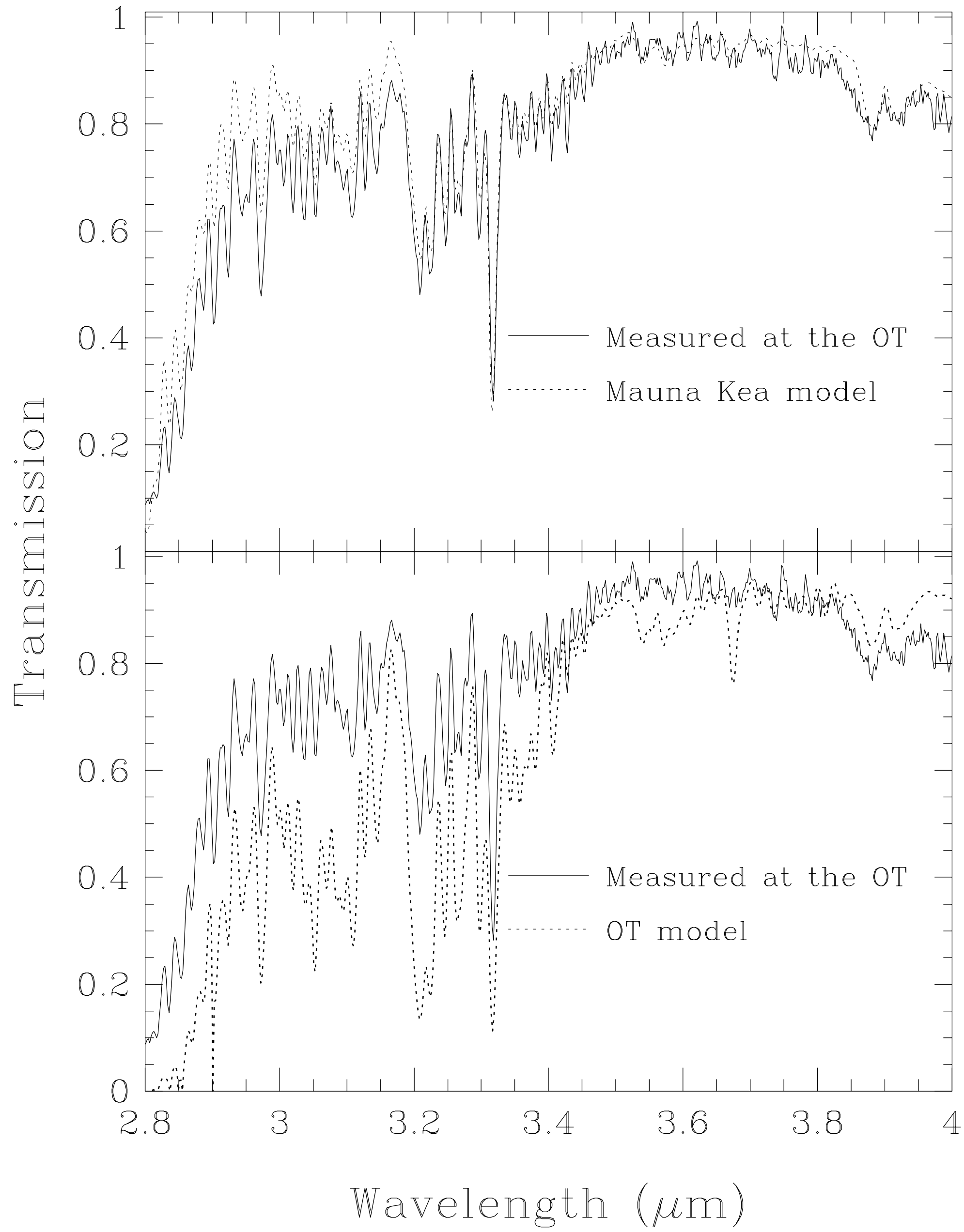

Figure 3.10: Measured atmospheric transmission at the OT with models for the predicted transmission at Mauna Kea and the OT.

Figure 3.10 presents two atmospheric transmission models [3.18] for this wavelength range. They are based on the USAF (United States Air Force) atmospheric code (PLEXUS[12]) and specified for Mauna Kea (~4000 m) and Teide Observatory (~2300 m) using the standard maritime conditions at their respective geographical positions. They do not have a number for precipitable water vapour as such, but integrate the full atmosphere along the line of sight. The models have had their spectral resolutions reduced to match that of the measured data. As can be seen, the models predict that observations around 3 μm should be very difficult from the OT; the

[12] Clark, F.O 1996, Plexus Program Office, Phillips Laboratory, supplied on CD-ROM.

atmospheric transmission is predicted to be on average only 40%, significantly below the 75% predicted for Mauna Kea.

3.7.4 Observations

In 1986 a near-IR cooled grating spectrometer with a resolution of about 700 was mounted on the 1.5-m Carlos Sánchez Telescope (TCS) at the OT. On a number of nights full *L* spectra were taken, i.e. between 2.8 and 4.05 μm. Vega was used as the standard star and was measured in the zenith. The data was obtained in late July when the water vapour is expected to be near a maximum. However the nights used were photometric and had low relative humidity. A measured raw Vega spectrum after being divided by the absolute Vega spectrum (to remove the λ^{-4} dependence) is presented in Figure 3.10. The response has been normalized to 0.95 near 3.8 μm, hence showing the total system response. No attempt has been made to remove the filter profile, grating efficiency or detector response but these will vary smoothly across the spectrum and so should not introduce high-frequency effects. The atmospheric effects however will tend to be at a higher frequency and hence by looking at a series of lines the effect of water vapour can be determined.

Figure 3.10 shows the measured system response at OT and the models for the OT and Mauna Kea. The most noticeable feature is that even without removing the detector response etc., the curve is an excellent match for the model of Mauna Kea whilst the comparison with the OT model is far poorer. This is confirmed when looking in closer detail:

- At 3.63 μm the model predicts that the OT should show a strong water-vapour line, while it is a lot weaker at the altitude of Mauna Kea. The spectrum measured at the OT is in excellent agreement with the Mauna Kea model showing hardly any line but in poor agreement with the OT model. The same is true for the two lines near 3.5 μm.
- The CH_4 line at 3.31 μm is clearly present in the measured spectrum. Also present is a significant feature near 3.25 μm. The model predicts that at the OT this feature should be as deep as the CH_4 line, whilst at Mauna Kea this feature is significantly weaker. Again, the measurements follow the Mauna Kea model far better than the OT model.

These results therefore imply that the conditions for IR observations at the OT are indeed far better than predicted by the model.

3.7.5 Water vapour at the Teide Observatory

An independent observational project confirms the stability of the OT for low water vapour work. Recently, Piccirillo et al. ([3.19]) have carried out mm-band observations of the cosmic microwave background (CMB) from the OT at 3.3, 2.1, 1.3, and 1.1 mm, with excellent results. They estimate that about 10% of the time during which they ran their experiment they enjoyed precipitable water vapour values under 1.5 mm. Also Watson et al. ([3.20]), based on their 30-Ghz measurements of the CMB obtain a water-vapour distribution peaking at about 3 mm. They further claim that the water-vapour content of the atmosphere on the OT remains very stable for nights.

3.7.6 Conclusions

The results shown above demonstrate that the OT, and by extrapolation the ORM, can have significantly lower extinction due to water vapour than the models predict if only its altitude is taken into account. Hence, no significant science, in the 1 to 15 μm region at least, will be lost due to water vapour by placing a 10-m class telescope at an altitude of about 2300 m in the Canary Islands as opposed to 4000 m on Hawaii.

3.8 Water-vapour measurement campaign at the ORM

Although the above study on the influence of water vapour on the IR spectrum of an astronomical source, concerns mainly the OT, the similarity between this site and the ORM both in height and in other meteorological conditions, suggests that also the ORM is an excellent location for observing in the IR. Unfortunately, it has only been recently that a monitoring campaign to obtain precipitable water vapour at the two proposed sites for the GTC has started. The following is a summary of the most important results of this campaign at Sites 1 and 2. Some key figures are given which, to a first approximation, indicate the quality of the ORM for infrared observations.

3.8.1 Method of measurement

The measurements have been carried out since June 1996, with two absorption radiometers built at the IAC, one of them located at Site 1 and the other at Site 2. These instruments measure the sunlight reflected off the Moon through a filter centred on the 946.7-nm water-vapour absorption line and through a continuum filter at 884.5 nm. The ratio of the signal found in both channels gives a precise estimate of the water-vapour column in the line of sight. This band has been recommended by NASA as the most suitable for remote sensing by satellite. The calculated values are converted into zenithal values with the standard secant law for a plane parallel atmosphere. Due to the maximum declination of the Moon during the campaign, measurements were generally carried out at lunar zenith distances of 25° or more, and almost never at zenith distances less than 20°. The design of these instruments followed a similar instrument kindly loaned to us by J. A. Quesada, which was used in the Calar Alto site-testing campaign, and had been calibrated with atmospheric balloons.

3.8.2 Typical errors in the measured values

The error can be estimated in absolute and relative terms:

1. It is possible to estimate the relative error between measurements. This is calculated by making several consecutive measurements and examining the dispersion. In this case an error of ~0.2 mm or ~7% of the typical total column is found.

2. The absolute error is more difficult to estimate, although it would be difficult to get an error better than 20%. In the results presented here, an absolute error of the order of 30% is assumed.

3.8.3 Results

Measurements were carried out on a total of 45 nights. On most of the nights the measurements were made simultaneously at both sites. On some occasions the observations at one or other of the sites were unusable due to instrumental or weather problems, for which reason the total number of nights with measurements is less than the total number of available nights for observation. The data and information on the observing nights are summarized in Table 3.4 and Table 3.5. On some nights many observations were made, for which reason there is an important bias in this sense.

	Site 1	Site 2
Total number of measurements	166	534
Median water-vapour column	3.3 mm	5.1 mm

Lower decile	0.5 mm	2.1 mm
Upper decile	8.3 mm	9.6 mm
%age of poor conditions (>6 mm)	24	39
%age of good conditions (<3 mm)	34	25
%age of very good conditions (<2 mm)	18	7
%age of excellent conditions (<1 mm)	5	0.5

Table 3.4: Results of the water-vapour measurement campaign in terms of measurements made.

	Site 1	Site 2
Total number of nights	33	42
Median water-vapour column	3.9 mm	5.2 mm
Lower decile	1.2 mm	2.1 mm
Upper decile	8.9 mm	10.4 mm
%age of poor conditions (>6 mm)	30	33
%age of good conditions (<3 mm)	33	22
%age of very good conditions (<2 mm)	27	5
%age of excellent conditions (<1 mm)	6	0

Table 3.5: Results of the water-vapour measurement campaign in terms of nights.

It should be pointed out that most of the observations were carried out in the summer, when a greater total column of water vapour is to be expected and during a year with very much worse meteorological conditions than is the norm for the ORM.

The difference as measured between the sites cannot be attributed solely to the difference in altitude between the two sites (about 100 m), which is of the order of 4.5%, or ~0.1 mm per 2 mm of total column; alternatively, the expected difference may be expressed as 0.2 to 0.3 mm for this campaign, and much less in good conditions. The results, however, are similar if they are expressed in terms of all the measurements carried out, instead of the medians for each night.

For two months of the campaign, the radiometers were interchanged between the two sites in order to check the reliability of the differences found and to ensure that these were not due to instrumental differences. The trends obtained with the radiometers interchanged were identical to those found with the radiometers in their original locations. Also, a routine of continuous cross checks was carried out by taking measurements with both radiometers in the same location. The calibration was carefully checked to ensure that both had the same scale and zero points.

In the near future further water-vapour measurements will be made using a mid-IR emission radiometer from Kitt Peak similar to those used for the site campaigns at La Silla and Paranal. It is planned to use the new data to set the absolute calibration for the whole water-vapour campaign for the GTC and to continue adding new measurements to strengthen the statistics.

3.8.4 Conclusions

The limited amount of precipitable water-vapour data available thus far for the ORM point towards slightly lower columns at Site 1.

3.9 Atmospheric extinction at the IAC observatories

The typical airmass extinction values provide a useful indication of the quality of an observing site. High airmass extinction values not only mean that light is lost, but also that the emission will be greater in the thermal IR, and the accuracy of the photometry will be reduced. A good site needs to have low extinction values which are stable for periods of at least a night.

Filter	Extinction per airmass

J	**0.09**
H	**0.05**
K	**0.07**
L'	**0.09**

Table 3.6: Typical near-IR values of extinction per airmass at OT.

The extinctions per airmass given in Table 3.6 are comparable with those of any other very high quality terrestrial site (including Mauna Kea); however, it should be noted that the extinction is very dependent on the actual filter profile, so an exact comparison is not possible. When very narrow band filters, centred on the best parts of the atmospheric windows, have been used on the 1.5-m TCS at the OT, extinctions per airmass as low as 0.03 have been measured at 2.2 μm.

Experience using the facility near-IR photometer on the TCS indicates that on photometric nights the typical rms scatter in the measured magnitudes of the standard stars is 0.01 mag. On specific occasions when the night has been used to set up a calibration for the instrument the rms scatter in 30 *L'* measurements of the same star can be as low as 0.005 mag. This indicates that during photometric nights the conditions at the OT can be superb for high-precision photometry, at least in the near IR.

3.9.1 Saharan dust

The Canary Islands are located close to the Western coast of North Africa. This situation has led in the past to the assumption that Sahara dust is potentially a problem for an observatory in the Canary Islands. However, as we show below, this is not the case. The Sahara dust clouds, which occasionally cover the observatory particularly during summer months, do not impact significantly on the fraction of nights lost for observations. Although these dust clouds can at times increase the atmospheric extinction, only on a very few nights do they seriously interfere with the observing programme.

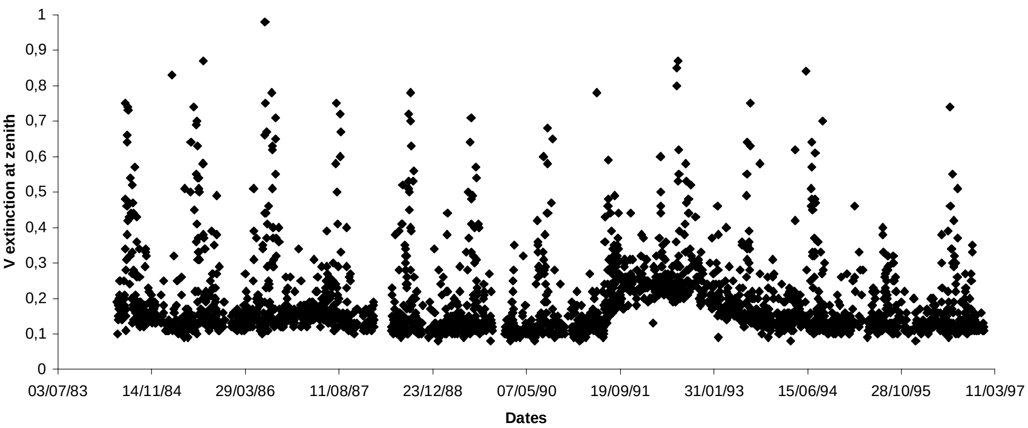

Figure 3.11: Atmospheric extinction at V measured at the CAMC.

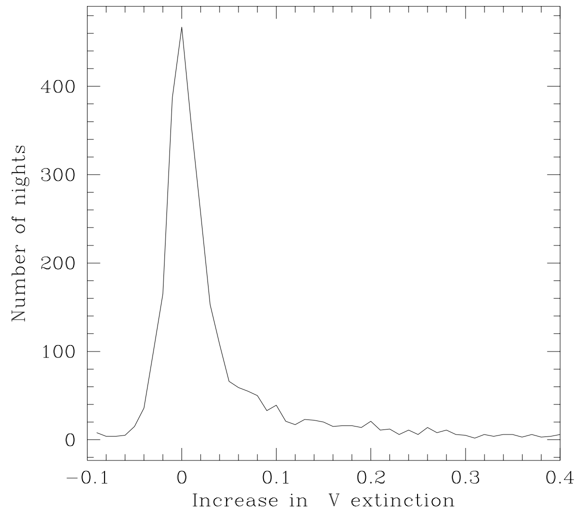

Figure 3.12: Histogram after 100-day median filter through the data and the result subtracted from the original data.

In order to assess the impact of the dust clouds we have examined the CAMC photometric database. This lists the measured visible extinction on each night of operation since 1984 [13]. The CAMC, located at ORM, operates automatically every single night, except for maintenance nights or when the humidity rises above a given limit. Figure 3.11 shows the extinction on each night listed in the archive. The effect of the Saharan dust can be clearly seen in the data as the points with significantly higher-than-average extinction. In general the baseline is at an extinction of 0.11 mag airmass$^{-1,}$ however this can vary significantly. It took two years for the dust from the mid-1991 eruption of the Pinatubo volcano to settle out from the upper atmosphere; during this time the average extinction rose by 0.1 mag. However, this extra extinction would be world wide and is independent of the Saharan dust. In order to remove the baseline drifts a 100-day median filter was run through the data and the result subtracted from the original data. Figure 3.12 shows the histogram of the result.

The distribution of excess extinction is Gaussian with a FWHM of about 0.05 with a long tail caused mainly by the Saharan dust. In the archive there are 2749 nights listed. Table 3.7 gives the breakdown of the number of nights where the additional extinction (AE) from Saharan dust can be considered as nil, light, moderate and heavy.

AE	Percentage of time
AE < 0.05	79%
0.05 < AE < 0.10	8%
0.10 < AE < 0.20	6%
0.20 < AE	7%

Table 3.7: Breakdown of the number of nights where the AE from Sahara dust can be considered nil, light, moderate and heavy.

3.9.2 Conclusions

[13] The data are available on the WWW ftp://ftp.ast.cam.ac.uk/pub/lpinfo/extinction/

The above data suggests that the Sahara dust is only a problem (AE > 0.2 mag) on at most about 7% of the nights. Also the Saharan dust usually arrives with southerly winds which also tend to bring cirrus. Hence the number of nights on which real science will be lost is very small.

3.10 Site selection

The two sites sampled have similar characteristics in terms of image quality and meteorology in general. The abnormal climatological conditions during a substantial part of the present campaign should, however, be noted, as these will certain influence the significance of the results obtained, and although in normal conditions, the statistics should be even more favourable, it should be stressed that the seeing statistics are very good and similar to those obtained during previous campaigns. Site 2 turns out to be slightly better in terms of image quality, although both sites are outstanding in terms of seeing and atmospheric stability. Furthermore, Site 2 would be slightly less expensive, though again both sites are viable for building the GTC. Further it has been shown that the condition for thermal IR observations are also adequate at both sites, and although the present data indicate that the precipitable water-vapour content above Site 1 is slightly lower, more data need to be gathered in order to establish this difference on a sounder basis.

Site 2 is currently the preferred choice for the GTC, given the advantage in image quality and the simpler geological conditions for construction work. The final choice of site, however, depends on the results from new measurements to confirm the extremely low water-vapour measurements obtained on Site 1.

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4. OPTICAL SYSTEM

4.1 Introduction

The optical system of the GTC will include the optical elements (mirrors, lenses, prisms, etc.), their optomechanical support, and the measurement devices necessary for controlling the optical system. This system will be responsible for forming an image of the sky in the focal plane of the scientific instrumentation. The challenge facing the project is to meet the strict image quality requirements using a segmented primary mirror.

This chapter describes the various options evaluated for the optical system of the GTC, and how those chosen satisfy the fundamental requirements. Active and adaptive optics schemes are discussed and the three mirrors of the optical system are described. Finally, plans for cleaning and coating the mirrors are outlined.

4.2 Design guidelines

The design of the optical system of the GTC will be constrained by most of the requirements given in Chapter 2. However, there are three fundamental requirements that drive the design:

1. The GTC must have an entrance-pupil area equivalent to a circular aperture of diameter 10 m. This will provide a significantly improved limiting magnitude over what is possible with 4-m class telescopes. This entrance-pupil area implies a segmented primary mirror. The current technological limit for monolithic mirrors is a diameter of 8.3 m, and this is not expected to increase.

2. The GTC must provide excellent image quality so as not to degrade the 0.4-arcsec FWHM visible seeing by more than 10%. To fulfil this requirement it is necessary to take into account the manufacture of the mirrors forming the optical system, their stability and the correct alignment of the system.

3. The main science instruments of the GTC must be available simultaneously to maximize operational efficiency.

4.3 General description of the optical system

The GTC will be a classical reflecting telescope with two mirrors to feed a Cassegrain focus. Additionally, a flat tertiary mirror, located on the elevation axis of the telescope tube, will feed two Nasmyth and four folded-Cassegrain foci. Figure 4.1 shows the arrangement of the foci, as well as the coordinate system used throughout this chapter.

All foci will be fed by the same secondary mirror. Furthermore, the tertiary mirror will be capable of switching between any two foci in under five minutes. This will enable any of the instruments mounted on the telescope to be accessed quickly.

Access to the prime focus and to a coudé focus will also be considered, provided that these do not seriously compromise the requirements of the GTC. In particular, prime-focus observing requires the prior dismounting of the secondary mirror, with the corresponding loss of operational efficiency.

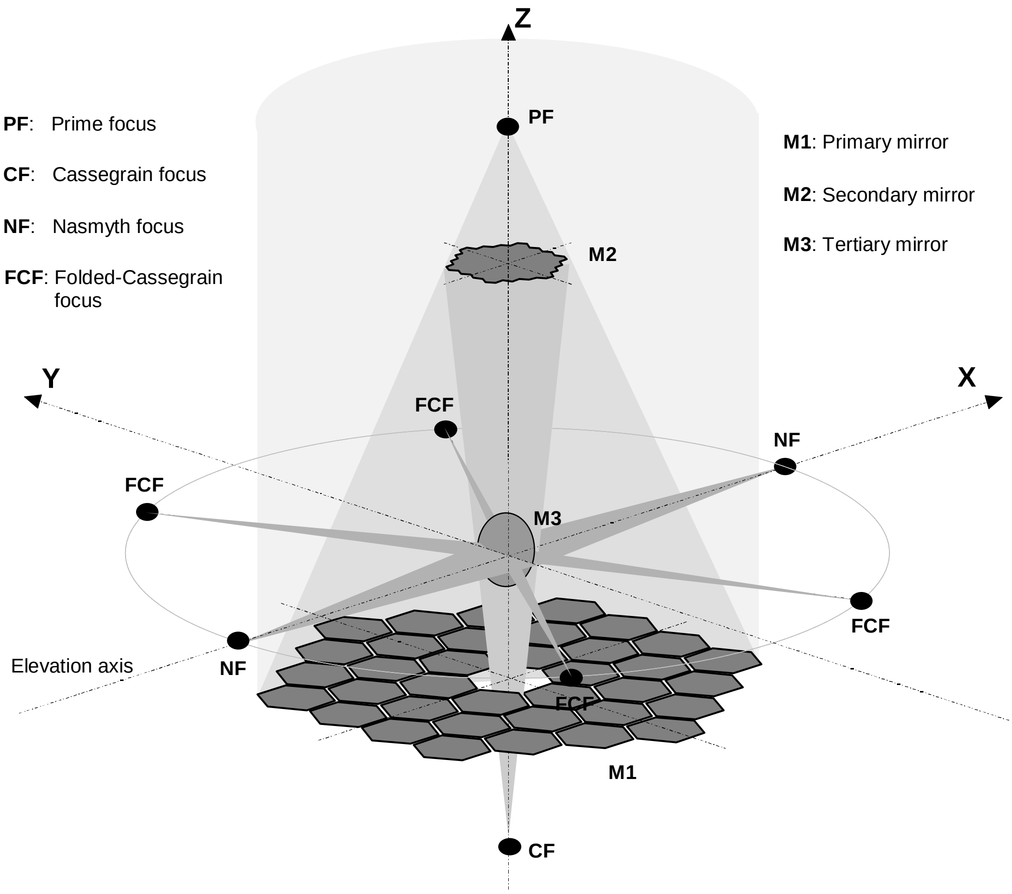


Figure 4.1: Optical system and foci.

The primary mirror will consist of 36 hexagonal segments forming a regular hexagonal pattern with a side length for each hexagon of 936 mm. The total surface area enclosed by the outer edge defined by this segmentation will be 84.2 m^2.

The position of each segment of the primary mirror will be actively controlled, such that all the segments will form part of the same nominal surface. Furthermore, the figure of each segment will be actively controlled.

The secondary mirror will be lightweight and have a serrated outer edge, similar to the outer edge of the primary mirror. This mirror will set the aperture stop of the optical system; therefore the effective collecting area of the telescope will be smaller than the area of the primary mirror.

The position of the secondary mirror will be actively controlled to maintain the alignment of the optical system.

The secondary mirror will have the ability to chop and correct the image motion during observations in the IR. This avoids the introduction of additional optical surfaces that would increase the thermal background. This capability of the secondary mirror will also be used to correct image motion due to windshake of the telescope.

The GTC will have active optics. This requires devices capable of measuring the image quality of the telescope and the capability of correcting the position of the secondary mirror, as well as the position and figure of the primary-mirror segments. Active optics will permit the correction of the inherent instability of the telescope, which would otherwise degrade the optical performance of the telescope, and it is crucial to achieve the excellent image quality required.

The GTC will incorporate adaptive optics as an integral part of the telescope design to provide the highest possible spatial resolution, although it will not be available on Day 1. The feasibility of constructing an additional secondary mirror with AO correction will be studied, but it is not foreseen that this secondary will combine the capability of AO correction and chopping. Therefore, in the case that an AO secondary mirror is built, the GTC would have two useful working modes, a visible/IR-chopping mode and a visible/IR-AO mode, each associated with its own secondary mirror.

4.4 Optical configuration

The GTC will have a classical Ritchey-Chrétien configuration, i.e. it will be free of the aberrations of spherical and field coma, the dominant aberrations being field curvature and astigmatism. The aperture will be set by the secondary mirror as a necessary requirement for controlling the telescope's emissivity in the IR. Figure 4.2 offers a schematic view of the optical configuration and Table 4.1 summarizes its basic parameters.

	Unit	
Primary mirror		
Focal length	mm	16500
Curvature radius	mm	33000
Conic constant		-1.002250
Maximum dimension	mm	11386.9
Secondary mirror (aperture stop)		
Curvature radius	mm	-3899.678
Conic constant		-1.504835
Maximum dimension	mm	1176.6
Primary–secondary distance	mm	14739.410
Back-focal distance	mm	3400.000
Effective focal length	mm	170000.000
Plate scale	arcsec mm^{-1}	1.21

Table 4.1: Basic parameters of the optical configuration of the GTC.

This optical configuration will be used to feed all the foci of the telescope. It is a consequence of the top science requirements to achieve high operational efficiency and simultaneous availability of imaging and spectroscopy over a wide wavelength range from the visible to the IR. Initially, two different configurations for the visible and IR were planned with the requirement that the instruments could work in both configurations (although with optimum performance in only one of them). However, the difference in image scale and field curvature between the two configurations was high enough to make this unrealistic.

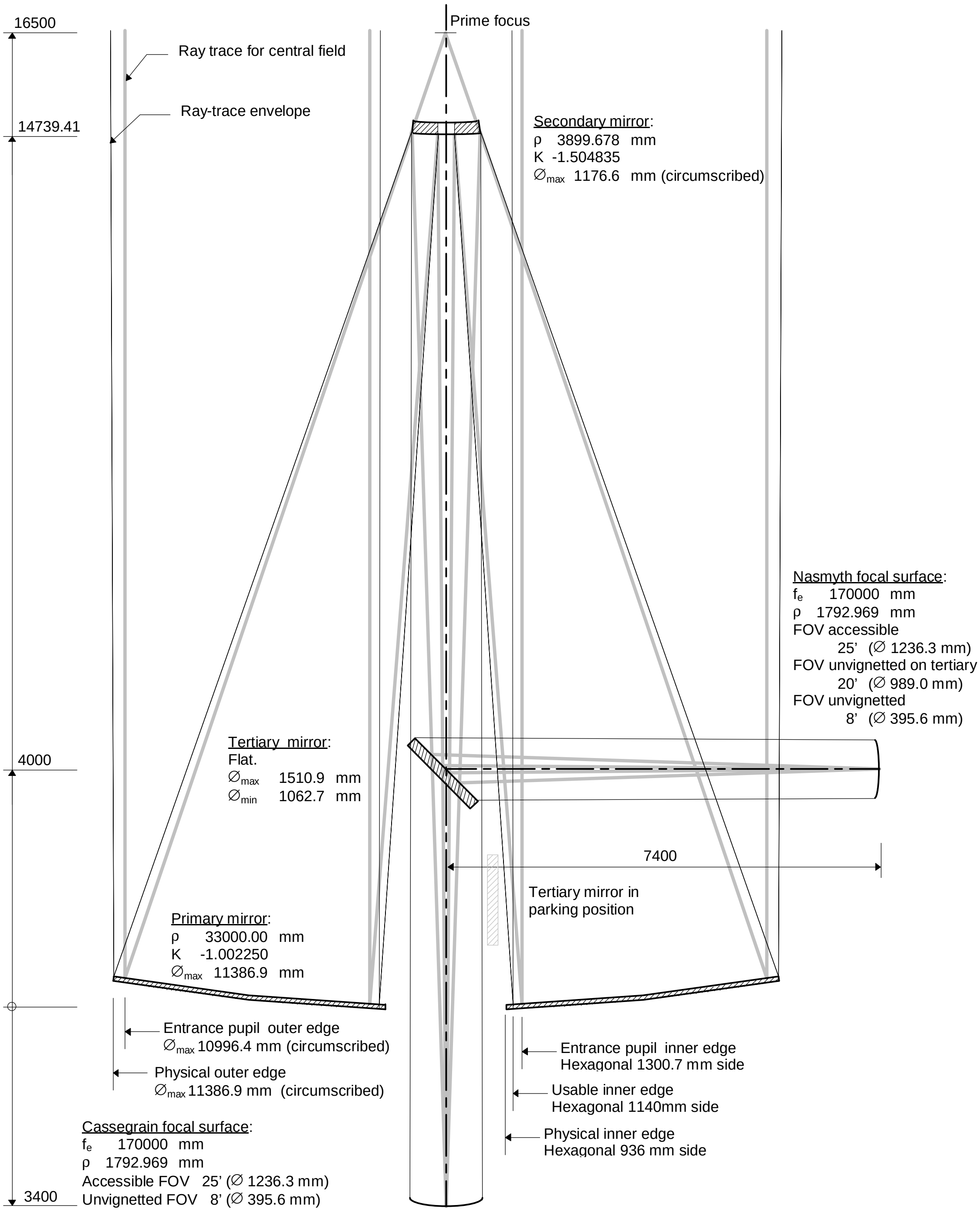
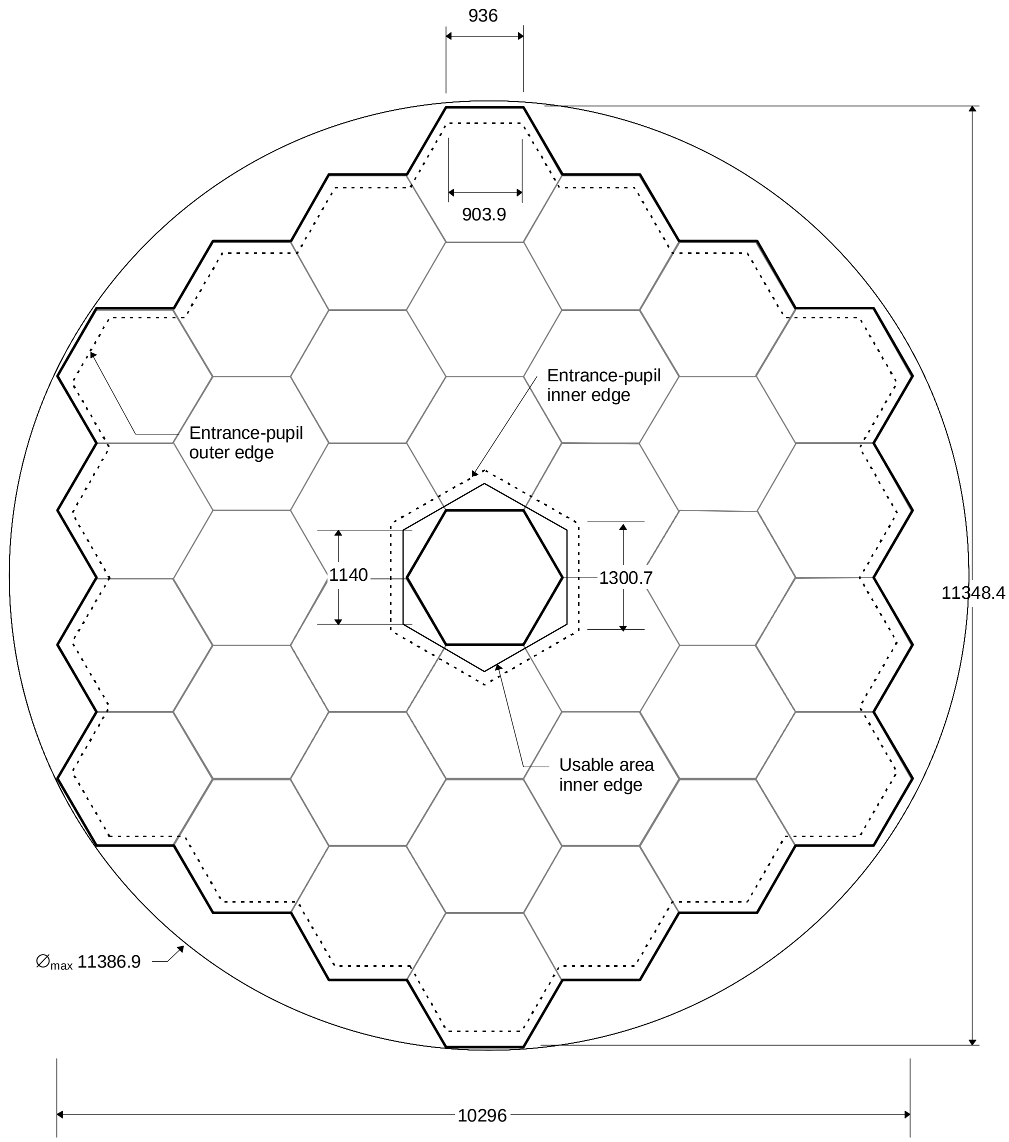
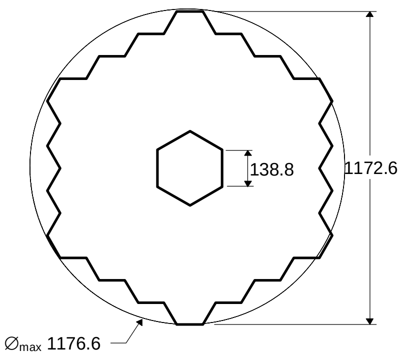


Figure 4.2: Optical configuration of the GTC (dimensions are in mm).

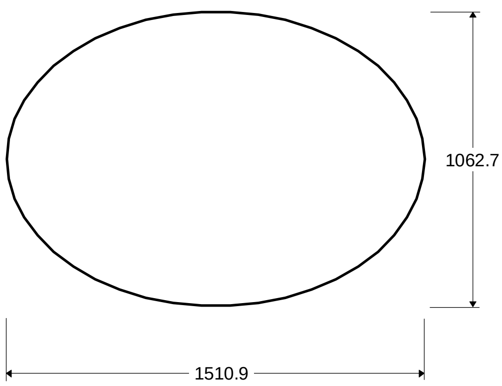
The sizes of the primary and secondary mirrors (see Figure 4.3) have been calculated to provide an entrance pupil with a surface area of 78.5 m^2 (i.e. the area of a circular aperture of diameter 10 m) and an unvignetted field 8 arcmin in diameter. The shape of the outer edge of the primary mirror is determined by the hexagonal array of mirror segments. The secondary mirror will have an outer edge similar to that of the primary. This provides the desired entrance-pupil area with the smallest primary-mirror area for the given unvignetted field.



a) Primary mirror and segmentation pattern.



b) Secondary mirror.



c) Tertiary mirror.

Figure 4.3: Plan views of the primary, secondary and tertiary mirrors (dimensions are in mm).

The inner edge of the primary and secondary mirrors will be hexagonal in shape. Their size has been calculated to provide an unvignetted FOV of 8 arcmin and to leave enough space to permit the tertiary mirror to be parked outside the envelope of the light beam (see Figure 4.2). The central obscuration of the pupil of the telescope system will be 5.6% of the total pupil area.

4.4.1 Mechanical design criteria

The choice of basic parameters, i.e. the focal length of the primary, the effective focal length of the telescope and the back-focal length, has been determined by mechanical criteria which have an important influence on cost. However, at no time have the basic scientific requirements been compromised. The main design criteria were to keep:

- Maintain the size of the secondary mirror within present-day capabilities for the fabrication of ultralight mirrors. The dynamic behaviour of this mirror is very important because it has to allow chopping and image-motion correction.
- The focal length of the primary mirror as short as possible to reduce the length of the telescope tube structure and the diameter of the dome.

The magnification of the telescope (the ratio between the effective focal length of the telescope and that of the primary mirror) has been selected to limit the size of the secondary mirror. This is mainly determined by the size of the entrance pupil and the magnification. The magnification will be 10.3, and the maximum dimension of the secondary mirror will be 1176 mm, which is within the reach of present-day ultralight mirrors.

The focal length of the primary will be 16500 mm. This has been reduced as far as possible in order to keep the telescope tube short and limit the size of the dome, which has a high cost impact. Smaller values would not affect the dome, whose minimum size could then be determined by other factors. A short focal length for the primary mirror will also increase the intrinsic stiffness of the telescope tube.

The back-focal length has been determined by two factors:

1. The distance of 7400 mm from the tertiary mirror to the Nasmyth foci, which is considered necessary for the location of the instrumentation at these foci (see Section 5.3).
2. The distance of 4000 mm from the elevation axis to the primary mirror, which is close to the natural balance position for the telescope tube.

4.4.2 Optical design criteria

The selected optical configuration is an acceptable compromise between the mechanical criteria, the simultaneous availability of the main instrument and the following optical design criteria:

- The magnification should be small. This would reduce the physical size of the field at the focus (which could carry smaller, potentially more economical, instruments) and would also produce smaller field curvature.
- The primary-mirror focal length should be large. This would result in smaller field astigmatism, which approximately varies inversely as the primary focal length, and in smaller field curvature, which approximately varies inversely as the square of the primary focal length for a constant telescope effective focal length.
- For visible observation it would be preferable for the primary mirror to set the aperture stop of the optical system. This would imply a smaller primary mirror for the same entrance-pupil area.

- For IR observations it is easier to limit the thermal background of the telescope by setting the aperture stop of the optical system at the secondary mirror. This would also simplify the control of stray light for visible observations.

- For IR observations, chopping and image-motion correction are required using the secondary mirror. This avoids the introduction of additional surfaces contributing to the thermal background, which is necessary for achieving the 5% thermal emissivity requirement.

The chosen optical configuration will use the largest primary-mirror focal length and the smallest magnification compatible with the mechanical criteria of the previous subsection. The magnification chosen may be further reduced at a later stage of the design, if it proves possible to increase the size of the secondary mirror without affecting its dynamical performance (see Section 4.8). For a single secondary mirror for both visible and IR observations it must set the aperture stop of the telescope.

Other considerations that have been taken into account in the selection of the primary-mirror focal length are:

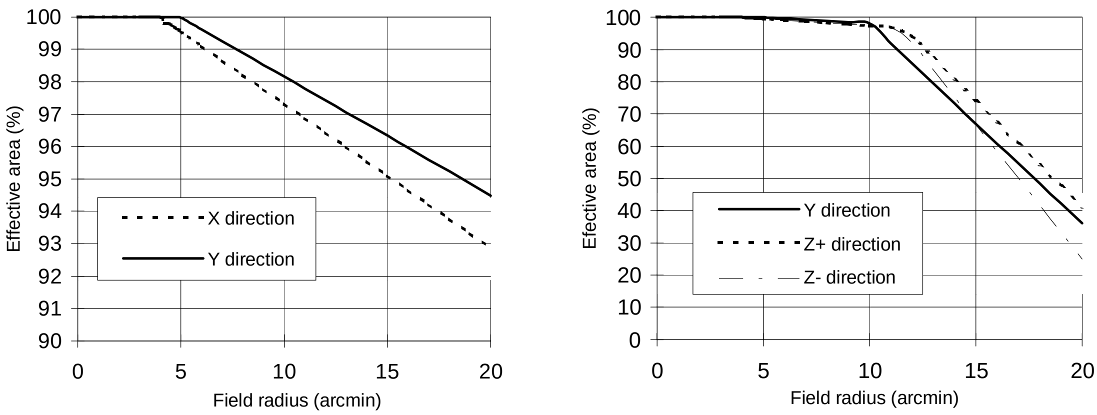
- The cost of manufacture of the primary-mirror segments does not significantly alter over the focal-length range 16.5–18 m (see Section 4.7.4).

- The effect of lateral misalignment of the primary-mirror segments on image quality increases inversely as the cube of the primary focal length (see Section 4.7). However, active correction of the segment figure will be adopted to reduce this effect.

The image scale will be 1.21 arcsec mm^{-1}. The aberrations of the selected optical configuration will be astigmatism and field curvature. The effect of field astigmatism will be to produce a geometrical image of 0.074 arcsec diameter at a 4-arcmin field radius. This is perfectly compatible with the image quality demanded in Sections 2.4.4 and 2.4.6. The field curvature will be strong, the least-confusion focal surface having a radius of curvature of 1793 mm. This will imply a defocused image of 0.78-arcsec diameter for a 4-arcmin field radius on a plane image surface. Nevertheless, this strong field curvature is considered to be correctable by the instruments to obtain excellent image quality over 8-arcmin fields [4.1].

4.4.3 Field of view

The optical configuration will have an unvignetted FOV of 8 arcmin. The unvignetted FOV has been kept as small as possible to minimize the area of the primary mirror for the given area of the entrance pupil, whilst meeting the scientific requirement (see Section 2.4.6.6). The vignetting for fields greater than 8 arcmin is shown in Figure 4.4(a). It is seen that a somewhat larger fields results in only a small loss of pupil area.



a) Primary-mirror vignetting. *b) Primary- and tertiary-mirror vignetting.*

Figure 4.4: Field vignetting due to the primary and tertiary mirrors.

The size of the tertiary mirror has been designed to provide a FOV of 20 arcmin at the Nasmyth foci without vignetting on the mirror. However, these foci will be vignetted for FOVs greater than 8 arcmin on the secondary mirror. In Figure 4.4(b) the vignetting for larger fields is shown.

The usable field at the folded-Cassegrain foci will be limited by the size of the holes that must be used in the elevation ring of the telescope tube. These foci will be limited to a FOV of 5 arcmin and will be used for small instruments.

Table 4.2 summarizes the available fields for each focus.

Focus	Unvignetted field	Available field
Cassegrain	8	25
Nasmyth	8	25(*)
Folded-Cassegrain	5	5
Prime	40	40

* 20-arcmin unvignetted on tertiary mirror.

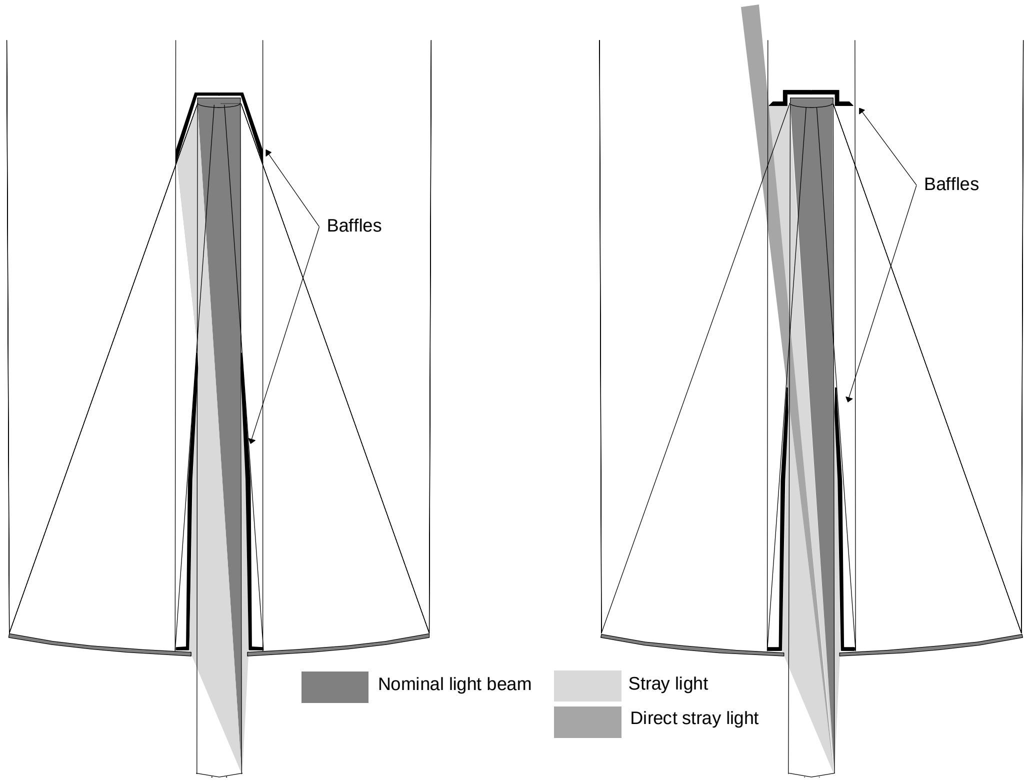
Table 4.2: Summary of the FOVs in arcmin at each focus.

4.4.4 Stray light

For visible observations it will be necessary to use baffles to prevent light outside the nominal beam from reaching the focal plane. It would be possible to avoid any luminous source from the direct view of the focal plane; however, this would mean using baffles of considerable size (see Figure 4.5(a)).These baffles create two basic problems. First, they mean increasing the central obscuration of the telescope, with the consequent loss of collecting area. Secondly, they have a large surface area, which would increase the telescope’s susceptibility to wind buffeting.

Therefore, the telescope baffle system will not provide complete protection for the focal plane of the optical system. The suppression of remaining stray light will need to be taken into account in the design of instruments. Nevertheless, a system of baffles providing partial protection will be implemented and will basically consist of a shortened baffle to screen the outer edge of the secondary mirror and another baffle on the primary mirror (see Figure 4.5(b)).

To maintain the high operational efficiency of the telescope, the secondary-mirror baffle will be retractable in less than 5 minutes to establish the necessary configuration for the suppression of the IR thermal background.



a) Complete baffles. *b) Partial baffles.*

Figure 4.5: Telescope baffle system.

4.4.5 Thermal background

For thermal-IR observations ($\lambda > 2.1$ µm) the background will be fundamentally due to thermal radiation from components at ambient temperature, particularly from the telescope. To minimize the thermal background from the telescope, the GTC will adopt the following scheme:

- The secondary mirror will be the aperture stop of the optical system.
- The IR instruments will have a cold Lyot stop conjugated with the secondary mirror. This will be 10% bigger than the aperture defined by the secondary mirror in order to simplify the alignment of the instrument with the telescope. The radiation from the space between the secondary-mirror outer edge and this Lyot stop will come from the sky and the minimal structural elements needed to support the mirror.
- The secondary mirror will have a central hole through which the focal plane will receive radiation directly from the sky rather than from the elements in the central obscuration of the nominal beam of the telescope.

In this way thermal radiation in the focal plane will be basically determined by thermal emission from the optical surfaces and from the structural elements that are unavoidably in the optical beam (e.g. the secondary-mirror support spider). The thermal radiation of the primary mirror will come from the emissivity of the segment coatings and from the gaps between the segments. With the current configuration of the segmentation of the primary mirror (see Section 4.7), the latter will contribute 0.7% of the total emissivity budget of 5% (see Appendix B).

4.4.6 Instrument subsystems

For a complete view of the optical system, it is necessary to consider the entire telescope-instrument system. The difficulties that the aberrations of the optical configuration will produce in the design of instruments has influenced the selection of the basic parameters of the optical configuration (see Section 4.4.2). Furthermore, there will also be particular cases where possible interference with other elements of the telescope will need to be taken into account.

This will be the case for instruments with elements arranged in front of the focal plane as part of their optical system, which could consequently interfere with the A&G system or even with the nominal beam itself in the case of the Nasmyth foci. Typical elements of this sort are atmospheric-dispersion correctors and field correctors (mainly for the strong field curvature).

A corrector placed in front of a focus will have to be used by all the instruments mounted at that focus. However, a single atmospheric-dispersion corrector will not compensate for the full wavelength range of the telescope, and only instruments covering a certain wavelength range could coexist at a focus using that corrector. Therefore, the design of this kind of corrector will depend strongly on the type and number of instruments planned for each focus. In any event, sufficient space will be provided at the foci to allow for such elements. Furthermore, some typical correctors will be pre-designed while the instrumentation of the GTC is being defined.

Another problem is field rotation, which will be corrected by mechanically rotating the whole instrument. At the Nasmyth foci, those instruments which cannot be rotated must provide their own system of field rotation. This could consist of an optical rotator or, alternatively, of a mechanical rotator turning only part of the instrument. In this case particular attention will be given to the synchronization between the field rotation of the A&G system and that of the instrument so as to minimize possible relative positional errors that might affect the quality of the pointing and tracking of the telescope.

4.5 Active optics

The design philosophy of the GTC is based on the full utilization of active optics. This is the capacity of the telescope to maintain the optical configuration automatically. Such automation will ensure that the required excellent image quality is achieved as a matter of routine [4.2].

The optical configuration is defined by the figure of the optical surfaces and their position with respect to the scientific instrument. The nominal optical configuration has been described in the previous section. The real optical configuration is formed by the real figure and position of the optical surfaces at each moment. The difference between the real and nominal configurations implies that the image formed at the foci will be degraded by optical aberrations.

The real optical configuration will differ from the nominal due to fabrication errors in the optical surfaces and following instabilities:

- *Gravitational instability:* Figure error and misalignment of the optical surfaces due to gravity when the telescope's attitude changes.
- *Thermal instability:* Figure error and misalignment of the optical surfaces due to temperature changes. The main effects are due to thermal deformations of the telescope structure, which cause misalignment of the optical elements, or distortion of the optical elements themselves, which arises from the lack of homogeneity in the coefficient of thermal expansion (CTE) or due to temperature gradients in the optical elements or their optomechanical support.
- *Temporal instability:* Figure error and misalignment of the optical surfaces due to ageing of the system. Temporal instabilities are unpredictable and include effects such as the relaxation of internal stresses, microcreep, maladjustment of connections, etc.

The optical systems of previous generations of telescopes were fixed to the telescope structures. Therefore, the whole system had to be designed to avoid or reduce the above errors. This design philosophy cannot be followed by the GTC, as it would be prohibitively expensive and the required image quality is considerably higher.

The optical system of the GTC will have active correction, i.e. the optical configuration will be controllable. This will allow the difference between the nominal and real optical configurations to be minimized by correcting the greater part of the instability errors. Active correction will also permit some fabrication errors to be corrected and hence, the manufacturing specifications can be relaxed.

To feed this active correction the GTC will have a set of instruments capable of measuring the optical configuration.

4.5.1 Active correction capacity

The active degrees of freedom of the optical system of the GTC will be the following:

- The position of the secondary mirror, which will have five degrees of freedom: Displacements *Ux*, *Uy*, *Uz*, and rotations *Rx* and *Ry* (axes are defined in Figure 4.1).
- The overall position of the primary mirror in axial displacement, *Uz*, and tip-tilt rotations *Rx* and *Ry*. The lack of the other three degrees of freedom is justified by the primary mirror support model outlined in Section 4.7.3.
- The figure of the primary mirror.

The degrees of freedom referred to in the first two points will be used to keep the optical system correctly aligned by moving the primary and secondary mirrors to correct the flexures of the telescope structure. Hence, the requirements of the telescope structure to maintain the optical alignment can be relaxed. The controllable figure of the primary mirror will allow the correction of the high spatial frequency aberrations of the optical system, which derive from the instability in the figure of the primary and secondary mirrors.

The figure and the position of the primary mirror will have a total of 324 active degrees of freedom. The segmented nature of the primary mirror splits these degrees of freedom into three different classes:

- *Alignment between segments:* This refers to the fact that the centroids of the images produced by each of the segments must coincide at the same point in the focal plane; hence, the tip-tilt movements of each segment needs to be controlled. This class will introduce 72 active degrees of freedom.
- *Phase between segments:* This means cancelling out the optical-path differences between the wavefront reflected by the segments. To achieve this it will be necessary to control the axial movement of each segment. This class will produce 36 active degrees of freedom.
- *Figure of the segments:* This means the change of the optical surface of the segments. Each segment will be controllable with six degrees of freedom (see Section 4.7.3). This class will provide 216 active degrees of freedom.

This separation is of great importance, not only in the design of the support system of the primary mirror (see Section 4.7.3) but also in the necessary measurement systems for active optics.

4.5.2 Open- and closed-loop active-optics correction

The correction of the telescope optical configuration will use the two processes of open- and closed-loop active optics.

The open-loop active optics process will control the active degrees of freedom in real time to correct the predictable gravitational and thermal instabilities of the telescope. This open-loop correction will be fed from the telescope behaviour model, which will be a numerical model for predicting how the telescope changes (structure gravitational flexures, deformations of optical surfaces, etc.) with position or ambient conditions (mainly temperature). The telescope behaviour model will therefore include the repeatable part of the gravitational and thermal instability.

The correction made by open-loop active optics will have residual errors as the telescope behaviour model cannot fully predict the real behaviour. The source of these residuals are:

- Temporal instability.
- Errors in the telescope behaviour model.
- The non-repeatable effect of thermal and gravitational instabilities.
- The effect of external perturbations such as wind buffeting, which cannot be included in the telescope behaviour model.

The closed-loop active optics process will reduce these residual errors by means of real-time feedback from a wavefront sensor using a natural reference star. This correction will be simultaneous with the scientific observations.

Closed-loop active optics will be possible only when there is a suitable reference star for the wavefront sensor, which will be the usual situation. The open-loop active optics by itself will permit the operation of the telescope; however, the image quality will not be as good as when closed-loop active optics is in operation.

The wavefront sensor used for closed-loop active optics will be integrated into the A&G system because it will need to be accessible during scientific observation in the same manner as the guide sensors. The spatial resolution of the wavefront sensor on the primary mirror will need to be sufficient for measuring at least the alignment between segments, and preferably also the local focus and astigmatism of the individual segments.

4.5.3 Calibration of the telescope behaviour model

The quality of open-loop active-optics correction will depend on the accuracy with which the telescope behaviour model represents the real behaviour of the telescope.

The behaviour of the telescope with respect to gravity or changes in environmental conditions will be basically constant, and the corresponding part of the telescope behaviour model will not change. However, this model will have to be updated to take into account the effects of temporal instability of the telescope, such as changes in the dimensions of the telescope structure and optical supports, errors in the telescope behaviour model for large changes in environmental conditions (seasonal temperature changes), or dimensional instability of the optical elements. The telescope behaviour model will also need to be updated to take the replacement of components of the telescope into account, in particular after replacing a primary-mirror segment.

The calibration will both create and maintain the telescope behaviour model.

The measurements required for the maintenance of the optical configuration will be difficult and time consuming. This complexity arises because no single measurement is capable of determining the figure and position of all of the optical surfaces in the optical system. The determination of the optical configuration will require several distinct types of measurements, and possibly instruments, each one giving partial information on the optical configuration. The reasons are the following:

- The wavefront measured at one position in the focal plane will contain the combined effects of the primary and secondary mirrors (and tertiary mirror at the Nasmyth focus). Furthermore, as the aperture stop of the optical system is on the secondary mirror, there will be information for only a part of the surface of the primary mirror. These two effects can be overcome by taking measurements in several positions, both in the unvignetted and vignetted parts of the FOV.

- The wavefront measurements using stellar sources will have perturbations due to atmospheric seeing. The effect of this perturbation can only be eliminated by summing measurements obtained from a number of short exposures, or by making measurements with long exposures, thereby averaging out the effect of the seeing. The total time needed to provide the necessary accuracy will be very dependent on the atmospheric seeing.

- The segmented nature of the primary mirror will produce discontinuities in the reflected wavefront. Although these discontinuities must be corrected, the more common types of wavefront sensors cannot detect this effect. Therefore, the GTC will require special instruments.

The calibration of the telescope behaviour model must be efficient in order to reduce loss of observing time. The availability budget in Appendix B assigns a maximum of only 2% for calibration procedures, which is equivalent to 15 minutes per night or to one whole night each 50 days. Hence, a fundamental aspect of the calibration is planning the measurements so that the telescope behaviour model can be updated accurately and rapidly. To achieve this, the following criteria will be used:

- As far as possible, the calibration instruments will be integrated into the A&G system of the telescope, so they will be accessible for carrying out calibration measurements in parallel with scientific observations, and therefore without loss of telescope time.

- The measurement procedures should not modify the optical configuration of the telescope, so they can be carried out in parallel with the scientific observations. Hence, procedures not compatible with this parallel mode should be avoided; for example, measurement systems for phasing the segments of the primary mirror based on stepping the segment axial positions and detecting the correct phasing condition [4.3].

- The calibration observations using starlight that cannot be carried out simultaneously with scientific observations will be planned using the queued-service observing mode (see Section 2.5.1.1). The loss of observing time due to calibration will be minimized by taking advantage of appropriate conditions, in particular adequate seeing.

- A technique should be implemented which allows the phasing of primary-mirror segments without starlight, so that it could be carried out during daytime without affecting the availability of observing time. This measurement can be carried out using an instrument which detects the discontinuities of the primary mirror in local inter-segment zones. This instrument could have a relatively small aperture (~100–200 mm), which would scan the inter-segment edges.

These criteria will permit the calibration procedure to be distributed in time. The telescope behaviour model will then be slowly and continuously updated as sufficient measurements are accumulated for this to be done with statistical confidence. Furthermore, the queued-observing mode will allow the calibration measurements to be scheduled with the scientific observations, so that the calibration measurements can be made rapidly when they are needed. The alternative strategy would be to allocate specific periods for the calibrations. Immediately after the calibration the telescope would be correctly adjusted; however, the temporal instabilities would then slowly degrade the image quality, and in general it is considered that this strategy is less efficient in the use of telescope time.

The Shack-Hartmann technique will be used to measure segment alignment and figure errors. This technique will permit the figure and alignment between segments to be measured simultaneously. However, it will not give any information on possible phase errors between the segments.

The goal will be to include this instrument in the A&G system, in the same manner as the wavefront sensor for closed-loop active optics. The difference between the two sensors is that the closed-loop active-optics sensor will run continuously during the scientific observations but with a relatively low spatial resolution on the primary mirror. The calibration will require a considerably higher spatial resolution and so brighter reference stars. It remains to be verified whether both sets of requirements can be met in a single instrument. However, the aim will be to give the closed-loop active-optics wavefront sensor the capability of measuring at least the focus and local astigmatism in the individual segments, to correct for the effect of thermal gradients and temperature changes (Section 4.5.2).

The measurement of the phasing among segments is more complex, and various techniques, proposed by several authors, have been studied [4.4].

Table 4.3 summarizes which degrees of freedom of the optical configuration are measured and corrected using open- and closed-loop active optics and calibration.

	Calibration	Open-loop active optics	Closed-loop active optics	
	Measurement	Correction	Measurement	Correction
Alignment between segments	(*)	X	X	X
Phase between segments	X	X		
Segment figure residuals	X	X	(**)	(**)

*** This measurement is made by the closed-loop active optics and used for calibration of the telescope model. The calibration instruments will probably provide measurements of alignment between segments, but the number of data is not significant with respect to the measurements from closed-loop active optics.**
**** This function will be available depending on the instruments present in the acquisition and guiding system.**

Table 4.3: Measurement and correction of degrees of freedom of the optical configuration using open- and closed-loop active optics and calibration.

4.5.4 Acquisition and guiding system

The A&G system of the GTC will determine the actual position of the aperture of the scientific instrument on the sky. The purpose of this measurement is to point and track the scientific instrument on the object of interest. Therefore, any possible errors not common to both the A&G system and the scientific instrument must be kept within strict limits. The A&G system will also carry out the measurements needed for closed-loop active optics (see Section 4.5.2).

A range of possible sensors has been proposed for the A&G system [4.5], which will be provided with the following:

- An acquisition camera, which will have the goal of accurately determining the position on the sky by identifying known sources. Also it will be used for locating objects whose positions are not accurately known.

- A slow guiding sensor, which will consist of a guiding sensor capable of operating up to readout frequencies of approximately 5 Hz.

- A fast guiding sensor, for image-motion correction using the secondary mirror. With this capacity it will be possible to obtain diffraction-limited images at 4.8 μm (3.5 μm with good seeing) by correcting image motion caused by the atmosphere. It will also allow windshake to be corrected.

- A closed-loop active-optics wavefront sensor, which will measure the alignment between segments, and preferably also detect the changes of local curvature and astigmatism of the segments (see Section 4.5.2).

Other possibilities, such as near-IR (NIR) guiding, have also been considered. However, these are not considered as priorities.

The A&G system will be capable of positioning these sensors in any part of the available field, whilst producing the least possible vignetting. While the telescope is slewing, the sensors could be pre-positioned at locations corresponding to the chosen guide stars, to provide high operational efficiency. This possibility is particularly important for the closed-loop active-optics wavefront sensor, which needs to be able to take measurements in various positions of the focal plane to give separate information for the primary and secondary mirrors.

It would be preferable if all foci were to possess the same set of acquisition, tracking and active optics instruments, so that the operation of the telescope would be the same for all the foci. This criterion will drive the design of the A&G system, especially with reference to the tracking and wavefront sensors. However, in practice the instrumentation present at each focus might have its own particular requirements. For example cameras for viewing spectrometer slits, which would carry out the task of acquisition, or the need to deploy the guiding sensor on axis or close to the axis for atmospheric image-motion correction.

4.6 Adaptive optics

The limiting magnitude attainable with a telescope depends not only on its collecting area but also on its ability to concentrate the collected light. However, the turbulent nature of the Earth’s atmosphere distorts incoming wavefronts and smears the images which would otherwise be diffraction limited. Naturally, this smearing also limits the amount of detail present in the image. In the visible, the blurred images have typical FWHMs of about 0.6 arcsec, while for the GTC a diffraction-limited image would measure 10 milli-arcsec.

The GTC will employ adaptive optics to correct wavefront aberrations caused by atmospheric turbulence and will therefore be diffraction limited. It consists of a wavefront sensor, a wavefront corrector and a control subsystem. The wavefront corrector is usually a deformable mirror. The feasibility of AO has been clearly demonstrated at several 4-m class telescopes [4.6, 4.7]. Application to 10-m class telescopes basically involves an increase in the required number of degrees of freedom in the wavefront correction.

This AO capacity will have a two-tier hierarchy:

1. Image-motion correction permitting diffraction-limited observation in the thermal IR, or even at wavelengths as short as 3.5 μm in the case of good seeing.

2. High-order AO (HOAO), which will consist of the correction of higher-order atmospheric aberrations. This correction will allow diffraction-limited images to be obtained at NIR wavelengths.

Since AO performance is strongly dependant on seeing conditions, the performance will be specified for a 'standard seeing scenario', corresponding to a seeing-limited image FWHM of 0.5 arcsec at 0.5 μm and an equivalent turbulent layer at 5 km above the telescope and moving at a speed of 10 m s^{-1}.

The AO system will be designed as an integral part of the telescope. This translates into the following criteria:

- The optical quality of the telescope must not limit the AO system.
- The measurements from the OA system will also be fed to the optical system of the telescope. In fact, the HOAO system will be one of the most sensitive tools for detecting some of the errors introduced by the telescope.
- There will be an artificial LGS system permitting sufficient sky coverage for AO to be used on a routine basis.
- All the IR instruments should benefit from the presence of AO, and not merely those instruments specifically designed to take advantage of it.

4.6.1 Image-motion correction

Image-motion correction will be carried out at the secondary mirror to avoid increasing the telescope's emissivity for thermal IR. The main scientific specification under the standard seeing scenario is to provide an on-axis Strehl ratio[14] of at least 0.33 at 4.8 μm.

Table 4.4 shows the Strehl ratios that would be expected from perfect correction of atmospherically induced tip-tilt in the *L*, *M* and *N* bands. For wavelengths above 4.8 μm the errors introduced by the optical system do not significantly degrade this type of observation, because these errors are limited by the image-quality requirement in the visible, as is quantified in Appendix B.

	Seeing=0.5 arcsec	Seeing=1 arcsec
L (3.5 μm)	0.155 (0.125)	0.003(0.0014)
M (4.8 μm)	0.37 (0.33)	0.04 (0.03)
N (11 μm)	0.83 (0.81)	0.55 (0.51)

Table 4.4: Strehl ratios for tip-tilt correction in the L, M *and* N *bands for seeing of 0.5 and 1.0 arcsec. The values in parentheses correspond to using a quadrant-type image-motion sensor.*

The wavefront sensor needed for the image-motion correction could be as simple as a quadrant-type image-motion sensor. However, the performance would be limited by 'centroid anisoplanatism', i.e. bias in the tilt measurements due to asymmetric aberration modes, and it is preferable to use a low-order wavefront sensor. The tilt sensing can be carried out either in the visible or IR; in either case the sky coverage for whole-aperture tilt correction should be practically complete. The tilt sensor would be positioned at the focus where the correction is

[14] The Strehl ratio is defined as the ratio between the on-axis intensity of the point spread function obtained with the real telescope and that which would be obtained with a perfect telescope. The Strehl ratio is useful for comparing images whose FWHM is diffraction limited, since it measures the fraction of corrected light.

required, either in the A&G system or in the instrument. On-instrument sensing would avoid errors due to differential flexures.

The image-motion correction will also allow some compensation for wind buffeting of the telescope. The object used as reference should be within the isokinetic patch of the object being observed in order to avoid adding the contribution of the atmospheric image motion of the guiding star instead of correcting it. The size of the isokinetic patch depends on the turbulent conditions (it is inversely proportional to the effective height of the turbulence) but is expected to be of order 2 arcmin.

If the size of the outer scale of turbulence (L_0) is of the same order as that of the telescope, then the gain in SR from image-motion correction will be less than that predicted by Kolmogorov turbulence models. There is very little data available on L_0 for the ORM. However, the correction of windshake alone is important enough to justify image-motion correction.

4.6.2 High-order adaptive optics

The main guidelines for the HOAO system include:

1. The primary scientific requirement is that the on-axis SR at 2.2 μm be at least 0.8 when the standard seeing scenario applies and there is a bright guide star (m_V=12) available on axis.
2. Provision will be made for a LGS, allowing an on-axis SR of at least 0.5 at 2.2 μm when the standard seeing scenario applies.
3. The system will also operate at wavelengths as short as 1 μm, although with a decreased SR with respect to 2.2 μm.
4. The range of the wavefront measurement and correction capability will be sufficient to operate when the seeing degrades to 1.65 arcsec (~92% percentile).
5. The FOV within which it will be possible to search for a guide star will be at least 2 arcmin. Inside this field, there will be no vignetting and the reduction of the SR due to optical aberration should be negligible.
6. The system stability will allow integration on the science instrument of at least one hour.
7. It should be possible to optimize the system performance in real time as a function of observing conditions, especially the seeing and guide-star magnitude.
8. The AO operation should be compatible with queued observing. It should then be possible to take advantage of excellent seeing conditions. This requirement implies that the changeover to AO operation should be fast and straightforward.

The performance of an AO system depends on a large number of factors, and a spreadsheet approach has been used to derive error budgets [4.8]. Using these error budgets, it has been found that a system which corrects on scales of size 1 m (in the entrance pupil) falls short of the scientific requirements, while a system which corrects on scales of ~0.55 m satisfies them with a certain margin. The number of actuators required to provide this correction is ~ 250 on the telescope pupil. Figure 4.6 shows a sample calculation of SR as a function of guide-star magnitude and separation from axis for a system with subapertures of size 0.56 m.

The error budget includes the residuals of the telescope errors after the AO correction, the most important of which are presented in Table 4.5. The effect of these residuals is to reduce the SR by ~10 % in the *K* band, and by ~ 25 % in the *J* band. These residuals are due to the segmented character of the primary mirror. Segmentation is particularly prejudicial to AO systems because the latter are based on the sensing of slopes or curvature in the wavefront; however, they are insensitive to discontinuities or segment phase errors.

Segment figure residuals	60 nm
Phase between segments	50 nm
Alignment between segments	20 nm
Noise of primary-mirror stabilization (Section 4.7.3.2)	60 nm
Segment vibration	30 nm
Total	105 nm

Table 4.5: Telescope wavefront residuals after AO correction.

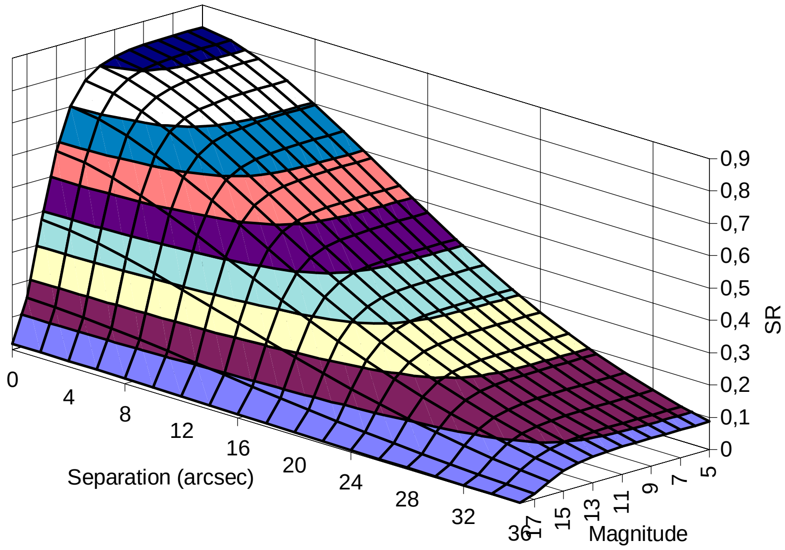


Figure 4.6: Strehl ratio at 2.2 µm as a function of magnitude and separation of natural guide star for a system with 250 actuators/subapertures.

Although simulations by other projects [4.9] indicate that the performance of systems based on slope or curvature sensing is similar, the technical feasibility of curvature systems with > 36 actuators/subapertures has not yet been demonstrated. It is therefore proposed to use a Shack-Hartmann type wavefront sensor. The wavefront sensor should be able to operate on either natural or sodium-laser guide stars. This implies that it should be possible to focus the wavefront sensor either at infinity or at an altitude anywhere in the range 90–100 km above the telescope. The range is necessary in order to track fluctuations in the height of the sodium layer.

The high-order wavefront correction may be carried out either near-focus or using an adaptive secondary mirror.

Most AO systems re-image the telescope pupil on to a small deformable mirror. A large number of optical surfaces is required, thereby substantially increasing the emissivity and decreasing the transmission. The increase in emissivity is at least 6%, but in a real system would be considerably larger. Also, the corrected beam is only available at the focus where the AO system is installed.

An adaptive secondary mirror would provide a corrected beam available at all foci (except prime). Depending on the design of the wavefront sensor, such a system could cause a negligible increase in emissivity [4.10, 4.11], and AO could be used at any focus provided with an AO wavefront sensor. For these reasons, the adaptive-secondary option is considered the primary choice for HOAO. Possible disadvantages of an adaptive secondary include the fact that it is likely to be more expensive, and will not be as easy to calibrate or maintain as a near-focus system. Furthermore, it will be required that this adaptive secondary mirror have a stability compatible with the use for non-AO observations, which implies that it must have good stability.

It is proposed that the adaptive secondary replicate the functions of the Day 1 secondary as far as is practicable in order to carry out AO observations as part of the normal queue-based operation of the telescope. The diameter of the secondary will therefore be 1.176 m, which can easily accommodate ≥ 250 actuators. The stability of the actuators will have to be such that the mirror can maintain its figure when used in passive mode. It is likely that the mirror will be too heavy to tip-tilt as a whole, and so the range of the actuators should be large enough to carry out tip-tilt as well as high-order correction. However, the actuator range required for chopping would probably be excessive. Therefore, it may not be possible to combine chopping with AO correction.

The secondary mirror will be conjugate with an aperture placed 138 m below the primary mirror. This will not be the optimum position of the wavefront corrector because placing it conjugate to some altitude above the telescope could increase the isoplanatic angle, and hence improve the sky coverage. However, the gain is likely to be modest. Furthermore, it will be preferable to place the wavefront corrector conjugate with the aperture stop of the optical system, otherwise the AO system would require an oversized wavefront sensor for off-axis guide stars.

Although an adaptive secondary would be equipped with position sensors, it will be necessary to measure the surface figure from time to time in order to calibrate the sensors. A Gregorian configuration would allow surface measurement in a fairly straightforward manner, e.g. using a point source at the prime focus. However, a Gregorian version of the secondary mirror would require the telescope tube to be significantly longer, which would then result in a larger dome. This option has been rejected.

Another possibility for testing the figure of the secondary would be to use a holographic plate. This would require the secondary mirror to be hung above an illumination system (e.g. at Steward mirror labs [4.12] secondary mirrors up to 1.8 m in diameter are tested by suspending them 2.4 m above a 1.8-m aspheric mirror).

4.6.3 Laser guide star

Simple models of the distribution of stars on the celestial sphere lead to a prediction that the proposed AO system will provide Strehl ratios ≥ 0.6 at 2.2 μm over 10% of the sky. While this satisfies an enormous number of viable scientific projects, it falls short of allowing adaptive correction wherever the telescope points. A sodium-laser guide star would provide Strehl ratios up to ~ 0.5 over the whole sky. With this system it would be possible to take advantage of the increased sensitivity provided by AO for all observations in the *K* band.

The guide-star projection system may be either mounted behind the secondary mirror or attached to the telescope tube. While the guide-star image elongation is minimized using on-axis projection, studies at the Keck [4.13] indicate that the difference in performance is small, especially at 2 μm. Separation of the sodium guide star from the diffuse Rayleigh-scattered light is simplified by the off-axis approach. The design of the secondary mirror would also be simplified. The optimum projection telescope diameter is ~2.5 $r_{0,}$ where r_0 is the Fried parameter. For 0.5 arcsec seeing, r_0 = 0.2 m and the optimum diameter is ~ 50 cm.

Laser technology suitable for guide-star operation is still under development. Pulsed systems are favoured since they allow upgrades to very high powers, and the pumping lasers may be located remote from the telescope. The possibility of high-power operation is important for the future implementation of multiple guide stars in the *J* band.

Future detailed studies will determine the best system both for deciding the location of the laser launch telescope and for selecting the kind of technology to be used. Furthermore, it will be necessary to study the possible effect of laser guide-star operations on the neighbouring telescopes (especially the TNG and the NOT), as well as on the safety of overflying aircraft, bearing in mind that Spanish regulations forbid flights over the ORM (see Section 3.2).

4.7 Primary mirror

The primary mirror will be formed from 36 hexagonal segments to be maintained in the correct position with respect to one another so as to form the desired optical surface. The problems associated with a hyperbolic segmented mirror of the type indicated have been described by the designers of the Keck Telescope [4.14].

Each segment will be an off-axis section of the nominal hyperboloid of the primary mirror. The 36 segments will be arranged in 6 groups of 6 identical segments. There will be 6 additional segments, one per group, to allow for the replacement of segments needing re-coating. The entire primary-mirror surface will therefore always be operative.

The challenge facing the GTC is to obtain a primary mirror of sufficiently excellent quality to deliver a required image quality of 0.112 arcsec FWHM (see Appendix B). This objective will be achieved by correct polishing of the segments and using active systems for maintaining the alignment of the segments and correcting figure errors introduced by gravitational, thermal and temporal instabilities.

The active control of segment figure will be very important because it will permit the control of the following factors affecting the image quality:

- Errors in the manufacture of the segments.
- Uncertainties in the measurement of the off-axis position and radius of curvature of the segments during manufacture.
- Positioning error of the segments during mounting on to the cell structure with respect to their real off-axis position.
- Instability of the blanks of the segments.
- Instability of the figure of the segments due to the support system.

The efficiency of correction will be achieved because the calibration procedures for these effects will be automatic, as has been said in Section 4.5.

4.7.1 Segmentation scheme

There are fundamentally two natural methods of segmenting a mirror: annular, with the segments arranged in circular rings, or hexagonal (the hexagon is the regular polygon that can cover a plane surface in the most circular shape[15]). Both types are shown in Figure 4.7 for 36 segments.

[15] Triangular and square segments can also accomplish this.

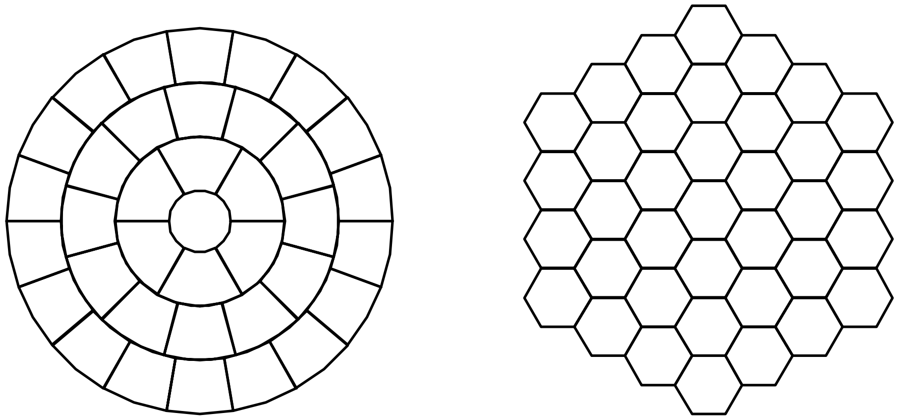


Figure 4.7: Plan view of circular and hexagonal segmentation.

Both alternatives have been studied [4.15], and hexagonal segmentation has been chosen for the following reasons:

- Hexagonally shaped segments give a more circular shape and provides potentially the best exploitation of blank material (if it is assumed that the segments must be extracted from circular blanks). Use of circular blanks to produce hexagonal segments should result in a 20% mass surplus over what is actually used, whereas for the annular segments the minimum mass surplus would be 57%.
- The vertices of the hexagonal segments have an internal angle of 120°. The annular segments have 90° corners, which are more difficult to polish.
- When the primary mirror is viewed from infinity the segments will appear as identical hexagons. However, due to the curvature of the mirror the actual segments will not be regular hexagons. Furthermore the maximum dimensions of the inner segments will be slightly smaller than those of the external ones. Nevertheless, the segments will be sufficiently similar so that only one mounting support needs to be designed, with only small compensatory adjustments being necessary for the individual segments (e.g. introducing small additional masses). This significantly simplifies the design and production of these supports. For annular segmentation, however, the segments in each annulus are sufficiently different such that a distinct design would be needed for each ring.

The main advantage of annular segmentation is that it provides a circular outer edge for the primary mirror, thereby maintaining axial symmetry in all optical elements and providing an axisymmetric diffraction pattern. In comparison, the diffraction image formed by the array of 36 hexagonal segments is complex, as shown in Figure 4.8. With this structure, it could be difficult to resolve a faint object close to a bright object. However, the peaks beyond the first diffraction ring have intensities of order 3×10^{-4} (i.e. 8.8 mag) with respect to the central peak, which is considered to be a sufficient dynamic range for detecting close objects. This diffraction structure could be observed only in diffraction-limited images in the thermal or near IR using HOAO, although in the thermal IR the background is so intense that it is improbable that this structure would be seen. In the NIR the structure could be seen when high SRs are obtained; in this case the shape of the pupil inside the instruments could be regularized to get a more regular diffraction pattern. Finally, in long-exposure observations the diffraction structure is smoothed by the rotation of the pupil with respect to the field of observation due to the alt-azimuth mount of the telescope.

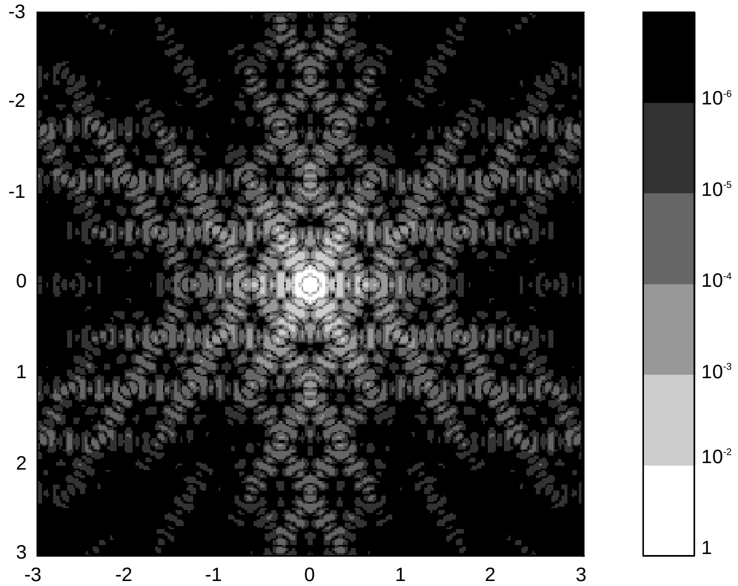


Figure 4.8: Diffraction image of a mirror with hexagonal segmentation of 36 segments. The intensities are normalized with respect to the maximum intensity. The scale is in units of λ/a, a being the side of one of the hexagons. The diffraction limit of the mirror is approximately $\lambda/6^{a}$.

To determine the number of segments, the impact of this parameter on various factors [4.15] was studied for 18, 36 and 60 hexagonal segments, 36 segments being arrived at as the optimum number.

In general it is preferable to use the smallest possible number of segments, due mainly to image-quality criteria. A smaller number of segments implies:

- A smaller total number of support points to be used for the same gravitational deflection. This is because for the same density of support points per mirror surface and the same thickness, the gravitational support distortion is smaller the larger the segment [4.16].
- More effective active-optics correction of the segment figures.
- A smaller number of units to control the primary mirror, which results in lower cost and higher reliability.
- Smaller total length of the inter-segment gaps. This decreases the lost area of primary mirror, which in turn decrease the thermal emissivity of the primary mirror.
- Less degradation of image quality due to phase errors between segments.
- Lower polishing cost. The polishing of the segments is generally cheaper per unit surface area for larger mirrors (see Section 4.7.4).

All the preceding factors point towards larger segments. However, the last point concerning the manufacture of the segments remains true only while this does not imply building new installations, in which case the investment tends to become a significant part of the cost.

Therefore, the criterion followed has been to use the largest segments within the capacities of potential polishers at reasonable prices. After consultations with these polishers, this limit has been set at 2.0 m, which means that the smallest possible number of segments is 36.

4.7.2 Blanks

The segmentation will appear as a regular hexagonal pattern when the primary-mirror is viewed from infinity, the side length of each hexagon being 936 mm. The plan view of each segment will differ slightly from a regular hexagon due to the curvature of the primary mirror. There will be a gap of 3 mm between segments. The blanks will be meniscus shaped with a thickness of 80 mm. Figure 4.9 is a schematic view of a blank.

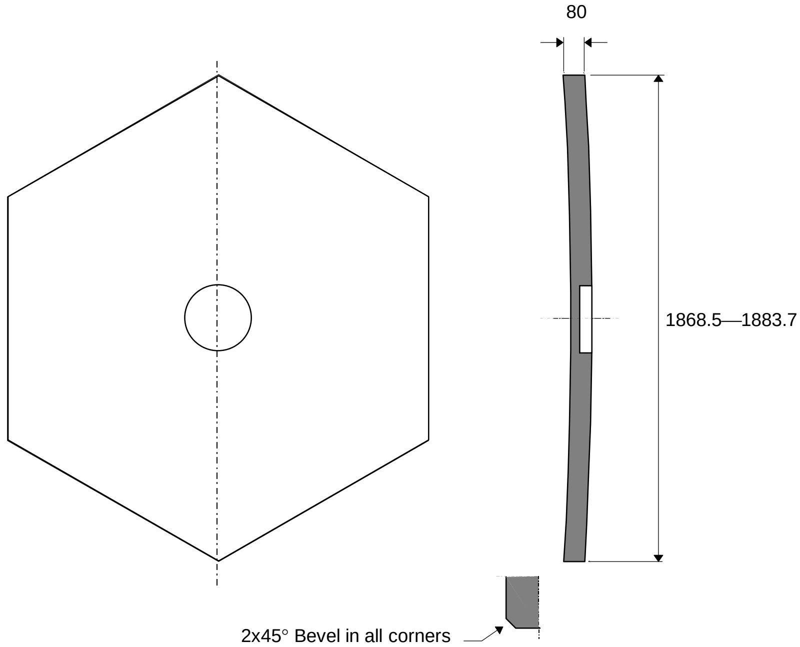


Figure 4.9: Primary-mirror segment blank (dimensions are in mm).

The segments will be manufactured from a material of almost zero CTE, possible candidates being ULE™, Zerodur™ and Sitall™.

The criterion for the choice of material is thermal stability. This is important since the nocturnal temperature at the ORM can undergo variations of about 11 °C over periods of two weeks, the mean nocturnal temperature variation being 2.8 °C (below 5 °C on 90% of nights) [4.17].

The CTE of the three materials considered is acceptable for limiting thermal instability due to thermal gradients inside segments. These thermal gradients originate through air temperature changes, which the segment will follow, but with a time delay. A heat flow of 5 W m^{-2} gives rise to a change in curvature of the segment of 18 nm rms, thereby producing a defocused image of diameter 0.12 arcsec (equivalent to 0.07 arcsec FWHM[16]) with a CTE of 50 ppb K^{-1}, which is typical for the materials considered [4.18].

The material must also have a homogeneous CTE. A CTE gradient of 10 ppb K^{-1} between the front and back surfaces of the segment gives rise to a defocused image of diameter 0.246 arcsec when the temperature changes by 2.8 °C. For a variation of 11 °C this defocusing is 0.97 arcsec, which is the worst possible case that can occur. In the case that CTE variations are produced with a higher spatial frequency CTE distribution the effect is much reduced [4.18].

This effect was studied by the W. M. Keck Observatory [4.19] with CTE data supplied from the quality control of Schott Glaswerke (the manufacturer of Zerodur™). From these data an image-

[16] The effect of a defocused image of the segments on the FWHM of a seeing image is approximately 0.587 ∅.

quality degradation of 0.162 arcsec FWHM was predicted for a thermal variation of 11 °C, this deformation being mainly concentrated (95%) in defocusing and astigmatism of the segments. However, no thermal instability in the figure of the segments has been reported. This supports the idea that the spatial distribution of the CTE of Zerodur in the segments of this telescope has a higher spatial frequency than was implied by the CTE data used, which consisted of measurements at only 18 points in each segment.

The thermal instability of the segments will be compensated using the active correction of segment figures described in the following subsection.

Another fundamental problem is the seeing created in the surface of the primary mirror. As many authors have established, and as summarized by Zago [4.20], the primary mirror is an important contributor to the seeing when it is warmer than the surrounding air. It is becoming widely accepted that the seeing induced by the primary mirror is negligible when its temperature is lower than ambient by about 1° C.

In principle, the GTC will not have any device for directly controlling the temperature of the primary-mirror segments. However, the dome will be air conditioned during the day to maintain the telescope at the expected night-time temperatures and the primary mirror will be well ventilated during the night, and hence prevent the seeing from being degraded (see Section 6.7).

4.7.3 Primary-mirror support system

The primary-mirror support system will have the following characteristics.

1. The lateral position of each segment (i.e. movements in the plane tangential to the segment at its centre) will be mechanically fixed to the mirror cell. Due to the asphericity of the primary mirror, the figure of each segment is a function of its lateral position. The active control of this lateral position is not necessary because the active figure control of the segments can correct this effect.
2. The axial position of each segment will be controlled actively by three positioners.
3. The relative axial position between the primary-mirror segments will be measured by position sensors located between segments.
4. There will be a closed control loop between the position of the segments as determined by the positioners and their position as detected by the sensors. This control subsystem will stabilize the relative position between segments so that the primary mirror can be considered as a rigid unit.
5. The figure of each segment will be actively controlled to correct the instabilities of figure, due basically to thermal and gravitational effects.

4.7.3.1 Segment support system

The mirror segments will be too thin to support their own weight without distorting as the elevation changes. A support system is required for each segment that will:

- Define the rigid-body position of each segment. Of these, the three axial degrees of freedom will be controlled actively (next subsection), while the three lateral degrees of freedom will be fixed.
- Support segment weight without the segment deforming.

- Resist the action of perturbations, mainly from wind, without the segment deforming or becoming misaligned with respect to the other segments.

- Deform the segment in a controlled manner.

- Guarantee the safety of the segment in all conditions.

- Enable the primary mirror and the support system to be easily maintained, particularly by allowing the segments to be easily removed from primary mirror cell for re-coating and to be reinstalled.

Only the first four functions will be dealt with in this section, as these have a direct impact on the primary objective of obtaining excellent image quality. The remaining points are listed since they will influence the design.

Each segment will be optimally supported on 36 points, which will reduce the gravitational deformation to 5 nm rms. The axial position of each segment will be defined by three points. Each of these three points will use a whiffletree to distribute the reaction over 12 mirror-support points kinematically (isostatically; see Figure 4.10), These points will be moved by their respective positioners in order to control the axial position of the segments.

Whiffletrees are passive mechanical systems with articulations that are usually flexure pivots, which do not need any kind of maintenance, and which with a suitable design can achieve almost negligible failure rates. The greatest disadvantage of this system is that the very nature of whiffletrees implies that there exist several levels of flexible elements that support one another, and whose flexibilities gradually accumulate. Therefore, they suffer from lack of segment support stiffness, and so the alignment of the segments will be more sensitive to external wind perturbations.

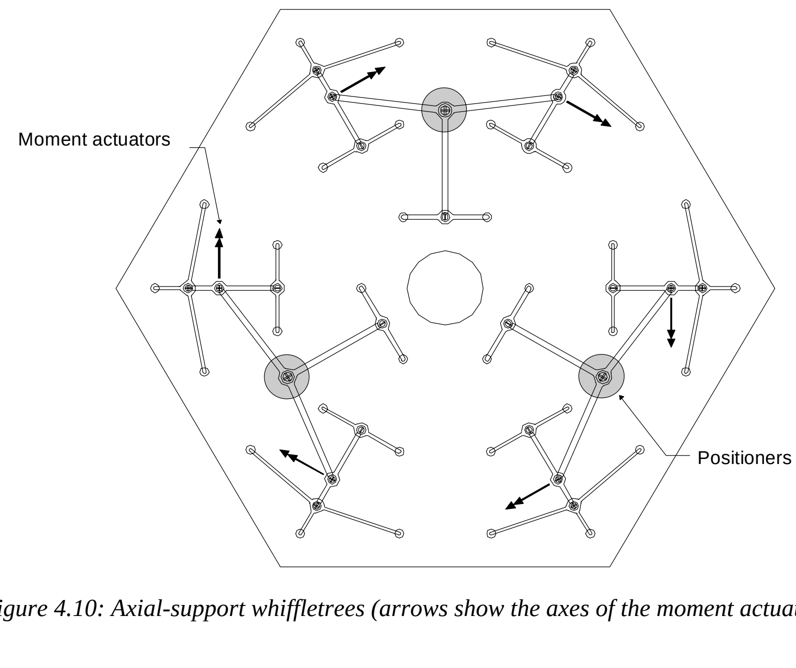


Figure 4.10: Axial-support whiffletrees (arrows show the axes of the moment actuators).

The lateral support for each segment will be close to its centre of gravity, using a similar principle as employed by the Keck Telescope [4.14] or the Hobby Eberly Telescope [4.21]. The lateral support cannot be actively controlled; it will be joined to the cell of the telescope and will fix the lateral position of the segment.

The figure of the segments will be corrected using moment actuators. These will introduce controlled moments in the articulations of the whiffletree to change the support-force distribution on the segment. The figure correction will be limited to 6 degrees of freedom in each segment, which will be obtained from the 6 moments, whose axes are shown in Figure 4.10. This arrangement has the advantage of not needing additional interfaces with the cell of the telescope.

The purpose of this deformation mechanism is the basic correction of the following errors:

- Lateral position errors of the segments: these errors have a fixed component that comes both from the error introduced during polishing of the segments and from their installation in the primary-mirror cell. They also have a variable component that depends on the instability of the cell. These errors are produced mainly in the focus and the astigmatic modes of the segment.
- Segment curvature errors due to inaccurate measurements in the manufacturing process.
- Thermal deformations of the segments due to lack of homogeneity in the CTE and temperature variations inside the blank, as has been described in Section 4.5.3.
- Deformations of the segment by thermal or gravitational effects in the support system.

It is conservatively estimated that this correction will be capable of reducing the errors in the slope of the wavefront to 25%. This limitation is determined from the difference between the required deformations and those it is possible to introduce, which will approximate to the eigenmodes of the segment. The correction level possible with this system implies that the accuracy of the force actuators does not have to be high, which will significantly reduce their cost.

As an alternative, the possibility was considered of using a support scheme in which the axial-support forces were actively generated. In this way, the axial support would take place on 12 points, each one of which would be divided into three by means of a simple tripod. Three of these 12 points would be used to define the axial position of the segment and the remaining 9 would be provided with force actuators to control the support forces necessary, depending on the telescope attitude. Figure 4.11 demonstrates this option.

The advantages of this type of design are that it simultaneously resolves the axial support and the deformation system of the segment, and that the connection of the segment to the defining points is more direct, which implies a greater stiffness of the support system and a lower sensitivity to wind perturbations. An inconvenience lies in the fact that the support-system interface with the primary cell becomes more complicated, while at the same time by increasing the number of active units the system will become less reliable. Moreover, previous analyses [4.18] have shown that the accuracy of these force actuators should be of order 0.1% of the nominal support force, which would imply that they are not simple. Therefore, the advantages of this option would not compensate for lower robustness with lower cost.

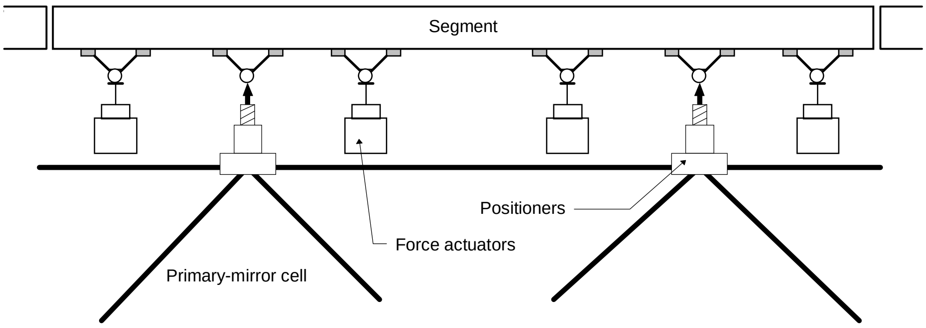


Figure 4.11: Axial support using active generation of support forces.

4.7.3.2 Active primary-mirror stabilization

To maintain the correct axial position of the segments independently of the deformation of the primary-mirror cell, each segment will be provided with three positioners capable of moving it in the three axial degrees of freedom. Each one of these positioners will move one of the axial-support whiffletrees of the segment. With these positioners it should be possible to correct the position changes between segments due to gravitational and thermal deformations of the telescope cell, which it is estimated will be of order 0.5–1 mm.

The relative axial position of the primary-mirror segments will be measured using two position sensors situated in each common edge between segments. Figure 4.12 is a plan view of the distribution of the 108 positioners and 168 sensors comprising the system. These sensors will not provide measurements of the global position of the primary mirror with respect to the cell structure, which will be derived from the absolute position of the positioners.

Finally, a control subsystem will provide feedback to the 108 positioners of the 36 segments with the 168 position sensors.

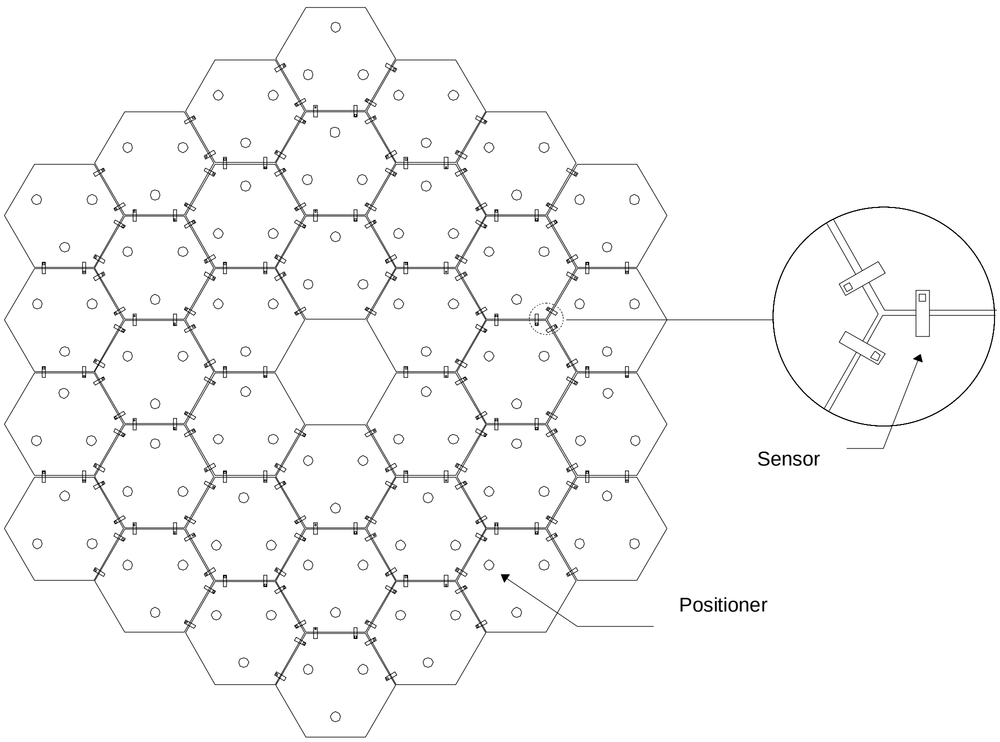


Figure 4.12: Plan view of the distribution of the segmented primary mirror showing the positions of sensors and actuators.

The performance of the positioners and sensors must be compatible with the excellent image quality required. That means that both have to be capable of resolving displacements of a fraction of the wavelength of light. The preliminary specifications for the positioners are an incremental accuracy of 8 nm and an overall accuracy of 5 μm over the entire travel of about 1.2 mm. The preliminary specifications of the sensor are a measurement noise of 3 nm and an accuracy of 10 nm (including thermal and temporal instability). The feasibility of similar positioners and sensors has been demonstrated by the Keck team [4.22] [4.23].

Given that the relative position between segments can be completely measured with the sensors, this system permits the stabilization of this position and guarantees the figure of the primary mirror insofar as the position between segments is part of the global figure of the primary mirror. The stability of the primary-mirror figure will depend on this stabilization system, and it is convenient to differentiate between three separate aspects:

1. The thermal, gravitational and temporal stability of the alignment and phase between the segments will be determined exclusively by the stability of the position sensors themselves. There are two competing effects:

    - The redundancy in the system (168 sensors but only 108 degrees of freedom to be controlled) will allow statistical averaging of the errors.

    - There are deformation modes of the primary mirror which have low sensitivity to the sensor readings [4.14, 4.24]. Therefore, the errors in the sensor readings become amplified when they are transferred to the surface of the mirror.

    The second effect is the more powerful and causes the mean square deviation of the surface of the primary mirror to be amplified by a factor of about 5 in comparison with the standard deviation of the random errors of the sensors. However, the GTC will have a closed-loop active-optics system capable of measuring the alignment between the segments while observing. These measurements provide further redundancy and are sensitive to the deformation modes which are difficult to detect with the segment sensors. The result is that random errors in the sensors are no longer amplified and become attenuated by a factor of approximately 2.

2. The jitter in the position of the primary-mirror segments due to the operation of the stabilization system will be determined by the noise of the positioners directly and that of the sensors after passing through the controller.

3. The system's rejection of perturbations will depend fundamentally on the bandwidth of the control system. For perturbations of very much lower frequencies than the bandwidth of this controller the stabilization system will react by completely eliminating the perturbation, so the primary mirror can be considered to be perfectly rigid. This active stiffness will diminish as the frequency of perturbation approaches that of the bandwidth, from which the rigidity of the primary mirror would be based on the passive performance of the segment support system.

The active-optics functions will determine the reference position between segments for the primary-mirror stabilization system.

The GTC will seek the maximization of the bandwidth of the controller in order to minimize wind perturbations. For this purpose, it will be necessary to achieve an adequate sampling frequency in the system. This goal has been established on the basis of two concepts: distributed implementation and local–global control strategy [4.24].

An outline of how this implementation is at present being planned is given in Figure 4.13. There will be a local control unit, called the node box, for each segment, whose function will be to control directly the three positioners that move the segment and the data acquisition for half of the sensors that interface at the segment. These node boxes will be connected by a communications network to the central processor of the stabilization system, which in turn will be responsible for interacting with the telescope control system.

The control system executes 37 control loops simultaneously. There will be a control loop for each segment between the three positioners and the governing sensors for the segment's node box. This control loop will be enclosed within the node box, and it will therefore be particularly easy to achieve high sampling frequencies (~ 50–100 Hz). Above these 36 controllers the central computer will update the 108 positioners by using information from the 168 sensors. This loop can be executed at a much lower frequency (1–10 Hz).

A global loop is optimum from the control point of view, since it has access to all the positional information of the system; this, however, means more demands on the network. Local loops do not require network communications, but they are only effective for attenuating the high-sensitivity sensing modes of the primary mirror and they are very inefficient for low-sensitivity modes. The combination of both types of control loops has as its aim the control of low-sensitivity modes by using the global loop, and also of the high-sensitivity modes by means of the local loops. This design is also favoured by the fact that the dynamic performance of the primary mirror is dominated by the frequency of vibration of the segments on the axial support system, which is local to the segments. The way in which the interaction between the local loops could affect the dynamical stability and the efficiency of the control system is now being studied.

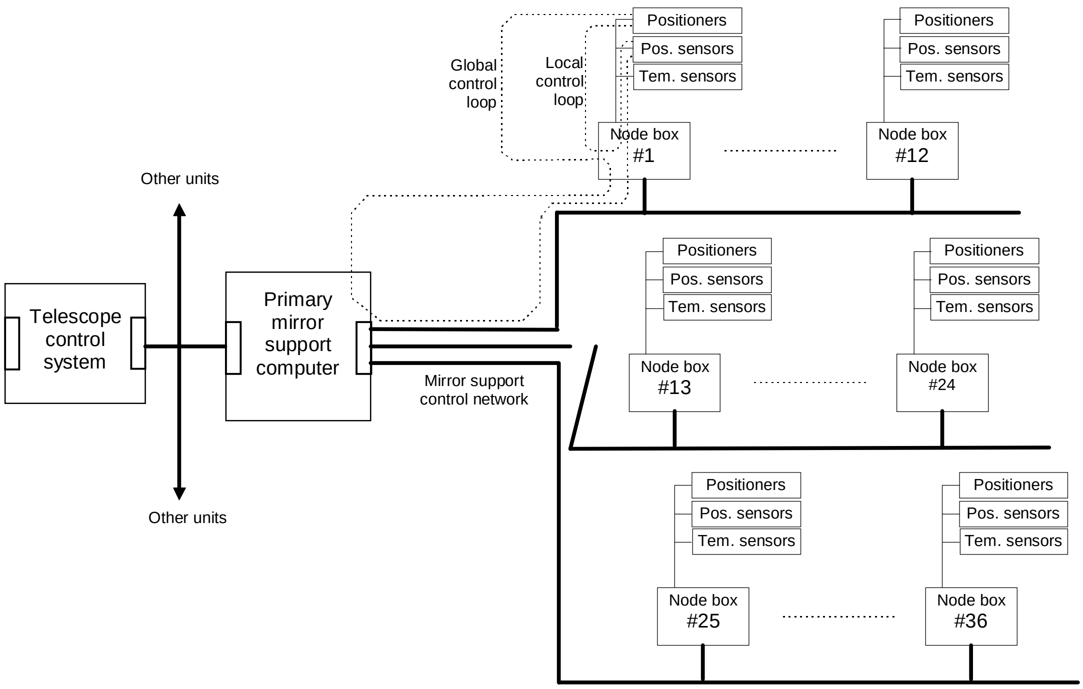


Figure 4.13: Control-system network showing the route of the global and local control loops.

4.7.4 Manufacture of the segments

The manufacture of the segments for a segmented primary mirror is a difficult task for three reasons:

1. All the segments are off-axis sections of a hyperboloid.

2. The off-axis position of each segment has to be specified with high precision.

3. The radius of curvature of all the segments has to be the same.

A starting point for the manufacture of the segments for the GTC is the technique of stressed mirror polishing developed for the manufacture of the Keck Telescope segments. The basic idea [4.25] consists in stressing the blank in such a manner that, when polished under stress as a sphere, it acquires the required off-axis hyperboloid figure when released from stress. The main restriction of this technique is that the process must be carried out on circular blanks, which are afterwards given their final hexagonal shapes by the removal of a substantial part of the excess material. In this process the segment undergoes a considerable deformation due to the liberation of internal stresses in the material. For this reason, stressed mirror polishing cannot be considered a sufficient polishing procedure by itself, but must form part of a process in which the errors arising from the cutting of the segments are corrected at a later stage.

The majority of large-optics polishers nowadays have computer-controlled polishing procedures that permit them to polish practically any required shape. In fact, it is possible to manufacture the segments directly in their hexagonal shapes and with their off-axis hyperboloidal figure by a more-or-less conventional process of numerically-controlled machining for generation of the required surface, to be followed by computer-controlled lapping and polishing.

The technique of ion-beam figuring can be considered as an extension of computer-controlled polishing. This technique is particularly attractive since the surface wear can be controlled with great precision without introducing unwanted high spatial frequency figuring errors and it does not have a different behaviour at the edges of the blank.

From the point of view of surface quality, the most attractive process is the use of stressed polishing followed by a correction of the surface through ion-beam figuring. Potentially, this process allows very smooth surfaces to be obtained with a low component of high spatial frequency errors, due, in the first place, to the smoothing effect of stressed polishing with an oversized tool and, secondly, to the fact already commented on that ion-beam figuring does not introduce high spatial frequency errors.

The time per unit area required for polishing a segment is generally independent of, or even slightly reduces with, increasing segment size. In the case of stressed polishing, in which the polishing is carried out with a full-size tool, the polishing time is practically independent of segment size. For computer-controlled polishing, however, the polishing time is basically proportional to the area to be polished, since the tool size tends to be limited by the degree of asphericity of the surface to be polished. In this respect, the primary-mirror focal length is influential because it can increase the asphericity of the primary mirror, although the effect is not significant within the range 16.5–18 m. The handling of the mirrors, an operation which contributes significantly to the cost of polishing, is less for a smaller number of segments.

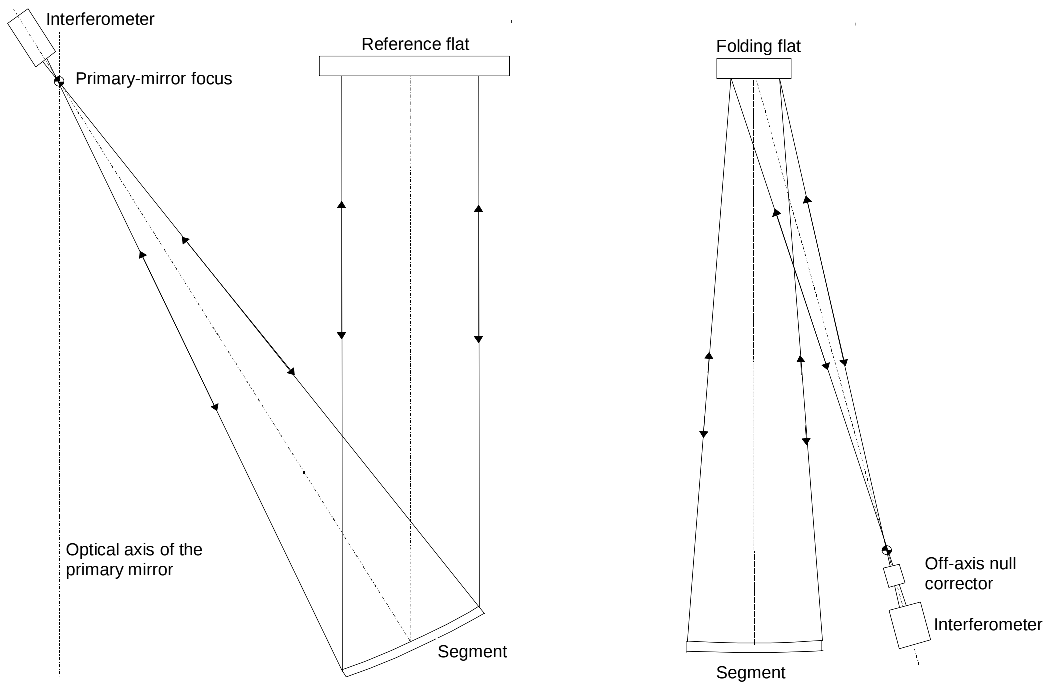
Therefore, it is considered that it will be cheaper to polish the necessary area of the primary mirror of the GTC if larger segments are used. However, as has already been noted in Section 4.7.1, with most large-mirror polishers crossing the 2.0-m threshold means a lack of availability of suitable installations for undertaking the polishing and could therefore imply an investment in infrastructure that involves substantial additional costs.

4.7.4.1 Testing of the segments

A fundamental aspect of the manufacture of the segments is their testing during the manufacturing process. In the case of a segmented mirror, the testing must measure with great precision both the off-axis position and the radius of curvature of the segment so as to guarantee that all the segments form part of the same surface.

The precision with which this measurement should be carried out is 0.25 mm for the off-axis position and 0.4 mm for the radius of curvature. The effect of these errors will be to introduce a FWHM image-quality degradation of 0.058 arcsec and 0.076 arcsec, respectively, however the active-optics correction of the segment figure will reduce this to an acceptable value.

Mirror segments will be tested interferometrically at focus with respect to a reference flat mirror, as shown in Figure 4.14(a). This test is null (i.e. there are no aberrations) for a paraboloidal mirror; the aberrations for a hyperboloidal primary mirror are sufficiently small to be measured in the interferometric test.



a) At focus. *b) At centre of curvature.*

Figure 4.14: Interferometric test of the segments.

Another possibility would be to test at the centre of curvature of the segment using an off-axis null corrector[17], see Figure 4.14(b). The advantage of this kind of test is that a plane reference mirror would not be necessary, or else its size would only need to be halved were it to be used simply for folding the beam. An additional advantage would be that the asphericity due to the off-axis position of the segment would be compensated by the null corrector, and therefore it would only be necessary to establish a correct centring of the segment against the beam of the interferometer, which is a much commoner task. A great disadvantage is the complexity in designing this type of off-axis null corrector.

[17] The null corrector would compensate the asphericity of the segment so that the interferometer would see it as a spherical surface.

4.8 Secondary mirror

The design of the secondary mirror of the GTC is constrained by the requirement that it must permit chopping. This imposes the need for as light a blank as possible for the mirror and the requirement that it be supported kinematically in order to have an easy interface with its necessary drives. Other projects have already successfully polished and tested convex hyperboloidal mirrors with diameters of around 1.2 m, so there are no doubts as to its feasibility.

The shape of the secondary mirror is shown in Figure 4.3(b). It will have a serrated outer edge, similar to the outer edge of the primary, and a maximum dimension of 1176 mm.

4.8.1 Secondary-mirror blank

The secondary mirror will have a stiff, light substrate which will be supported kinematically on three points to facilitate the interface with its drive system (see following subsection).

An important aspect for reducing the mass of the secondary mirror is the relaxation of its gravitational deformation requirements since this can be corrected by means of the primary mirror, within the active-optics scheme of the GTC. A deformation of 100 nm rms will be allowed, which will be of trefoil[18] type due to the three-point kinematic support chosen.

The initial choice is for a secondary mirror made of lightweight ULE™ or Zerodur™. Preliminary analyses indicate that such a mirror could weigh approximately 60 to 65 kg [4.26] by using a wall thickness of about 2 mm to lighten the core of the substrate and hence achieve a mass reduction of 85%.

An alternative would be to use materials of high stiffness, such as beryllium or silicon carbide in the manufacture of the secondary mirror. In this case, it could weigh 35–45 kg on the basis of designs carried out for projects such as Gemini [4.27] or the VLT [4.28] [4.29].

The ultralight beryllium or silicon carbide mirror alternatives would in all certainty suppose a substantial increase in the cost of the mirror substrate. This cost increase would be acceptable only were it to be compensated by a concomitant reduction in the cost of the drives. However, at present it is considered that the mass reduction achievable is not sufficiently high to justify the extra cost. In any case, it should be mentioned that the concept of a glass secondary mirror could be revised due to questions that still remain open, such as the fatigue performances of ULE™ and Zerodur™ or the continuous evolution of the market for materials such as silicon carbide, which could result in price reductions.

4.8.2 Secondary-mirror drives

As described in Section 4.5, the secondary mirror has two motion requirements. First, it must be able to move in five degrees of freedom so that, within the active-optics function, it maintains the alignment of the optical system independently of thermal and gravitational deformations of the telescope tube, the secondary mirror itself and its support mechanisms. Secondly, it must also be able to carry out chopping and image-motion correction.

For the active optics the velocity response requirement is low since the effects that are to be corrected vary slowly. The drives, however, must have great precision since the errors in the position of the secondary mirror affect both the pointing and the image quality of the telescope due to the coma introduced by the misalignment between the primary and the secondary. Hence,

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[18] This is a deformation of order 3 that responds to the expression $r\cos(3\theta)$ in polar co-ordinates.

the accuracy of positioning of the secondary mirror must be compatible with the pointing requirements of the telescope, and the precision and jitter of motion must be compatible with the guiding requirements. However, the coma effect introduced by the positioning errors of the secondary is much less than the image-motion error, thereby not limiting the precision or the jitter of the drives. Castro [4.30] gives the preliminary requirements for the active optics function of the secondary mirror.

For chopping , the secondary mirror must rotate in *Rx* and *Ry* so that the image moves in the focal plane. This chopping will consist in a sequence of positions (two or more) that is continuously repeated. As has been established in Section 2.4.10, the chopping function must permit:

- A range of ±1 arcmin (on the sky).
- Repeatability of 0.03 arcsec rms. (on the sky).
- A precision of 0.01 arcsec rms. (simultaneously in *Rx* and *Ry*).
- The settling times between chopping positions are 10 ms for throws of 15 arcsec (on the sky) and 40 ms for throws of 2 arcmin (on the sky).

As described in Section 4.6.1, for observations at wavelengths greater than 4.8 μm, diffraction-limited images will be obtained with image-motion correction. The requirements for this function are covered by those for chopping, since motions of the order of 1.5 arcsec (on the sky) with settling times of the order of 100 ms are required. The precision requirement are similar for both functions.

The correction of defocusing introduced by atmospheric seeing would allow only a modest improvement in SR. Therefore, the secondary mirror will not in principle be required to carry out fast focus correction. This will be included only if it does not complicate the design of the drives needed for chopping.

There will also be a system to compensate the inertial forces induced when moving the secondary mirror during chopping or image-motion correction. This is required to avoid introducing unacceptable perturbations in the secondary mirror socket.

4.9 Tertiary mirror

The tertiary mirror, shown in Figure 4.3(c), of the GTC is important for two reasons: its use for changes between foci and its influence in the alignment of the optical system at the Nasmyth and folded-Cassegrain foci.

To attain high operational efficiency the tertiary mirror will have to allow the changeover in observations between the Cassegrain, Nasmyth and folded Cassegrain foci in under 5 minutes. The mirror mount will have a rotation drive to direct the beam to the Nasmyth or folded-Cassegrain focus. Additionally, the tertiary mirror will be removable to allow the beam to pass to the Cassegrain focus. A drive that moves the tertiary mirror from its nominal position to a parking position above the primary mirror seems to be the most feasible solution. This has the drawback that the central obsuration of the optical system must be slightly increased to 5.6% of the effective area in order to provide sufficient space for accommodating the mirror. The possibility of completely removing the mirror from the telescope and the feasibility of carrying out this operation automatically in 5 minutes will also be studied. In this case the central obscuration could be reduced to 4% of the pupil area.

Currently it is estimated that the tertiary mirror will not need drives to allow its position to be actively corrected for aligning the optical system at the Nasmyth and folded Cassegrain foci. Although the motions of this mirror produces a deviation of the optical beam that must be corrected in order not to disturb the alignment of the instruments with the telescope, this deviation can be corrected by moving the secondary mirror.

4.10 Coating and cleaning of the mirrors

The baseline of the mirror coating and cleaning programme has been developed to meet the following science requirements (see Chapter 2):

1. High efficiency in the spectral range 0.3–15 μm. It should be possible to change quickly between observing with the main instruments.

2. The telescope emissivity with freshly coated mirrors should be below 5% at the Cassegrain focus (with 3% as target value) beyond 2.1 μm. Of this total of 5%, the coating of the primary mirror is budgeted to contribute 2% and the coating of the secondary mirror 1.3%.

3. The maximum allowable degradation of the emissivity is 3% with respect to the emissivity of recently coated mirrors.

A priority for the GTC coating and cleaning programme will be to find the most economical solution without compromising the above requirements.

The segmentation of the primary mirror gives special characteristics to the re-coating and cleaning operations. First, when a segment is removed from its position in the primary mirror for re-coating, an identical segment will be installed in its place, for which reason 100% of the primary-mirror surface will be available 100% of the time. Secondly, the processes of in situ cleaning are particularly important owing to the fact that it will never be possible to have 100% of the mirror surface recently re-coated.

According to investigations and experience at other telescopes [4.31] [4.32] a reasonable frequency for in situ cleaning is about one cleaning process per month. This allows a period of up to two years between re-coatings of the primary mirror. For a mirror consisting of 42 segments (including the 6 spares), this means an average of one of the segments re-coated every two or three weeks. These rates have to be verified for the environmental conditions at the ORM.

4.10.1 Mirror coatings

The properties of gold, silver and aluminium have been compared as possible coatings for the three telescope mirrors [4.33]. Gold coating cannot be used for any of the three mirrors because its low reflectivity in the visible would not allow the permanent availability of the total wavelength range of the telescope. The specified maximum emissivity of the primary and secondary mirrors necessitates a silver-coated secondary mirror and an aluminium- or silver-coated primary mirror. For reasons of economy, the Day 1 configuration will be an aluminium-coated primary and tertiary mirror and a silver-coated secondary mirror. As the emissivity of a freshly coated aluminium mirror is very close to the maximum allowable emissivity of the primary mirror, the possibility of depositing silver instead of aluminium coatings on the primary-mirror segments in order to lengthen the periods between renewal of the coating will be considered.

As silver coatings degrade quite badly over time, it is necessary to apply a protective overcoating. The detailed design of the silver coating has not yet been undertaken but will be part of the coating-chamber design subcontract. Besides the low emissivity (see point 2 in Section 4.10), an important aspect of the silver coating design is to push the UV reflectivity, in particular at wavelengths between 300 and 340 nm so that the requirement in point 1 of Section 4.10 will not be compromised.

The surface area of the mirror segments and the kinds of materials that will be deposited will allow the use of physical vapour deposition (PVD) using electron guns, as well as sputter deposition of the mirror coatings. PVD techniques in general give higher deposition rates and thus cleaner coatings with lower emissivity, but it is more difficult to achieve good uniformity over large surfaces. A sputter deposition chamber will be of smaller dimensions than an electron gun evaporation system and will thus have lower manufacture and maintenance costs. The final coating technique will be decided at a future design stage.

4.10.2 Mirror cleaning

Mirror cleaning refers to two different actions: stripping off the old coating before re-coating the mirror and cleaning the mirror surface while it is still mounted on the telescope (in situ cleaning).

Stripping off of the old coatings will be done by means of standard procedures of wet chemical etching immediately before coating the mirror.

Possible in situ cleaning methods are CO_2 snow cleaning, EXCIMER laser cleaning and peeling. As a standard technique, CO_2 cleaning will be used on the GTC mirrors because it is fast and easy to apply. The initial results of work carried out by the IAC at the Teide Observatory confirm the cleaning re-coating frequencies mentioned in Section 4.10 [4.34].

The technical equipment consists of CO_2 tanks, hoses and the outlet nozzle. With the telescope pointed horizontally a technician with the cleaning equipment can move along the face of the mirror on a lift platform. Peeling will be applied if necessary to complement CO_2 cleaning locally. Also, depending on how frequently mirror cleaning will be necessary, the future installation of a laser cleaning system will be considered for reasons of economy.

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5. TELESCOPE MECHANICS

5.1 Introduction

What is meant here by telescope mechanics is that part of the system formed by the structure of the telescope itself, the main subsystems of bearings, drives and encoders of the azimuth and elevation axes, the instrument rotators and cables wraps; the auxiliary subsystems, such as the primary mirror cover, counterweights, and safety subsystems locking pins, brakes, end stops, access equipment, etc.

The main task of the telescope mechanics will be to support the optical system and the scientific instrumentation, and, in conjunction with other systems of the GTC, to maintain their alignment, as well as the pointing and tracking of any astronomical object, with extreme precision and accuracy**.** These tasks will have to be carried out in a hostile environment, in which the telescope will be subject to variable wind and thermal disturbances.

In this chapter, the conceptual design of the telescope mechanics is presented, the main options evaluated and the final choices described. The telescope structure and the results of the analyses that have been performed are discussed, together with the main and auxiliary subsystems.

5.2 Design guidelines

The mechanical design of the telescope is primarily driven by the requirements of image quality and the established optical configuration. Since the primary mirror and the alignment between the primary and secondary will be controlled actively, the requirements on the telescope structure to maintain primary–secondary mirror alignment under the influence of gravity could be relaxed. The dynamic performance of the telescope structure will be fundamental in order not to limit the response of the drive system in terms of the pointing and tracking requirements. Also, the dynamic performance of the telescope structure will govern the response of the telescope to wind perturbations.

The basic design guidelines of the telescope mechanics, derived directly or indirectly from the established requirements of the GTC (Chapter 2), are as follows:

- The telescope will have a Ritchey-Chrétien optical configuration, with a segmented primary mirror of 16500 mm focal length, an entrance pupil area equivalent to a circular aperture of 10 m diameter, the aperture stop at the secondary mirror, and a total effective focal length of 170000 mm. The optical configuration will be parfocal; in other words, the Cassegrain and Nasmyth foci will have the same optical path from the secondary mirror.

- The telescope will have a Cassegrain, two Nasmyth and four folded-Cassegrain foci. Changes between the Cassegrain and the Nasmyth or folded-Cassegrain foci will take 5 minutes, which means that the tertiary mirror should be removable within the same time limit, or, if possible, dismountable. The design should also anticipate the possible implementation of a prime and a coudé focus.

- The telescope must be as compact as possible, so as to minimize dimensions and the cost of the dome. The telescope will therefore have a conventional alt-azimuth mount, not only for its compactness, but also for its structural simplicity and performance.

- The stiffness of the telescope structure must be maximized, but not if this leads to excessive weight. Misalignments due to gravitational deflections or non-elastic behaviour of the telescope structure must not cause any optical misalignments that could not be compensated by the active-optics control system.

- The lowest eigenfrequency of the telescope structure must be sufficiently high so as not to limit the response of the drive system in terms of the pointing and tracking requirements, and to minimize wind-induced perturbations. The telescope structure must absorb the residual inertial forces generated by the chopping of the secondary mirror or for the operation of an adaptive secondary mirror.

- The telescope structure must allow a smooth flow of air around and through the elements, especially those located above the primary mirror, and create minimum disturbance of the air flow in this area. This would also permit a reduction of temperature gradients between the different structural elements. Thermal gradients in the telescope structure must not cause any significant optical misalignments that could not be compensated by the active-optics control system.

- The telescope structure will have low thermal inertia to reduce temperature differences between the telescope structure and the surrounding air so as not to induce thermal turbulence that would degrade the seeing and consequently the image quality.

- The telescope structure must have low sensitivity to wind buffeting in order to minimize induced image motion. For this purpose it will be necessary to use structural elements that offer low cross-sections to the air flow. However, a compromise must be reached with the thermal inertia requirements.

- The telescope will have a low and stable emissivity for optimum performance in the infrared.

- The telescope design must not preclude the operation of adaptive optics and must accommodate the installation of an artificial star system with a laser launch telescope.

- The mass of the telescope structure must be minimized in order to reduce costs and thermal inertia.

- The telescope mechanics must allow movement in the three degrees of freedom (azimuth, elevation and field rotation) with high precision and accuracy.

- The GTC is not required to operate in the presence of seismic activity; nevertheless, the telescope will need to withstand any foreseeable seismic activity at the ORM during its working life without any significant damage being occasioned to its parts.

- Finally, the feasibility of manufacture and integration, as well as logistic support (Section 9.2.5.7) must be considered in the design of the telescope mechanics.

5.3 General description of telescope mechanics

The telescope will have a conventional alt-azimuth mount, with the elevation axis above the primary mirror. The Cassegrain and Nasmyth foci will be located at a distance of 7.40 m from the intersection of the elevation and azimuth axes, mainly because of the parfocal configuration adopted and the dimensions of the primary mirror. This will allow a reasonable positioning of the foci, and of the bearing, drive and encoder elevation axis subsystems, as well as contributing to the self-balancing of the telescope tube. The structure will be about 27 m high, 27.8 m between the extremes of the Nasmyth platforms and 13 m wide (see Figure 5.2 and Figure 5.3). This will give the telescope structure a sufficient degree of compactness, the radius of the dome being determined almost equally by the mount as by the tube.

The structure developed [5.1] is based, both for the tube and the mount, on an open structural design, formed by a space frame, in a similar manner to that proposed by Medwadowski for the Keck Telescope [5.2] [5.3]. Compared with more traditional designs based on structures formed by welded metal plates, this type of structure is the one which best meets the requirements of least weight, least thermal inertia, best ventilation and least wind resistance, and which maximizes stiffness and dynamic performance. However, the welded metal-plate option has been chosen for the elevation ring because it basically transfers loads in bending and in torsion, whereas the rest of the telescope structure transfers in compression and tension only.

Space frames can achieve greater structural efficiency if the trusses are already axially stressed or compressed. This yields very high local specific stiffness at the nodes of the structure which then becomes more suitable for receiving point rather than distributed loads. The structure has been designed to achieve the required stiffness as structural stresses will be moderate.

The telescope structure will be supported on a pier by a single girth ring which forms part of the azimuth bearings (see Section 5.5.2). Hydrostatic bearings and optical-tape encoders for both the azimuth and elevation axes have been chosen.

Friction and direct drives are two possible options being considered for the drive subsystem. The friction drive option is more compatible with the structure designed. If a direct-drive system were adopted, the impact on the telescope-mount typology could be significant because this type of drive generates distributed loads. In this case, the structure design would need to be modified to adapt itself to the way in which the load were transferred. A space-frame structure could still be used, but based on a different typology. For example, a double azimuth girth ring could be employed, or even a hybrid structural design with structures made of welded metal plates to give support to the elevation and azimuth drives, with a space frame to connect both.

The coordinate system for the telescope structure is the same as that indicated in Chapter 4 (Figure 4.1). Note that the *x*-axis is coincident with the elevation axis.

The following scaled schematic diagrams show the layout of the necessary ports for the optical beams and instrumentation, as well as the main dimensions of the telescope structure (Figure 5.1, Figure 5.2 and Figure 5.3).

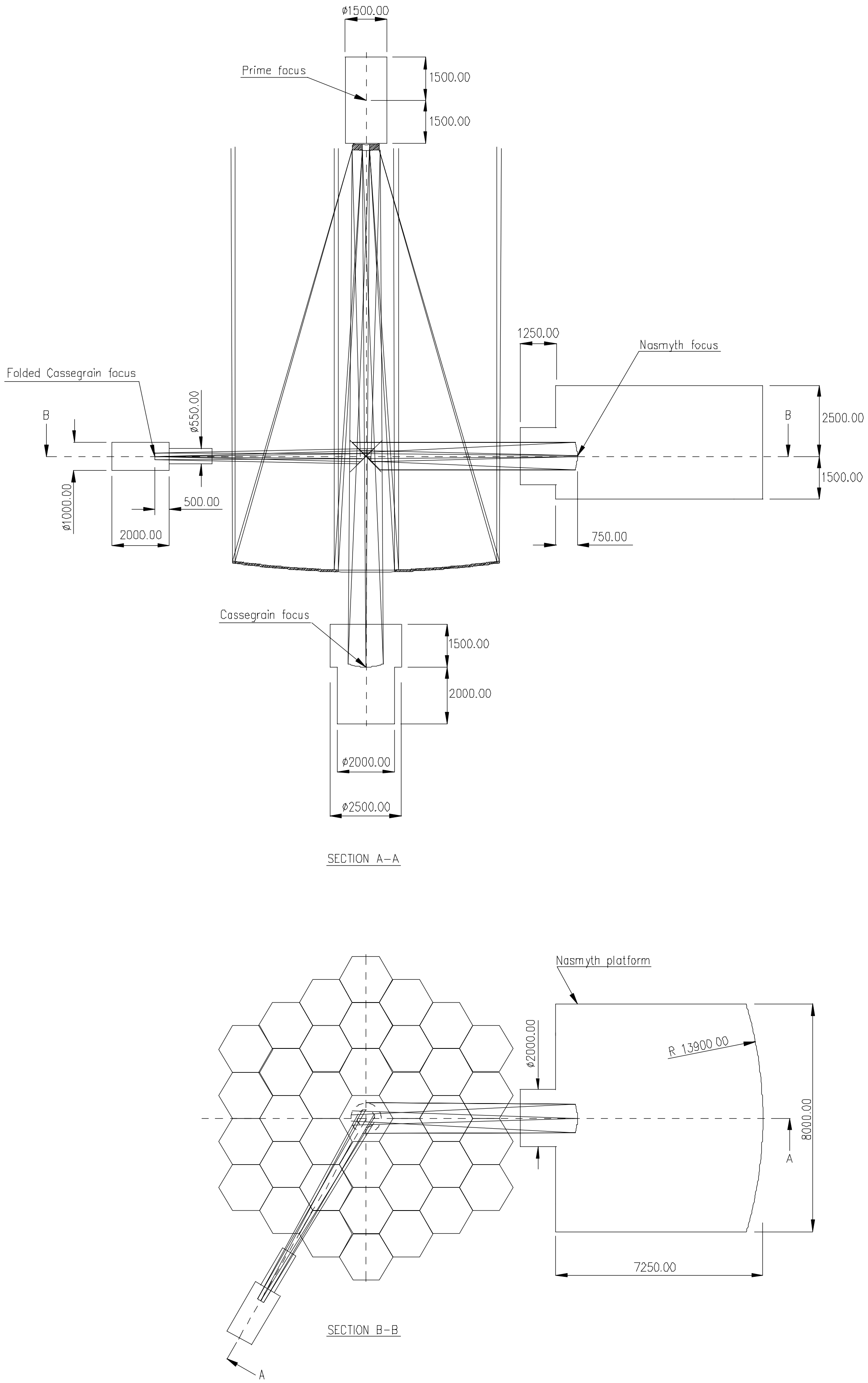

Figure 5.1: Layout of GTC ray path and foci (dimensions are in mm).

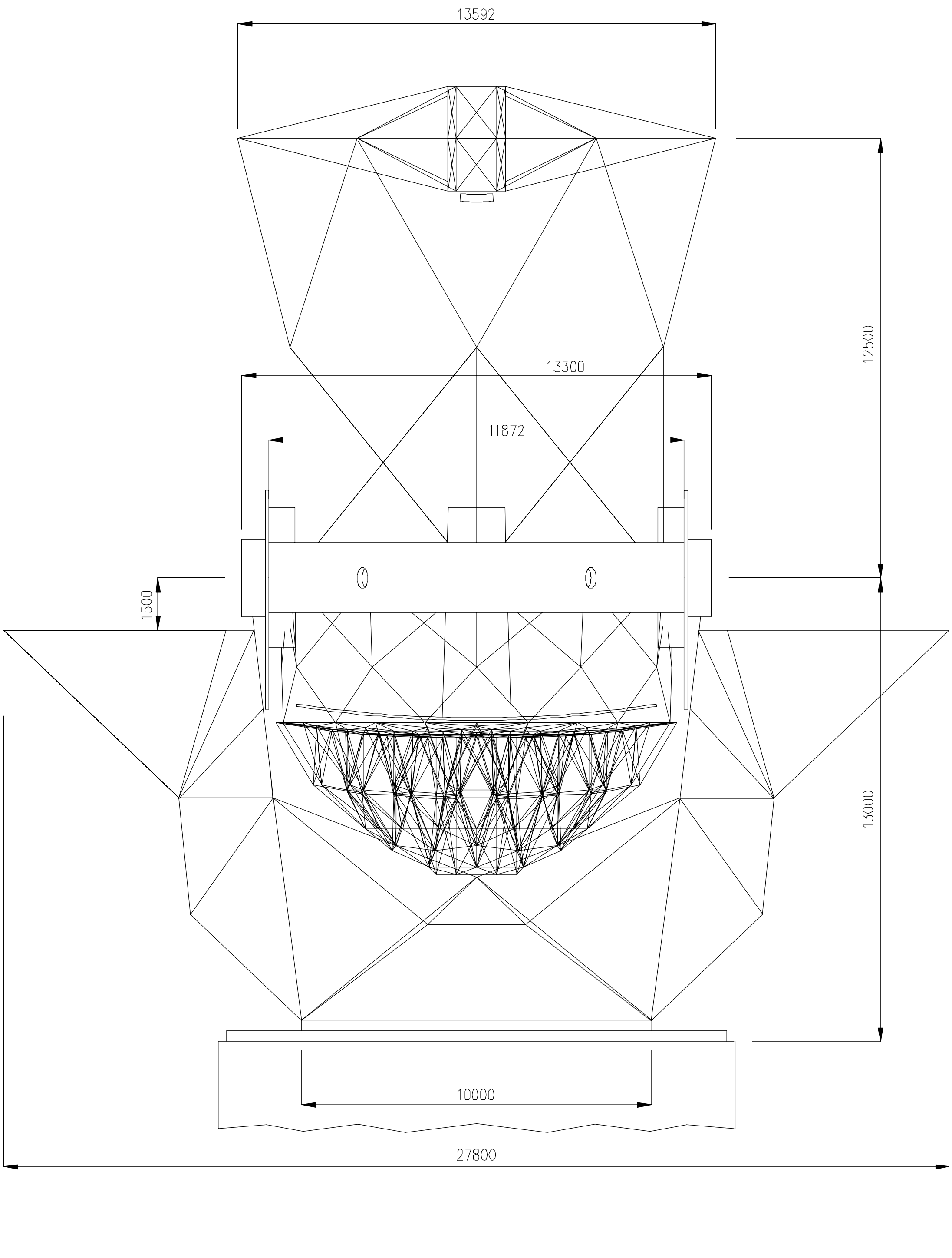

Figure 5.2: Frontal (x-z) view of telescope structure (dimensions are in mm).

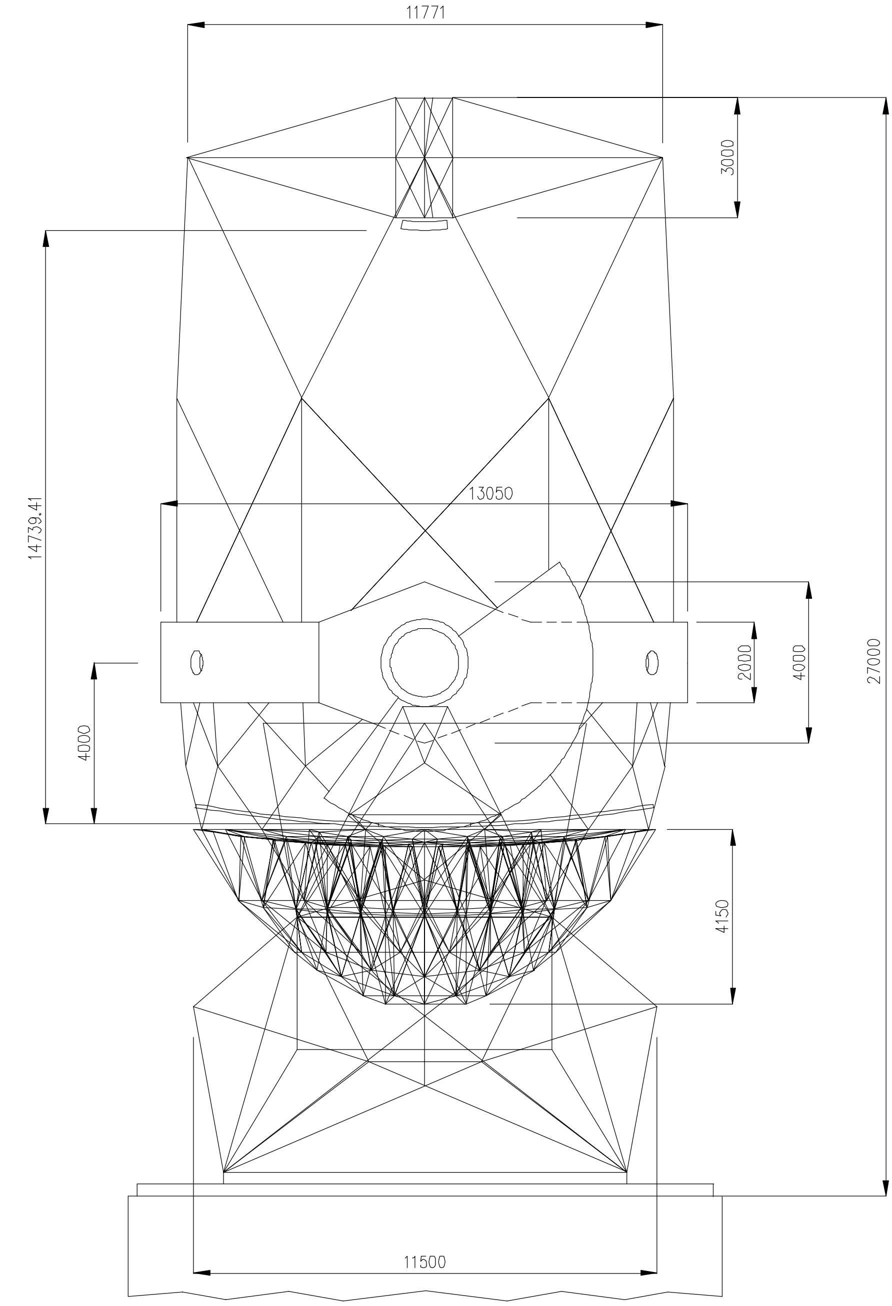

Figure 5.3: Lateral (y-z) view of telescope structure (dimensions are in mm).

5.4 Telescope structure

The telescope structure can be subdivided into two main elements, the tube and the mount. These in turn can be further divided into various subsystems. The chosen design is based on an optimization of the various subsystems, and of the complete structure, using finite-element analysis. The structural subsystems of the telescope are shown in Figure 5.4.

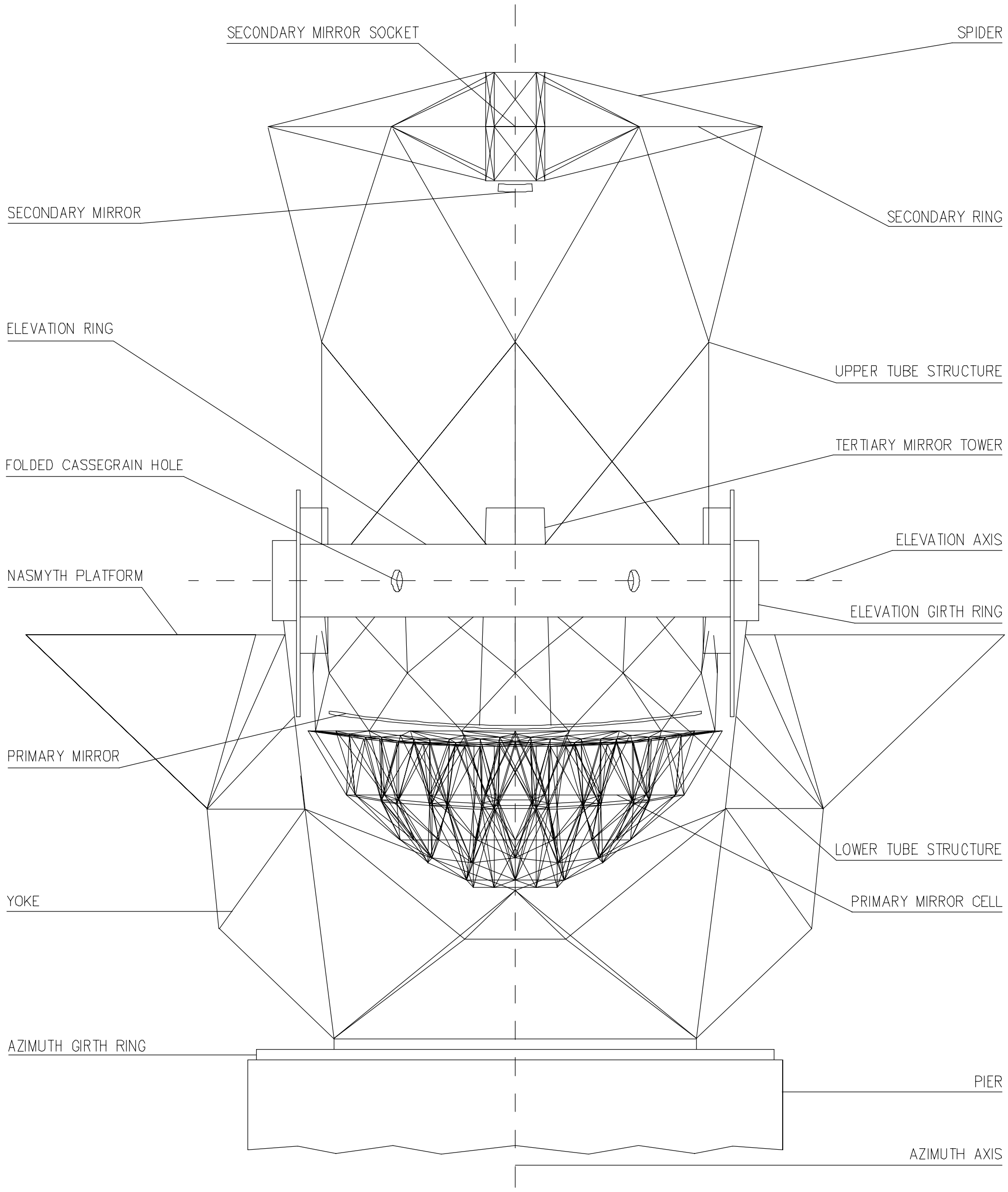

Figure 5.4: Subsystems of the telescope.

5.4.1 Telescope tube

The telescope tube is responsible for supporting the primary, secondary and tertiary mirrors, as well as the instrumentation at the Cassegrain and folded-Cassegrain foci, and for maintaining the optical alignment within the range correctable by the active optics. This subsystem can be further divided into the following main structural parts:

- Primary-mirror cell.
- Lower tube structure.
- Elevation ring.

- Upper tube structure.
- Top end ring.

Traditionally, each of these parts has always fulfilled quasi-independent structural functions, which meant each being designed and analysed separately. In this way, the elevation ring was designed as a rigid part that made up the elevation axis, and from which the primary mirror and Cassegrain instrumentation, the secondary mirror and the tertiary tower were supported almost independently.

This design policy was supported by the fact that the lower tube structure that connected the elevation ring to the primary-mirror cell had to provide a simple interface that allowed the dismounting of the cell for the handling of the primary mirror during the process of re-coating. However, with a segmented primary mirror this restriction does not exist, since the cell no longer needs to be dismounted in order to handle the segments, which can be passed through the upper tube structure. This consideration has permitted a design of the lower tube structure that gives a better and greater structural connection between the cell and the elevation ring. In this way, the elevation ring will help in providing stiffness for the cell perimeter, and the cell will help to stiffen the elevation ring.

5.4.1.1 Primary-mirror cell

The primary-mirror cell will be one of the most important and complex structural subsystems since it will have to support each of the segments that form the primary mirror, together with their active and passive support systems (Section 4.7.3). At the same time it will allow the optical system to maintain the alignment and phase of each segment. The lower part of the cell will support the Cassegrain focus and maintain its alignment with the primary mirror. Additionally, the tertiary mirror module[19] and its tower will be supported by the upper part of the cell to reduce the number of structural elements in the optical path and hence minimize the emissivity. The tertiary mirror tower will support the optical baffles of the primary mirror and could also serve as the central support for the primary-mirror cover. The cross-section perpendicular to the optical axis will be hexagonal and slightly smaller than the primary-mirror hole.

Besides its own weight, the cell will have to bear that of the following elements:

- The primary mirror (16560 kg).
- The primary mirror active and passive support system (5100 kg).
- The Cassegrain focal assembly (6000 kg).
- The tertiary mirror module (750 kg).

A space frame with a dome-shaped typology has been adopted to improve the structural behaviour and provide a better connection with the elevation ring. This allows a circular edge and symmetry with respect to the axis of the telescope tube, thereby securing a high stiffness and high accessibility to the mechanisms housed therein. It will be necessary to provide access to the back of the primary-mirror segments for the operations of installation and maintenance of their support system, as well as for the removal of segments.

The cell will be formed by three layers:

[19] The tertiary mirror module will be formed by the mirror itself and its associated mechanisms.

1. The top layer, which will support the primary mirror and its support system will have three interface nodes for each hexagonal segment of the primary corresponding to the three positioners for each segment. This layer generally matches the curvature of the mirror itself in such a way that, for a given segment, the three positioners are parallel to the normal to the segment at its centre.
2. The middle layer, which will have its nodes distributed in a hexagonal grid corresponding to a projection of the segments on a plane, thereby facilitating access to the mechanisms associated with the support system of the primary mirror.
3. The dome-shaped bottom layer, which allows access to the Cassegrain focus, a significant part of which will be within the primary-mirror cell structure.

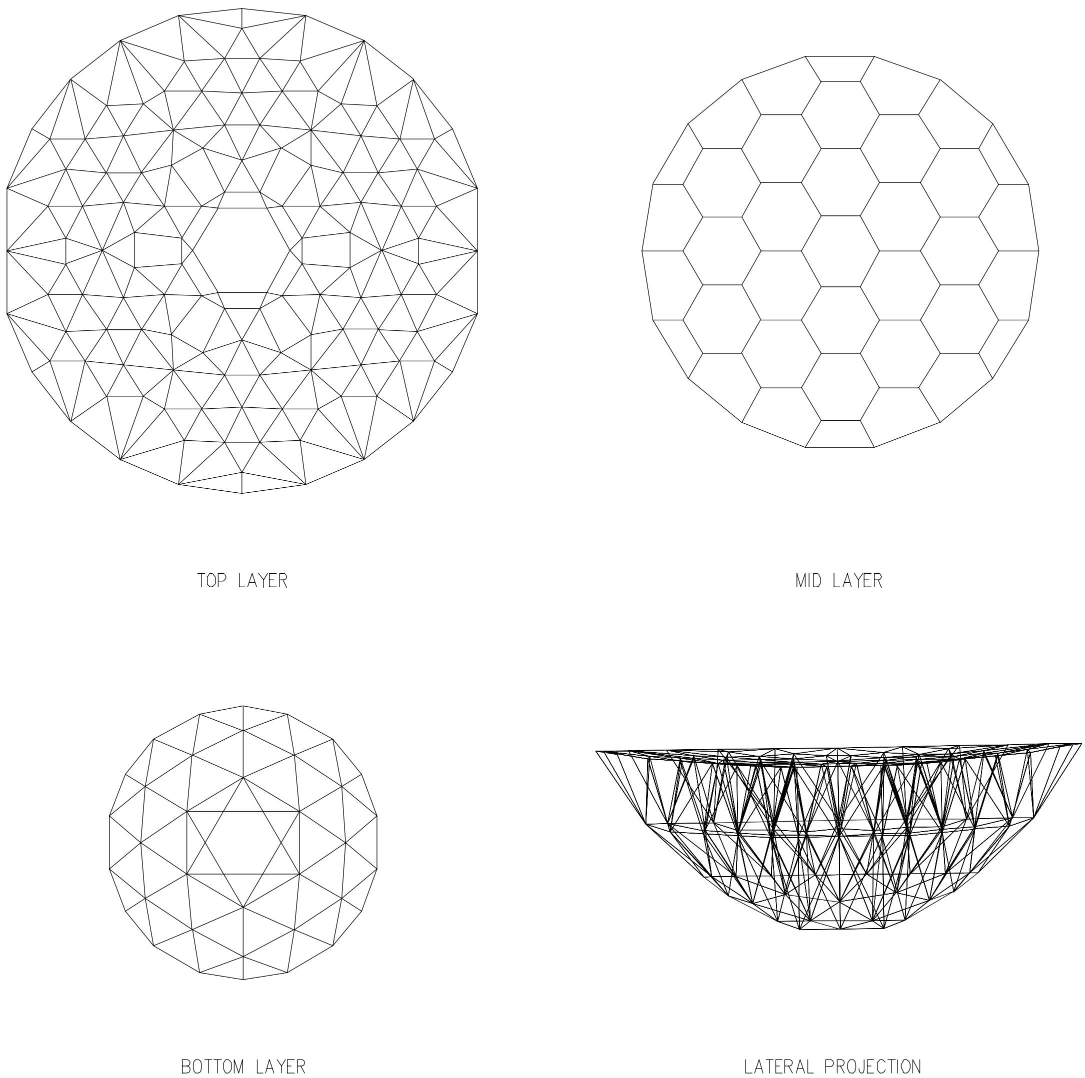

Figure 5.5: Primary-mirror cell structure.

The central nodes of these three layers serve as anchorage for the tertiary mirror tower and the interface with the Cassegrain focus. These two elements are not yet incorporated into the structural design.

In the distribution of diagonal trusses, the minimum number necessary for ensuring the stability of the structure has been used, while avoiding triangular zones of large deformity. At the same time, their number has been kept to within a certain limit with the aim of minimizing weight and allowing clear access.

The cell will have an external maximum diameter of 11.46 m and a total height of 4.15 m. The middle layer will be at a distance of 1.70 m from the top edge. Figure 5.5 shows a sketch of the primary-mirror cell structure.

5.4.1.2 Lower tube structure

The lower tube structure will connect and transmit the loads of the primary-mirror cell to the elevation ring. The selection of a circular configuration in the cell, together with the quasi-circular configuration of the elevation ring, allows an increase in the number of connecting trusses between both. This will provide a balanced, rigid and light transition based on three levels of nodes distributed in dodecagons. The transition from the first level, linked to the elevation ring, to the intermediate level, will be of a conical shape which describes a regular dodecagon. The third-level nodes, connected to the upper layer of the cell, will be rotated 15° with respect to the level above.

5.4.1.3 Elevation ring

The elevation ring will support and transfer the loads from the telescope tube to the yoke, through bearing and drive subsystems of the elevation axis. It will also support the elevation girth rings of the hydrostatic bearings and part of the drive system in the elevation axis of the telescope and support the instrumentation located at the folded Cassegrain foci.

The design of the elevation ring is driven by the local stiffness requirement, especially near the elevation axis where the shear stress is the highest. For this purpose, a traditional typology based on a welded metal plate hollow beam has been adopted. Although the primary-mirror geometry also suggests a hexagonal typology, the criterion for optimization of the stiffness-to-weight ratio has led to the proposal of a quasi-circular typology, thereby obtaining a greater stiffness compared to a hexagonal shape. Near the elevation axis the cross-section will be variable in height, due to the large holes which are necessary for the Nasmyth foci.

This typology will allow the primary-mirror cell to be held in place by means of the lower tube structure with a greater number of nodes, which will reflect favourably on the overall performance of both the elevation ring and the cell itself.

5.4.1.4 Upper tube structure

The upper tube structure will support and transfer loads from the top end ring and from the secondary-mirror module[20] (or, where applicable, from the prime focus instrumentation), to the elevation ring.

There are two features that affect the design of the upper tube structure. First, the hexagonal shape of the segmented primary mirror suggests that the upper tube structure typology should also be hexagonal. Secondly, since the primary mirror and the alignment between the primary and

[20] The secondary-mirror module will be formed by the mirror itself and its associated mechanisms, as well as by the baffling of this mirror for the visible configuration.

secondary will be controlled actively, it is not necessary to adhere strictly to traditional Serrurier geometry[21].

The stiffness of a variety of upper tube structure designs was examined, and a similar design to that proposed by Lubliner for the Keck [5.4] was finally adopted, since this offered the greatest stiffness of all the types studied. The upper tube structure will be based on tubular elements distributed in three levels of nodes. The first level is connected to the elevation ring and, together with the intermediate level, arranged in a plane equidistant to the elevation ring top surface and the secondary ring, to form two parallel hexagons circumscribing the hexagonal shape defined by the primary mirror. The third level will be rotated by 30° with respect to the primary mirror. Its nodes will connect the secondary ring, whose geometry will also be hexagonal.

5.4.1.5 Top end ring

The top end ring will support the secondary mirror module (or, in place of this, the prime-focus instrumentation), thereby transferring the loads to the elevation ring through the upper tube. It will be divided into the following elements:

- The secondary ring, which will be a hexagonal element connected to the top nodes of the upper tube structure, and which will be located near the centre of mass of the secondary-mirror module.
- The spider, which will be the set of six pairs of flat bars supporting the socket of the secondary-mirror module (or the prime focus instrumentation) from the secondary ring.
- The secondary-mirror socket, which could be a circular or polygonal lattice tower. Due to the different dimensional requirements, the secondary-mirror socket will support the secondary-mirror module by means of an auxiliary spider, whereas the prime-focus instrumentation will be directly supported. The mass of both the secondary-mirror module and the prime-focus instrumentation has been estimated at 2000 kg each.

The secondary ring supporting the spider must circumscribe the primary mirror. In order to minimize the light blockage it is desirable for the spider to have a very narrow cross-section and to be perpendicular to the sides of the segmented primary mirror so as to be aligned with the gaps between the primary-mirror segments. Therefore, the hexagon that forms the secondary ring will be rotated and be larger than those that form the upper structure. This will result in better structural performance by transmitting forces only axially (tension or compression) through the nodes that connect the spider to the secondary ring.

In order to meet performance requirements in the IR, the telescope will need a low and stable emissivity and a high-precision chopping secondary mirror (Section 4.8.2). The latter imposes severe dynamic demands on the telescope structure. The spider will be pre-tensioned and arranged non-radially to improve the stiffness and dynamic performance, above all in terms of torsional response. Although this non-radial spider configuration is not optimal for the emissivity, due to the greater resulting light blockage, a compromise must nevertheless be reached with the dynamic requirements. The shadow generated by the spider on the primary mirror will be limited to 0.5% of the primary-mirror surface, which will be stable over 7 arcmin (see Section 2.4.8) during chopping. Also, the non-radial configuration of the spider arms will have a pronounced effect on

[21] In the Serrurier system both the upper and lower tube structures consist of four isosceles triangles on a square base, with the special property that at any orientation the static flexure due to the gravity is such that the primary and secondary mirrors undergo parallel translation without rotation, so maintaining proper alignment of the optical system.

the secondary-mirror socket if it is to guarantee the necessary dynamic response. Wind loads, together with residual actions of the secondary module or of the prime-focus instrumentation, will determine the design of the spider.

5.4.2 Telescope mount

The telescope mount is the subsystem that, jointly with the azimuth and elevation bearings and drives, will provide the telescope's two axes of rotation. It will transmit the loads of the telescope tube to the pier on which it is supported. Furthermore, the telescope mount will support the Nasmyth platforms.

The axial and radial bearings which define the azimuth axis, will allow the rotation of the mount relative to the telescope pier. The girth ring of the bearings will act as an interface between the pier and the mount.

The mount structure connects the elevation-bearing supports to the azimuth-bearing supports and rests on the azimuth girth ring fixed to the pier. The mount structure can be divided into two main elements: the yoke and the Nasmyth platforms.

5.4.2.1 Yoke

The yoke will be the main structural unit of the mount. It will support both the telescope tube (through the elevation rings) and the Nasmyth platforms, and transfer the loads to the pier through the azimuth bearing and drives.

For monolithic mirrors the need to dismount the primary-mirror cell is an important factor in the design of the mount, in particular a large space is required between the tube and the mount. However, with a segmented mirror this restriction no longer applies. This gives greater freedom in design of the mount, particularly if it is based on space frames. Figure 5.6 shows the mount structure.

This subsystem is based on an inverted braced framed structure. This structure is formed by two supporting arms connected by a horizontal lintel. The arms will receive and transfer the loads through their lower nodes to the azimuth girth ring attached to the pier. These nodes form the corners of a lower horizontal square base, which is inscribed within the azimuth girth ring. The lintel will be formed mainly by the square base and a raised central bracing square.

The guidelines for the geometry of the structure have concentrated on respecting the space requirements for the surrounds of the structural subsystems of the tube and minimizing the height of the mount. Moreover, an effort has been made to reduce the size of the square base, and consequently of the azimuth girth ring, the pier and hence the cost of both.

5.4.2.2 Nasmyth platforms

The Nasmyth platforms will be directly supported by the arms of the yoke and will provide the base structure for the Nasmyth instrumentation, A&G systems, instrument rotators, etc. Each platform will measure $8 \times 7.25\ m^2$ and have a load capacity of 10000 kg.

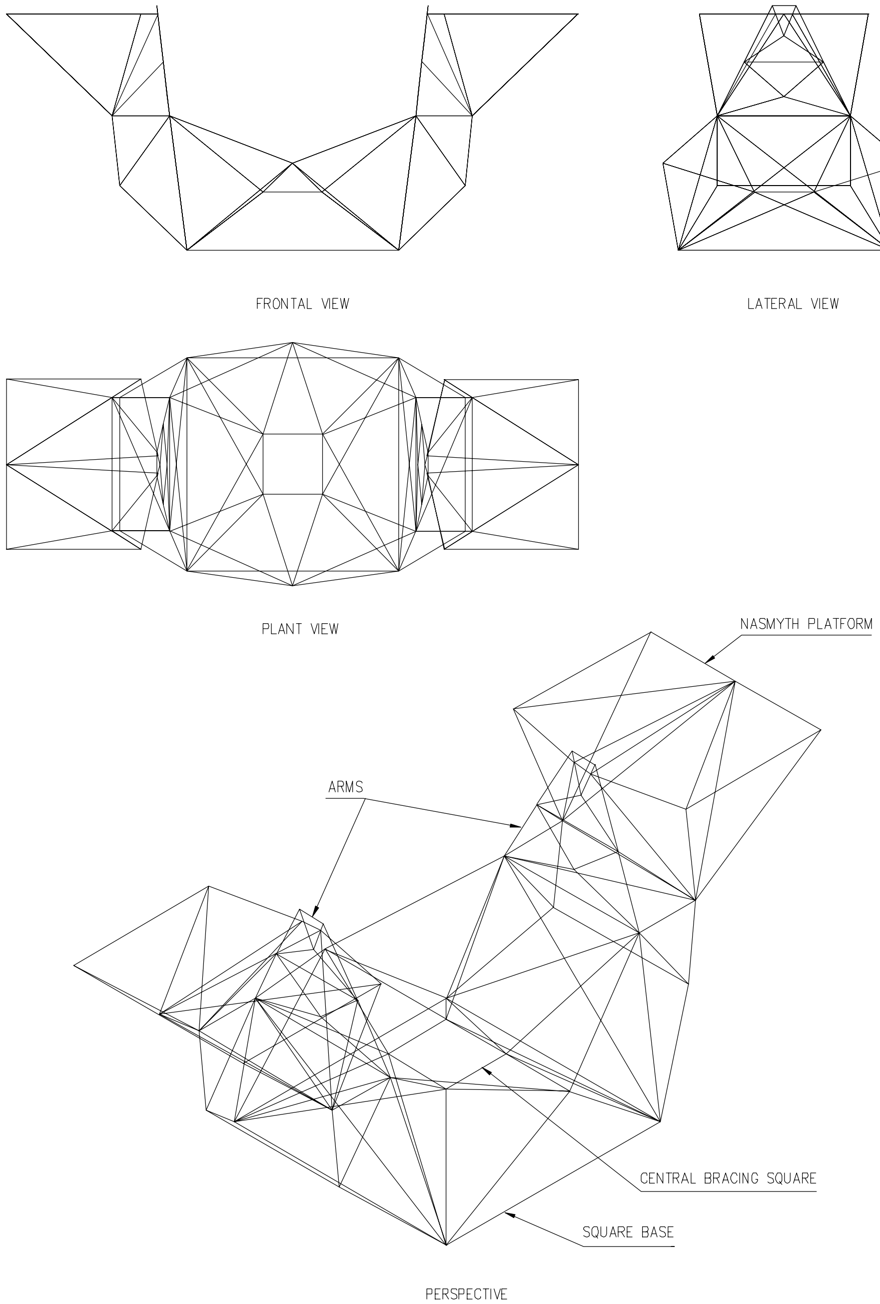

Figure 5.6: Mount structure.

5.4.3 Static and dynamic response of the telescope structure

The very large telescope projects of today require higher performance than those of previous generations of telescopes, this requirement being driven mainly by the need for higher image quality. For the telescope structure this translates into the eigenfrequencies which measure the dynamic and, indirectly, the static performance. The eigenfrequencies, which are approximately proportional to the square root of the deflections under gravity, are related to the static performance of the structure. It is therefore a measure of telescope sag and hence of the alignment of the optics with changing elevation. Furthermore, it is the most important mechanical input into servo analysis and so affects the tracking. Another important aspect is that present-day telescopes are being designed to operate in compact, well ventilated enclosures, which result in greater exposure of the telescope to wind. So the structural performance of the system must be improved, which is no trivial task.

The significance of the dynamic performance of the telescope structure and its associated lowest eigenfrequencies has been widely discussed elsewhere [5.5] [5.6] [5.7] [5.8]. There are several reasons why a stiff structure with higher eigenfrequencies will give superior performance:

- Excitation of the structure by wind loading will be reduced.

  The dynamic performance of the telescope has a significant effect on the ability of the telescope to reject wind-induced image motion. The most significant sources that can produce image motion due to the wind loading are structural deformations and control servo errors. The wind spectral energy for high mountain sites is significant at 1 Hz, at which point the spectral power falls with increasing frequency. Above 5 Hz it is believed that there is insufficient energy to excite the telescope structure. There are three issues here:

  1. At low frequencies, where the wind spectral power is high and most likely to excite the structure, the telescope control system will respond to load perturbations, but there will be a servo error which results in a tracking error. The effect of the locked-rotor frequency[22] on servo errors has been studied by Ulich [5.7], who found that the servo error for a locked-rotor frequency of 4 Hz will be five times as large if the structure has a locked-rotor frequency of 8 Hz, so it is clear that high eigenfrequecies are required.

  2. The telescope response to wind loading outside the servo bandwidth must be considered. High structural eigenfrequencies allow a wide telescope drive servo bandwidth. As the wind spectral energy decreases with increasing frequency, the servo system will be able to respond to the wind loads that are most likely to cause image motion.

  3. There are eigenfrequencies which are different from the locked-rotor frequencies, i.e. the lateral and fore-aft modes. These modes could be excited by the wind gust spectrum, thereby producing both pointing and tracking errors.

- The tracking error due to the motor torque ripple and motor cogging will be reduced.

  The effect of the lowest structural eigenfrequency on the telescope tracking error has been studied by Schier [5.8], who found that if the lowest eigenfrequency was reduced by 30%, the error would increase by a factor of 3.

- A stiffer telescope structure will allow higher servo gain and higher acceleration rates. These give faster settling times and hence increase the observing efficiency.

- The possibility of the telescope structure being dynamically coupled to the vibrations generated as the enclosure rotates is reduced with high eigenfrequencies and the correspondingly wider servo bandwidth.

Since the eigenfrequecies are taken as a measure of telescope stiffness, the difficulty is to determine which mode shapes are associated with image motion. It is easy to see how the elevation and azimuth locked-rotor frequencies are important. If a torque impulse from the drive motors is considered, the structure will oscillate at the locked-rotor frequency. The influence of other modes, for example the lateral and fore-aft modes, is less obvious. The fore-aft mode is in line with the reaction force from the elevation-drive motors. This allows energy to be injected into

[22] This is a fictitious frequency that would be present if we were to fix the motor shaft so that it could not move and then shook the telescope structure.

the structure to excite the mode when the elevation axis is driven. The disturbances due to wind loading on the telescope structure will excite both the lateral and fore-aft modes depending on the wind direction relative to the enclosure opening.

Finite element models are being developed to analyse the static and dynamic performance of the structure. These models do not include the real stiffness of the drives, hydrostatic bearings or pier, which at this stage are considered to be infinitely stiff. Furthermore, the secondary spider are not pre-tensioned and the tertiary mirror is not included. The loads considered are gravity (acting on the passive and structural masses given in Table 5.1 and Table 5.2) and a static wind loading of 1000 N on the secondary. At this stage this value is a reasonable estimate, although verification with numerical and/or tunnel simulations is planned. There are a local model related to the top end ring that includes the pre-tensioning of the spider. Additionally, a preliminary study is currently in progress to evaluate the pointing and tracking performance of the GTC and its dependence on telescope eigenfrequencies with a reduced model.

5.4.3.1 Analysis results

Preliminary results of the finite-element analysis are summarized in this section. A list of masses and inertias for the telescope is given in Table 5.1 and Table 5.2.

System	Function	Elements	Mass (kg)
Tube	Passive	Primary mirror	16560
		Primary-mirror support system	5100
		A&G system, rotator and instrumentation on Cassegrain	6000
		Module of secondary mirror or prime focus	2000
		A&G system, rotator and instrumentation on folded Cassegrain (for the 4 foci)	4000
		Other: drive discs, encoders, etc.	12000
		Total tube passive mass	45660
	Structural	Spider	4356
		Upper tube structure	22390
		Elevation ring	36973
		Lower tube structure	6122
		Primary-mirror cell	8908
		Total tube structural mass	78749
		Total tube assembly	124409
Mount	Passive	A&G system, rotator and instrumentation on Nasmyth (for the 2 foci)	20000
		Nasmyth platforms (for the 2 foci)	2000
		Total mount passive mass	22000
	Structural	Yoke	91535
		Total mount assembly	113535
Telescope		Total telescope rotating weight	237944

Table 5.1: Telescope mass list.

Assembly	I_{xx}(kg m^2)	I_{yy}(kg m^2)	I_{zz}(kg m^2)	x_g(m)	y_g(m)	z_g(m)
Tube	4.916 10^6	5.263 10^6	3.510 10^6	0	0	0
Tube+mount vertical	9.639 10^6	14.441 10^6	10.536 10^6	0	0	-2.627
Tube+mount horizontal	9.636 10^6	13.563 10^6	12.289 10^6	0	0	-2.627

Table 5.2: Telescope inertia properties. The coordinate system is indicated in Section 5.3.

If the optics are perfectly aligned at zenith, the following gravitational misalignments and image motion will occur between the primary and the secondary mirrors and the Cassegrain instrumentation when the tube is rotated from the zenith to the horizon:

	Max. value
Defocus (mm)	0.77
Decentring (mm)	0.066
Tilt between primary and secondary mirrors (arcmin)	0.254
Misalignment of Cassegrain instrumentation (arcsec)	0.639
Image motion (arcsec)	13.281

Table 5.3: Gravitational misalignments.

The image motion due to a static action of 1 kN from wind on the secondary mirror is 0.083 arcsec. These values are consistent with the range of the active optics control of the primary and secondary mirrors.

Table 5.4 shows the eigenfrequencies and mode shapes of the telescope.

Frequency (Hz)	Mode shape description
3.47 (1)	Lateral mode
7.84 (1)	Elevation locked-rotor frequency
10.21 (1)	Azimuth locked-rotor frequency
13.59 (1)	Axial vibration of primary
20.05 (1)	Axial vibration of secondary
27.9 (2)	Torsional vibration of secondary
101.0 (2)	Rotational vibration of secondary

1) These values come from the global model that does not include pre-tension on the spider.
2) These values come from the local model of the top end ring that include pre-tension on the spider.

Table 5.4: Eigenfrequencies and mode shapes.

It should be noted that the lowest eigenfrequency, the lateral mode, cannot be directly excited by the telescope drives and therefore does not affect the control-system bandwidth. However, at this low frequency the wind spectral power is high and most likely to excite the telescope structure. This mode is due to a local effect in specific areas of the telescope mount. Future optimization of the mount structure will increase this eigenfrequency. This will provide a better dynamic response, which is necessary to reject wind-induced image motion.

5.4.4 Thermal aspects

There are three fundamental aspects related to temperature-dependent phenomena that could affect the behaviour of the telescope:

1. Thermal gradients between the structure and its surroundings could cause thermal turbulence produced by convective currents of cold or warm bubbles of air passing through the optical path, thereby degrading the seeing and consequently the image quality.

2. Thermal gradients between different structural elements could degrade the pointing and tracking precision of the telescope in open loop, as well as producing misalignment of optical elements.

3. Temporal temperature variations can affect the alignment of optical elements and instrumentation, as well as tracking accuracy in open loop over long periods.

These last two aspects, due to their low frequency and repeatability, can be modelled provided that there is a correct sensing of temperature throughout the structure. In this way the impact of the effects described will drastically reduced.

For all these reasons it is essential to maintain a uniform temperature, as close as possible to that of the surrounding air. Furthermore, the structure should have a low thermal inertia and should be treated with low-emissivity coatings to prevent sub-cooling by radiation to the cold night sky. In any case, these aspects must be studied in depth in order to identify and limit their impact.

It is also planned to install an active cooling system for those subsystems of the telescope mechanics which have a significant power dissipation.

5.5 Main bearings

The bearings referred to in this section are those of the azimuth and elevation axes of the telescope. Externally pressurized hydrostatic bearings [5.9] [5.10] have been chosen since these provide excellent smoothness of motion, large load capacity, high stiffness, zero static friction, low dynamic friction, good damping capacity, low cost of maintenance and relatively low cost of installation. Roller bearings would not meet the requirements owing to their behaviour and the dimensions of the subsystem.

The hydrostatic bearing system will be formed basically of the following components:

- Axial and radial hydrostatic pressure pads.
- A system of high-pressure injection and low-pressure return pipes.
- A hydraulic subsystem, comprising tanks, filters, pumps, distributors, flow control devices, security devices, etc.

There will also be a temperature control unit in the hydraulic subsystem for the precise regulation of the oil temperature. The oil supplied to the hydrostatic pads will be pre-cooled before reaching the bearings so as to eliminate or reduce thermal turbulence in the telescope chamber (Section 6.7.1).

The pressure pads must be self-aligning, i.e. with a capacity to absorb small misalignments caused by errors in manufacture or mount, as well as load eccentricities. For this reason they will need to have multiple-recess cavities so that a self-aligning torque is produced in them when the oil film becomes non parallel.

The configuration of the bearings for each axis is highly dependent on the configuration of the telescope structure, as is described in detail in the following section.

5.5.1 Elevation bearings

The elevation bearings will provide the positioning and support for the telescope tube assembly, transmitting the load (weight, wind, etc.) to the mount. It will be formed by two or four axial pads, four radial pads and the elevation girth rings.

As the chosen typology for the structure uses a space frame for the mount (Section 5.4) and welded metal plates for the elevation ring, it is preferable for the mount to receive point loads and for the elevation ring to receive distributed loads. Furthermore, there would be extra complication for the high-pressure piping if the pads were attached directly to the elevation ring. Therefore, the pads, both axial and radial, will be attached to their mounting brackets at the top of the yoke and the girth ring will be fixed to the elevation ring.

The telescope assembly will be supported through the elevation girth ring on four inclined master radial pads, two on each side. This will provide cross-axial as well as vertical support hence defining the radial position and making the system isostatic. These four pads must support the

124.5-tonne weight from the telescope tube and each will have a stiffness of about 1.4×10^{10} N m^{-1} [5.10].

The axial position of the axis will be defined by two or four hydraulically pre-loaded axial guiding pads acting in opposite senses and arranged on both sides of the elevation axis. One will be the master defining the axial position of the telescope tube, and the remaining ones will be slaves carrying more of the load.

Therefore, of the hydrostatic pads that define the position of the tube with respect to the mount, five are masters, defining five of the six degrees of freedom of the tube. The sixth degree of freedom (rotation about the elevation axis) will be defined by the drive of this axis.

The hydrostatic-bearing arrangement for the elevation axis are shown in Figure 5.7.

5.5.2 Azimuth bearings

The azimuth bearings will provide the positioning and support for the telescope mount, transmitting the load to the pier. It will be formed by four axial pads, four radial pads and the azimuth girth ring. The azimuth girth ring will have a diameter of approximately 14 m and so will need to be segmented. These segments will be either welded or screwed together and it will be necessary to analyse its construction and installation carefully.

As the structure of the mount will be based on a space frame, it is preferable for it to receive point loads. The axial and radial pads will be arranged in the lower part of the mount and the girth ring will be fixed to the top of the pier. This will optimize the force distribution and minimize the moving mass of the telescope, which will result in an improvement in dynamic performance. This arrangement will increase the complexity of the cable wrap, which will also have to include the hydraulic pipes for both axes.

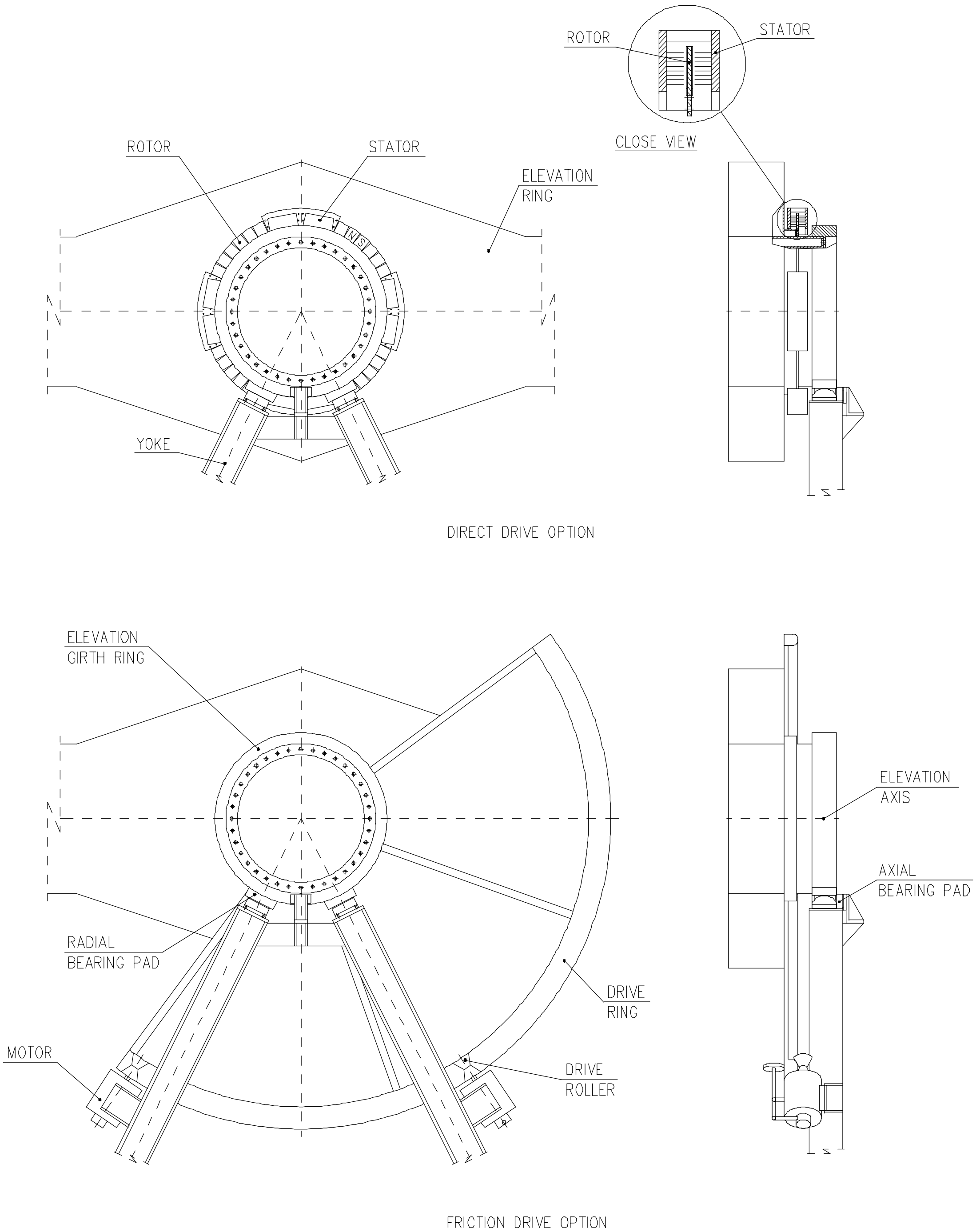

Figure 5.7: Hydrostatic bearing arrangement and drive options for the elevation axis.

The overall weight of the telescope structure will be supported by the girth ring through the four axial pads, which will be masters. These four pads will define only three of the telescope's degrees of freedom defining the verticality of the azimuth axis: vertical displacement, and roll and pitch rotations. Therefore, the system will be hyperstatic. These four pads must support the 238-tonne weight of the full telescope rotating mass and each of them will have a stiffness of about 2.1×10^{10} N m^{-1} [5.10].

The four radial pads define the transverse position of the azimuth axis by constraining the two horizontal displacements. For this reason, two of the pads will be masters and will be arranged at 90°, while the other two pads will be slaves, being hydraulically pre-loaded.

To summarize, of the eight hydrostatic pads that define the position of the mount with respect to the pier, six are masters, defining five of the mount's degrees of freedom. The sixth degree of freedom, rotation about the azimuth axis will be defined by the drive of this axis.

5.6 Main drives

Two alternatives for the drives of the main axes of the telescope, direct and friction drives, are being studied. Direct drives have a better dynamic response because they are stiffer and there is no stiction (static friction). For direct drives there is no possibility of accuracy deterioration, such as encountered with friction drives as a result of wear. Therefore, for the performance, the direct-drive option is presented as the optimum solution. However, the final choice will depend on more detailed analysis to determine whether the friction drive is capable of reaching the dynamic specification at an appreciably lower cost than that of the direct drive. It is intended that both axes will used the same type of drive to simplify development and maintenance.

Whichever drive type is chosen, the motor will be of the brushless type because these can operate over a wide range of speeds, and their configuration permits better heat dissipation and faster response. Another important feature is that, with no moving parts (except for the bearings), they do not generate frictional heat, acoustic noise or dust. Furthermore, the direct motor will be of the axial field type.

Direct motors give rise to higher levels of heat emission than motors with transmission. However, in both cases the cooling of the motors will be essential.

The tracking accuracy requirement of the GTC makes a sinewave commutation, current-fed drive mandatory. The sinusoidal waveform minimizes torque ripple, and the torque output is nearly constant. The current-fed specification is necessary for obtaining the same torque from the different motors (friction drive) or from the different stator segments (direct drive).

The azimuth drive will move the mount and the telescope tube, as well as the instruments. Owing to the zenith blind spot of the telescope and to the pointing requirements (see Section 2.4.11), the accelerations and velocities in azimuth will be higher than those in elevation. The minimum angular range will be 453.3°, with an objective of 540°, and velocities and accelerations will be greater than 2.3° s^{-1} and 0.1° s^{-2} [5.11]. The inertia to be overcome in the azimuth axis is about 12×10^6 kg m^2 [5.1]. These values give an acceleration torque of 21450 N m. If wind action is taken into account, the maximum load torque is 43410 N m [5.12].

The elevation drive will move the telescope tube and the attached subsystems. The specific power of this drive should be maximized as it will, in turn, be moved by the azimuth drive.

The angular elevation interval will range from –1° to 91° with respect to the horizontal (see Section 2.4.11). The velocity and acceleration attainable will need to be at least 0.75° s^{-1} and 0.11° s^{-2} [5.11]. The tube inertia in the elevation axis is about 5.0×10^6 kg m^2 [5.1]. These values give an acceleration torque of 9600 N m. If wind, eccentricity and other effects are taken into consideration, then the characteristic maximum load torque is 27980 N m [5.12].

5.6.1 Direct-drive option

The direct motor consists of a plane annular disc of large diameter where permanent magnets are located (Figure 5.7). The orientation of the poles of the magnet give rise to an axial magnetic flux. There are windings on both faces of the disc to give a double axial air gap. Since there is no intermediate transmission (i.e. the motor torque is equal to the load torque), the motor currents are greater than in friction systems.

This option requires uncommon sizes and characteristics for large torque motors, which must be manufactured in parts and assembled on site. Recent developments in direct motors for large telescopes have made consideration of this alternative possible [5.13] [5.14]. The drive is completely modular with the advantage of being able to operate without the full complement of stator sectors. In this case the most important effect would be the corresponding loss of the motor torque.

In the case of the azimuth drive, the possibility of the permanent magnet being part of the telescope pier or of the mount is an aspect that needs to be analysed in detail. At present both possibilities are being considered. In either case both the lower part of the mount structure and the pier must guarantee the air gap tolerances of the motor. The stator will be composed of four or more sectors. The traction force will be distributed, while point forces are preferable for the typology of the mount structure. Therefore, the interface between the mount and the motor must transform the distributed forces into point forces. This will introduce a certain constructional complexity with regard to the frictional transmission system.

In elevation, the permanent magnet will be situated on each side of the elevation ring, which is better suited to receiving distributed loads. The size and radius of the stator segments will significantly affect the structure to which they are attached as this structure must provide the necessary stiffness. The angles at which the segments are placed could give rise to a net transversal load on the bearings. The option of placing the stator segments in a spread-out arrangement eliminates this effect but introduces a certain complexity in construction. These aspects must be evaluated when an option is chosen.

Although the direct-drive motor has a better performance, the design of the structure is currently orientated towards a friction motor. More detailed studies could lead to a reappraisal of the proposed mount. Figure 5.7 shows a sketch of the drive options for the elevation axis.

5.6.2 Friction-drive option

In this type of drive, the transmission of the motor traction to the driven element is carried out through the friction that arises in the contact between two friction wheels. The drive ring is the larger, while the drive roller is the smaller. The contact force between these wheels must be such that, in terms of the coefficient of friction, it is capable of moving the telescope without slippage, with wind loads taken into account. In this type of transmission, alignment errors give rise to problems of what is known as ‘drift-slip’. Additionally, in the low- or zero-speed zones, there is ‘stick-slip’. Both effects produce discontinuities of movement which are difficult to reproduce since they arise from frictional phenomena. One way of minimizing the stick-slip effect is the active pre-loading of the friction wheels. The motors will be arranged in flexible mounts in order to reduce alignment and geometrical errors (e.g. ellipticity, eccentricity) in both wheels. These problems do not arise with direct motors.

In the case of the azimuth drive the azimuth drive ring would be embedded in the concrete pier, with eight motors situated at the four corners of the lower part of the mount. The cabling and piping would be relatively complicated since they would move with the mount. Given the great size of the azimuth drive ring, this would be segmented. In this case the two main problems would be the joining of the segments and their machining.

In elevation, the drive ring would be joined to the elevation ring, with two motors on each side of the tube in order to minimize the torsional deformations of the ring. The size of the drive ring would be less than 360° since the range in elevation would be 92°. The angular arrangement of the motors gives rise to the same kind of problem as with direct motors regarding the net load on the bearings.

5.7 Main encoders

This section refers to the encoders of the azimuth and elevation axes of the telescope. The encoders give the position feedback to the servo system that controls the drives of the main axes. The encoder system will consist of a main system and could additionally include an auxiliary system. The most demanding requirement for the encoders is an open-loop tracking accuracy of 0.1 arcsec rms over 10 minutes. In the error budget it has been estimated that the encoders will give rise to an error of 24 milli-arcsec rms [5.15]. Basically two types of encoders have been considered: friction coupled and tape.

Owing to the demanding precision requirement, the friction-coupled encoder was discarded as the main encoder system due to the mechanical slippage and hysteresis usually present in this type of encoder which produce non-repeatable errors.

Among the tape encoders the Heidenhain optical-tape option (model LIDA) [5.9] [5.10] [5.16] has greater precision than and a similar price to the Inductosyn magnetic encoder option and is therefore the one selected. This encoder has recently been improved by Heidenhain to incorporate compensation electronics and is capable of meeting the requirements of the GTC. This encoder is based upon a 40-µm pitch optical scale. After interpolation and digitization, with an interpolation factor of 2^{12}=4096, a linear resolution of 10 nm is obtained. The linear precision required at the radius of the encoder rings will be 0.40 µm rms, which is feasible with LIDA tape [5.16].

The azimuth tape will be mounted in a ring, 14.1 m in diameter, set into the telescope pier. At least four heads for reading the tape will be used, which will be situated in the four corners of the lower part of the mount structure. The resolution will be 0.29 milli-arcsec and the required precision will be 12 milli-arcsec rms. The elevation encoder will be located on a ring 8 m in diameter with a resolution of 0.52 milli-arcsec and a required precision of 20 milli-arcsec rms. The ring will be fixed to the elevation ring, in the same way as the drive ring and the bearing girth rings. In this case the use of a complete ring and multiple heads give rise to a certain complexity in construction. For this reason the combined use of axis translation sensors together with a ring sector and a read head is planned. The use of one or other technique will have to be evaluated in detail.

The read heads must maintain an air gap with the tape of 800±150 µm. This distance has to be maintained by means of a roller and a pre-loading system that will guarantee roller contact. The read head has to have a certain flexibility in the axial direction to absorb the relative movements of the tape, as well as a great stiffness in the transverse direction so as not to introduce read errors.

Given the size of the tape support ring, thermal gradients could give rise to important measurement errors. To these errors must be added the geometrical errors of the tape support ring. Multiple read heads will be used in order to eliminate a large part of the periodic errors produced (eccentricity, ellipticity, etc.) [5.10] [5.17].

The heat generated by the hydrostatic bearings could distort the encoders, and this must be taken into account. Moreover, the manufacture of large diameters encoding rings can give rise to excessive costs. These two aspects, together with construction, will require a detailed analysis to determine the most suitable diameters, above all in the azimuth axis which needs a relatively large ring.

The use of friction-coupled encoders as an auxiliary system will be considered if the combined performance with tape encoders is improved.

5.8 Instrument rotators

The instrument rotators are the subsystems that, at each focus, compensate for the image rotation produced as a consequence of the alt-azimuth mount of the telescope. The mechanical instrument rotators will be deliver as part of the telescope mechanics, so they will not have to be included in the instruments development. The instrument rotators will support the A&G systems of each focal station. In the cases of the Cassegrain and folded-Cassegrain foci, the rotator will directly support the instrumentation. The instruments at Nasmyth can be either mounted directly on the platform[23] or on to the mechanical rotator which will be capable of supporting several tonnes.

The precision requirements are not as high as for tracking in the main axes, since the positional accuracy required is related to the rotation of a given image diameter at the outer edge of the field of view at a given focus. For a worst-case scenario where the guide probe is 15 arcmin off axis, the angle of the rotator must be accurate to about 2 arcsec if the error in the position of the object is to be accurate to better then 0.01 arcsec [5.18]. Owing to this lower accuracy requirement, the alternatives for the rotator mechanisms, bearing, drive and encoder subsystems could be based on more traditional solutions, such as crossed roller bearings, gear transmission drives and gear-driven optical encoders.

The instrument rotator will be a cylindrical assembly comprising:

- A fixed ring bolted directly to the interfacing piece with the structure (primary-mirror cell, elevation ring or Nasmyth platform).
- A crossed roller bearing.
- A rotating ring that interfaces with the instrument support structure.

The moving part will have a precision gear mounted around its periphery. This gear will be meshed with two precision pinions, each of which will be driven, via a reduction gearbox, by a servo motor, in order to eliminate mechanical backlash. Multiple gear-driven high-resolution absolute encoders and incremental encoders will be used for position feedback, directly from the main gear ring. The Cassegrain and Nasmyth rotators will have a rotation range of about 540°.

5.9 Cable wraps

5.9.1 Main axes

Pipes and cables will be conveyed from the telescope pier on to the telescope mount using the azimuth cable wrap. This is required to maintain the correct disposition of the cables and so prevent stresses building up as the telescope rotates, which could result in their snapping. Similarly there will be an elevation cable wrap for those cables and pipes that are passed from the mount on to the telescope tube. These cable wraps must have their own mechanisms, and not be dragged by the drives of the main axes of the telescope, which could affect the pointing and tracking accuracy.

5.9.2 Instrumentation

[23] In this case there will be the option of using an optical rotator or a mechanical rotator that rotates only a part of the instrument.

The cabling for the instruments situated at the different foci will also need to be rotated in a controlled manner with the instruments. There are two possibilities:

1. The cable wraps and instrument rotators are activated by the same drive.
2. The cable wrap has an independent drive, with the aim of relaxing the demands on the instrument rotator drive.

For the folded Cassegrain foci, because of the smaller size of the instruments and because these will practically not need to be interchanged, the first option will be adopted. For the Nasmyth and Cassegrain foci, the choice of options will require the carrying out of further detailed analysis.

5.10 Auxiliary subsystems

5.10.1 Primary-mirror cover

In most telescopes, the primary mirror has a protective system to act as a safeguard against possible damage from dust, impacts, etc. when the telescope is not in operation, and which is provided with the necessary mechanisms for its opening and closing, as well as a locking mechanism when the telescope is stationary.

The size of the GTC primary mirror, as well as in situ cleaning techniques (see Section 4.10.2), call into question the need for and the viability of a primary-mirror cover, for which reason further analyses should be carried out in order to reach a decision in this respect. The telescope may also may be parked horizontally, in which case the need for a cover is not so evident.

5.10.2 Counterweight system of the telescope tube

Although the telescope tube is designed to be well balanced, it is anticipated that trimming weights will be required so that the centre of gravity of the telescope tube remains on the elevation axis when the position of the tertiary mirror is changed or instruments are interchanged. This system will be situated in the elevation ring and consist of weights and the necessary displacement mechanism. The counterweight system must be automatic, remote controlled and monitored, and the weights must remain in their last commanded position. This could be accomplished either by the use of electrically actuated brakes and/or a mechanical design of drive system and position sensors. In order to trim the telescope it will be necessary to provide some kind of sensor system. One possibility would be load sensors to detect and control the correct balance; another would be to use the asymmetries in the azimuth and elevation axis drive-unit currents. A small manual adjustment of the balancing might be necessary, and provision should be made for this.

5.10.3 Protection and safety systems

Auxiliary devices will be provided for guaranteeing the safe and correct operation of the GTC. These will allow the installation and maintenance of the telescope mechanics and include devices for supporting and locking the structure, such as brakes, end-stops, hydraulic jacks, locking pins and safety mechanisms.

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6. ENCLOSURE AND SERVICES

6.1 Introduction

The installations of the GTC include the buildings, urbanization and auxiliary equipment required for the operation of the facility. Foremost among these installations are the enclosure and the annexe building. A telescope enclosure normally comprises a fixed base and an upper revolving metal structure which encloses the telescope chamber. This revolving structure, regardless of its geometrical shape, is called the dome. The annexe building must provide the necessary support services.

Several options for the GTC building have been evaluated. In particular, different dome types and distribution schemes for the support areas to be incorporated in the installation have been assessed. A summary of the present status of this evaluation is presented here. These options fully satisfy the scientific requirements and have been adopted as a solution for specific parts of the installation.

6.2 Design guidelines

The design guidelines for the installation, derived directly or indirectly from the requirements of the GTC described in Chapter 2, are that:

1. The installation will permit the maximum exploitation of the excellent astronomical quality of the GTC site, for which purpose:

    - Full thermal control will be provided for the entire installation, with special attention to the environmental conditions in the telescope chamber.

    - The possibility of turbulent surface-layer air negatively affecting astronomical observations will be minimized.

    - The possibility of wind-induced telescope vibrations, and transmission of vibrations between the separate foundations of the buildings and the telescope pier through the ground, will be minimized.

2. The installations are required to support tasks of operating and maintaining the GTC (optical elements, instrumentation, etc.) in such a way as to maximize the available observing time and guarantee the safety of equipment and personnel. For this purpose:

    - Adequate accessibility and handling equipment for operating and maintaining the installation will be provided, both inside the telescope chamber and in the support areas. Within the telescope chamber accessibility to all points of interest (telescope foci, optical elements, mechanisms and motors, the dome, etc.) will be taken into account.

    - Provision will be made for the handling of equipment. The installation of cranes will be optimized in order to cover all the handling functions to be undertaken in a given area or between areas with a minimum number of elements. Other necessary means, such as lifts, trolleys, platforms and stairways, will also be provided.

    - The storage of sundry parts is envisaged with a view to maintaining order and avoiding any possible misuse of areas not destined for this purpose.

3. The total protection against adverse weather conditions will be provided for the telescope, instrumentation and all installation subsystems in general, for which purpose:

- The installation will be designed to withstand the most extreme foreseeable environmental conditions as defined in Section 3.2.1.

- Preventive measures will be taken against penetration into the installations of water resulting from horizontal and upward directed rain, which occasionally occur during the winter at the ORM.

- Snow and ice loading on the dome and annexe are foreseen, and measures will be taken counter the risk of snow or ice falling into the interior of the telescope chamber when opening the dome shutter during winter.

- Similarly, in addition to the typical structural loads usually taken into account in the design of any high-mountain installation (ice loading on railings, cables, etc.), steps will be taken to minimize the risk of ice falling from the dome.

- Measures will be taken to prevent the build-up of dust inside the telescope chamber.

4. Considering that the construction work is to be undertaken in a protected natural zone, specifically on the boundary of the Caldera de Taburiente National Park, every effort will be made to reduce the ecological impact on the area resulting from the GTC installation to an absolute minimum.

6.3 General description of the installation

The GTC installation will comprise three main components: the enclosure, the annexe building and specific external installations. The total surface area occupied by the installation, whose general layout is shown in Figure 6.1, will be approximately 4000 m^2.

The main element of the enclosure is the dome, a revolving spherical structure which will house the telescope, the scientific instrumentation and those elements considered essential for the operation and maintenance of the telescope. The dome will be supported on a fixed cylindrical base, which will surround the telescope pier. This structure and the area enclosed within its interior will be designated the enclosure base.

The annexe building will adjoin the base in the downwind direction. The annexe will provide support and auxiliary service areas for the installation, such as the control room, stores, maintenance workshops, cleaning and optical coating areas. To minimize the area of the annexe and to simplify some of the handling operations, some of the support areas will be included in the enclosure base.

The external installations will be located away from the buildings. These installations will include access routes, cargo bays, parking space, heat extractors and cooling ducts, heat exchangers for air conditioning and refrigeration, water purification plants, drainage, emergency generator and transformer stations.

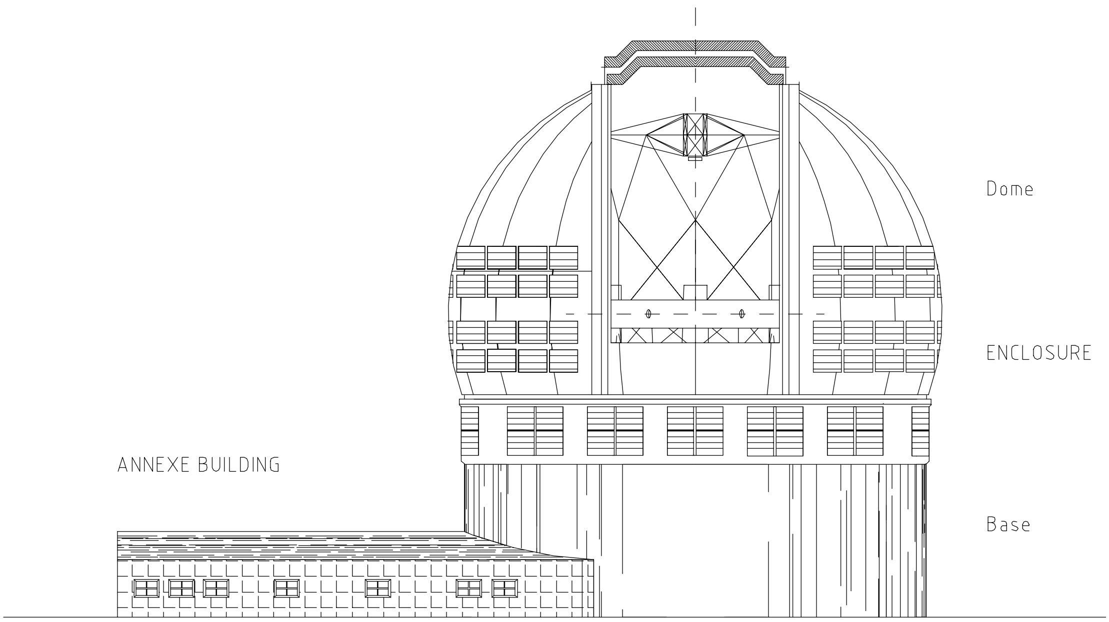

Figure 6.1: General layout of the GTC installation.

6.4 Enclosure

6.4.1 Dome

Given that the relation between the dome and its shutter is of prime importance, it is imperative to consider both jointly. For this purpose, the following guidelines have been taken into account:

- The dome will allow the telescope to observe without obstruction for elevation angles between 15° and 1° past zenith. The dome shutter will allow telescope azimuthal movements of up to 2° without the need for rotating the dome.
- The dome will be able to make full rotations about the azimuth axis in both directions and will continue to rotate until the order to stop has been received. The specifications for velocity and acceleration of rotation of the dome are derived from those corresponding to the azimuthal movement of the telescope [6.1]:
    - The velocity of rotation will vary between 0 and at least 2.3° s^{-1}.
    - The acceleration of rotation will be between 0 and 0.1° s^{-2}.
- The precision of positioning of the dome will be 0.1°.
- The maximum time for closing the dome will be 3 min.
- Windows will be built into the dome structure to allow natural ventilation of the telescope chamber during observations. This will maintain optimal environmental conditions inside at the lowest possible cost. When there is insufficient wind speed, a forced ventilation system will be used. In order to optimize the natural ventilation system, aerodynamical studies based on numerical simulations are being undertaken at present [6.2] [6.3] which will be complemented in the near future by wind-tunnel tests.
- To minimize the possibility of wind-induced telescope vibration and to permit the use of the telescope even in average wind speeds up to 22 m s^{-1} (the operational limit), the wind speed

inside the telescope chamber will be controlled by means of a porous folding protective screen for the dome slit and adjustable louvres in the ventilation windows. This design solution will permit the dome shutter to be kept completely open during observing and will aid the natural ventilation of the telescope chamber. In cases where the wind speed and direction might affect the telescope, the protective screen will diminish the wind speed inside the dome while leaving the optical light path free.

- In adverse environmental conditions, the dome will afford complete protection to the telescope and its instrumentation. In the structural design of the dome, besides the weight of the structural, insulating and enclosing elements, the following overloads[24] will be taken into account:

    - Live load: a weight distribution of 150 kg m^{-2} is estimated.

    - Snow and ice loading: 240 kg m^{-2}.

    - Wind loads: two wind-speed regimes, averaged over 15 minutes, will be considered, one of 22 m s^{-1}, which is the operational limit, and the other of 56 m s^{-1}, which is the survival limit of the dome. Wind gusts up to 67 m s^{-1} will be taken into account.

    - Seismic loads: a ground acceleration of 0.1 *g* will be considered.

    - Moving parts should initiate and stop their movements smoothly, for which reason the resulting load will be of small magnitude and will be taken into account only in the calculation of connection elements.

  In [6.4] further details can be found on the overloads that will be taken into account in the structural design of the dome.

- Means will be provided for operational and maintenance tasks to be carried out inside the telescope chamber, such as the mounting of instrumentation at the various foci or the manipulation of the optical elements, with particular attention being given to the primary-mirror segments. Similarly, means for cleaning the dome will be provided so as to avoid dust accumulation.

6.4.1.1 Dome-type options studied

In order to select the dome type a technico-economic study has been carried out in which the most important parameters that determine the efficiency of the dome during its life-cycle have been qualitatively, and in some cases quantitatively, evaluated. This study is based on two possible geometrical models: a spherical dome (Figure 6.2(a)), similar to that adopted for the Keck and Gemini projects, and a cylindrical (or polygonal) dome (Figure 6.2(b)) similar to the one chosen for the VLT (Very Large Telescope) and Subaru projects. In both cases the enclosure base is considered to be cylindrical. Although other geometries could have been studied, the additional cost in assessing numerous dome types, together with experience already gained from other projects, led to the identification of these two dome models as those requiring a detailed study and in-depth comparative evaluation.

The following parameters were established for the comparison of dome-type options:

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[24] In estimating the overloads Spanish regulations and Regulation ANSI A58.1 have been taken into account, the dome being classified under category III, as a strategic installation.

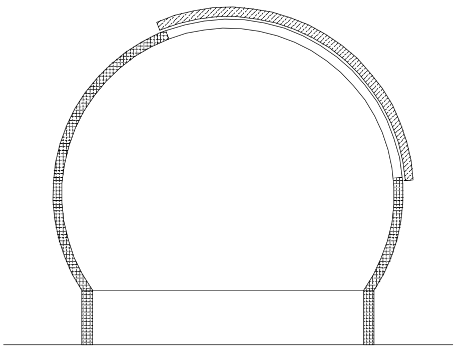
- Viability, times and costs of manufacture and assembly, both of the structure and of its principal components (shutter, windows, wind protectors).

- Structural behaviour both of the rotating structure and the shutter assembly. Within this parameter were also included aspects such as the risk of snow and ice falling into the telescope chamber when opening the shutter in winter, the ease with which each dome type could accommodate wide openings for natural ventilation without affecting its resistance, the aerodynamic behaviour of each of the dome types and their stability in withstanding severe wind conditions as well as possible seismic tremors.

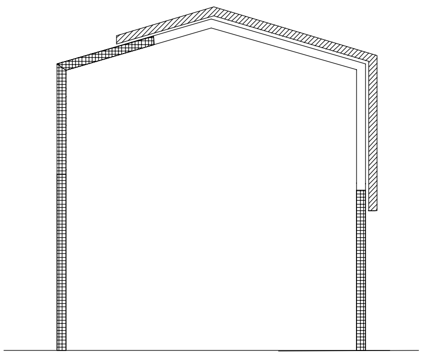
- Dome support, for which the following aspects were considered: movement of the dome by means of simple and safe drive mechanisms guaranteeing the established dynamical requisites in terms of velocity, acceleration, stopping criteria and non-transmission of vibrations to the telescope; ease of access and handling of elements for the operation and maintenance of the telescope, its instrumentation and the dome itself; and the cost associated with the different dome types with regard to operation and maintenance during the life-cycle of the installation (e.g. air-conditioning cost).

- Protection against adverse meteorological conditions: a comparison was made of the snow, ice and wind loading that could be produced on each of the dome types, and the guarantee of the structure being proof against rain, snow, dust, etc., was studied.

- Estimation of the impact of the dome on the attainable image quality: aerodynamical simulations were carried out to study the effect that up-lift[25] of air might have in increasing the turbulence conditions of the surface layer outside the dome towards the direction of observation on the one hand, and, on the other, the ease of installation and operation of the thermal control systems of the dome.



a) Spherical dome.



b) Cylindrical dome.

Figure 6.2: Dome-type options studied.

The details of the evaluation of options can be consulted in the documents [6.4] and [6.5].

6.4.1.2 Description of dome type selected for the GTC

The spherical dome type, with an internal radius of 16.5 m supported on a cylindrical base of 15.5 m internal radius (see Figure 6.3), was chosen for the GTC. There will be at least 2 rows of windows installed all round the dome to allow a continuous flow of air through the telescope chamber.

[25] Up-lift refers to the part of the air flow that rises over an obstacle rather than going around it.

The following is a summary of the advantages offered by this type over its cylindrical counterpart:

- Lower construction cost, given the lower quantity of materials necessary for the structure.
- Better structural behaviour: lower wind and snow loading, better aerodynamical behaviour, higher stability of the assembly, higher vibrational frequencies. Also, due to the opening sequence of the dome shutter, the risk associated with snowfall into the interior of the telescope chamber is lower.
- Lower cost of dome support: owing to the smaller volume of air enclosed inside the telescope chamber, the costs of air conditioning and forced ventilation are reduced. Owing to the lower mass, less power is needed to activate the rotation motors.

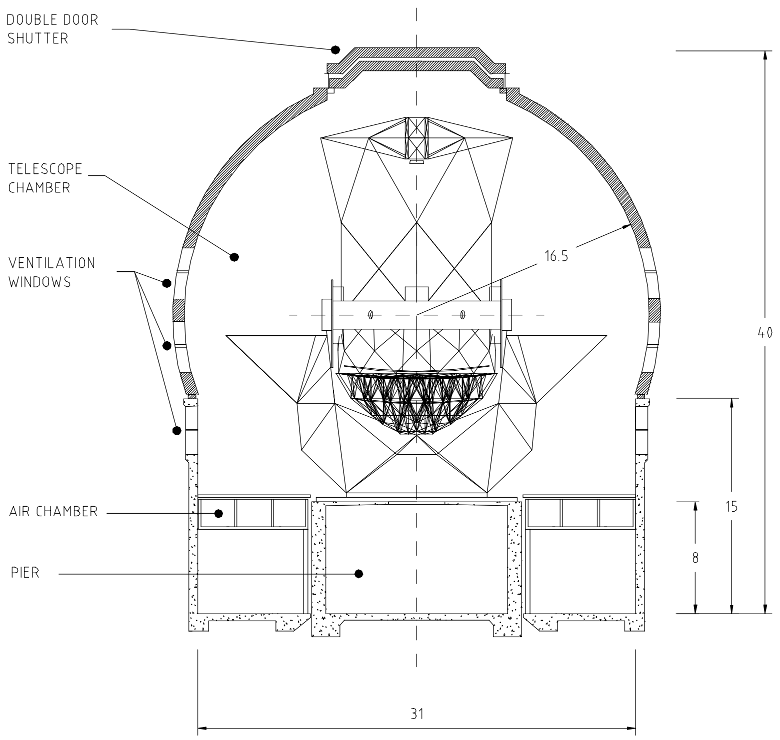


Figure 6.3: Selected dome type (dimensions are in m).

Among the disadvantages of this type of dome are the following:

- Less flexibility for installing windows with a large effective area perpendicular to the wind flow. In this regard it should be pointed out that the aerodynamical studies now being carried out (see Section 6.4.1) will be considered in greater detail with the object of confirming that the spherical type chosen will permit the installation of sufficient apertures to guarantee adequate natural ventilation. Numerical simulations carried out to date are quite encouraging.
- In the simulations carried out, a slight disadvantage is detectable for the spherical dome as compared with the cylindrical dome with regard to the up-lift effect. Nevertheless, it is also observed that the slope of the terrain surrounding the installation (18% on average) has a much greater effect on this phenomenon. However, even with the up-lift effect the quality of the seeing inside the telescope chamber and its immediate surroundings will be guaranteed by the average temperature difference measured at the telescope site between 1 and 6 m above

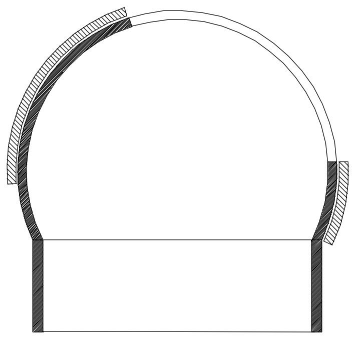
ground level (only 1°C), the rapid mixing of air flow (even at low wind speeds) and the safety margins provided with the air entrances higher than 10 m above ground level.

Dome shutter

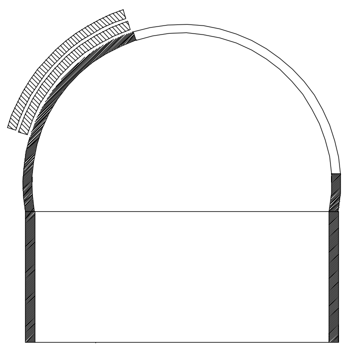
The dome shutter will accommodate the required elevation-angle range for the telescope with the smallest possible dome diameter while ensuring improved natural ventilation of the telescope chamber. Two alternatives for the dome shutter have been studied:

1. Double sliding doors, in which both the main and secondary door slide on circular rails (Figure 6.4(a)). In this alternative, each door has a simple drive mechanism and guide-rails, can form a single part, and is robust, light and with well sealed closure surfaces. One variety consists of a small foldable, instead of sliding, door; this arrangement allows for observing at altitudes close to the horizon and will also permit natural ventilation; nevertheless, a drawback is the presence of a large cantilevered structure during observations.

2. The second type incorporates a telescopic door divided into two parts, one sliding over the other, thereby allowing a longer aperture slit and the presence of ventilation windows in the wall opposite to the slit, with the smallest possible dome (Figure 6.4(b)). This solution has other advantages similar to those of the previous type and also eliminates the structural problem of the cantilevered door, but with the attendant complications of construction and ensuring the tightness of the seal during closure. This alternative is the probable solution for the dome shutter.



a) Double door shutter (traditional arrangement).



b) Double door shutter (telescopic arrangement).

Figure 6.4: Alternatives for the dome shutter.

The design of a system for melting and removing ice and/or snow near the shutter assembly is envisaged. This will maximize the availability of the telescope for observing during winter and will reduce the possibility of ice and snow falling into the telescope chamber during the opening of the dome.

Telescope chamber floor

On the basis of the aerodynamical studies carried out, the usefulness of raising the floor of the telescope chamber, level with the top of the pier, has been identified. The floor will therefore be situated above the surface layer and near the natural ventilation windows so that the airflow crosses the dome without forming eddies in the interior which would otherwise be produced in the empty space surrounding the pier of the telescope.

The telescope chamber floor will be a double platform with an air chamber in its interior and will be supported by the structure forming the base of the enclosure. Some additional advantages of this arrangement are:

- Thermal isolation of the telescope chamber from the base of the enclosure. The temperature of the floor could also be actively controlled to contribute to the thermal control of the telescope chamber.
- Reduction of the volume of air to be constantly renewed in the telescope chamber while observing and to be controlled by air conditioning during the day.
- Provision of an access level to assist in the operation and maintenance of the telescope and dome.

The floor of the telescope chamber will need to be isolated from the pier in order to avoid the transmission of vibrations. It will also have to allow movement of equipment and personnel between the telescope chamber and the base of the enclosure during operation and maintenance.

Visitors' gallery

A visitors' gallery inside the telescope chamber is envisaged in order to prevent possible disturbances caused by visitors such as the introduction of dust inside the telescope chamber and the generation of additional thermal loads.

Handling equipment inside the telescope chamber

The installation of two cranes inside the telescope chamber is envisaged: one with a capacity of 10 tonnes for general purposes, including the handling of scientific instruments and the secondary-mirror assembly, and another with a capacity of 1 tonne, of high precision and smoothness of movement, for the handling of primary segments. There will also be auxiliary equipment, such as trolleys and a service lift for communication between the enclosure base and the telescope chamber.

The 10-tonne crane could be used as a support during the phases of assembly and mounting of the telescope. However, it is planned that the mounting of the telescope will be carried out mainly with the help of a crane provisionally installed outside the enclosure, the parts being passed through the dome slit.

6.4.2 Enclosure base

The dome will be supported on a fixed cylindrical concrete base of 31 m internal diameter and approximately 15 m high. This height allows the incorporation of one row of windows in the upper part of the enclosure base, well above the surface layer. This row will improve the ventilation of the mirror cell and keep the dome very small, thereby reducing costs.

The base will surround the telescope pier and will house some of the support areas in its interior (see Section 6.4.2.1). There are basically three advantages in using this zone to incorporate support areas:

1. The proximity to the telescope chamber of the support areas of most frequent use (the area for cleaning and coating of optical components and the instrumentation laboratory). This will result in the minimization of handling equipment needed, and in a reduction of the duration of these kinds of tasks and of the risks entailed therein.

2. It allows certain equipment to be brought into close proximity with the telescope, particularly the equipment necessary for producing a laser guide star or the oil pumps for the hydrostatic bearings.

3. It allows the efficient use of an existing volume[26], with the consequent reduction in floor space required for the annexe. This will result in a reduction in the total terrace area of the installation and a correspondingly lower visual impact of the complex.

Heat transmission from the enclosure base to the telescope chamber will be minimized. This means that heat produced by solar radiation and from machinery situated inside the base itself will have to be reduced as much as possible, with due consideration being given to insulation and air conditioning of the areas inside the enclosure base.

Protection must be provided against the infiltration of water from rain or snow.

The transmission of vibrations to the telescope through the ground must be avoided. For this purpose the foundations of the enclosure base will be independent of those of the telescope pier.

The enclosure base will have the necessary equipment (e.g. cranes and trolleys) for handling the various kinds of cargo, whether in the enclosure base or between the telescope chamber and the support areas located in the annexe.

In the configuration eventually adopted for the enclosure base a path will be kept free for a light beam directed from the telescope to a possible coudé room.

The height of the enclosure base above ground level will permit the incorporation of an air space for thermally isolating the telescope chamber (see Section 6.4.1.2).

6.4.2.1 Support areas included in the enclosure base

Figure 6.5 shows a plan view of the various support areas of the GTC. In the final stages of the design, the layout of some of these areas could be modified for optimum utility.

The areas allocated for the cleaning, coating and storage of primary-mirror segments have been strategically situated next to each other and very close to the telescope chamber in order to minimize maintenance times and guarantee safe handling of optical elements. A study will be made of the possibility of these areas being given clean-room classification.

<u>Cleaning area for optical components</u>

The cleaning area will be situated inside the telescope enclosure base for ease of access and handling in the carrying out of the periodical cleaning tasks prior to the re-coating of the optical components of the telescope.

The optical component will arrive directly from the telescope or, in certain cases, from the primary segment store (see below). Once cleaning is finished, the mirrors will be transferred to the coating area.

Contemplated among the necessary facilities for the cleaning room are the collection, neutralization and storage or elimination of chemical residues generated during the removal of the

[26] The pier of the telescope will rise 8 m above ground level in order to position the primary mirror well above the possible influence of the surface layer for any orientation of the telescope.

old optical coatings, the extraction of the gases generated during this process and the supply of deionized water and chemical products necessary for the process.

Coating area

The coating area will provide a controlled space for housing the coating chamber. The control panel, and the necessary electrical and mechanical equipment will also be located in this area, together with all the support facilities required for the coating process. The pump area for obtaining high vacuum conditions in the coating chamber will be kept separate and the gases generated during pumping will be evacuated.

The coating area will be thermally isolated from the telescope chamber, with particular attention being given to the vacuum-pump room, which would also be air conditioned. The latter may not be necessary since the coating chamber will be used only during the day, when observing is not in progress.

Primary-mirror segments store

The six primary-mirror spare segments will be stored here. Some of these segments could have passed through the cleaning and re-coating process and be ready for mounting on the telescope. This room will be located very close to the cleaning and coating area.

Laser guide star equipment

A room will be allocated in the enclosure base for housing the laser guide star equipment to be used during observations with adaptive optics (see Section 4.6.3). This room must be near the telescope to reduce the length of the path up to the guide star projection system and also thermally controlled since the attendant equipment will dissipate between 25 and 40 kW.

Hydrostatic-bearing oil-pump room

It is convenient for the hydrodstatic-bearing pumping plant to be near the telescope pier in order to minimize the inflow and return oil piping (see Section 5.5). This plant will be one of the main generators of heat inside the installation (of the order of 60 kW) and needs special attention from the point of view of thermal control, given that it will remain in operation during the whole period of observation. Therefore, the room in which the pumps are to be situated must be isolated and the heat generated therein must be removed so as not to affect the observations. Furthermore, the oil in the inflow pipes needs to be pre-cooled.

Instrumentation and optical calibration laboratory

The room for materials and assembly of GTC instrumentation or for instrumentation from outside institutions will be housed in this laboratory, which will have space for temporary storage of instrumentation. Also under review is the need for a clean room within the laboratory.

6.4.3 Telescope pier

The pier supporting the telescope will be a rigid cylindrical structure, formed by a ring of concrete, of approximately 15 m external diameter and height above ground level of 8 m. The pier will be a hollow cylinder through which the coudé beam, pipes and cables will pass. The girth ring for the hydrostatic bearings for azimuthal movement of the telescope will be situated on top of the pier. This azimuthal girth ring will support the entire structure of the telescope and its instrumentation. The pier will therefore be sufficiently rigid in order to support this load and avoid vibrations being transmitted to the telescope.

To minimize the transmission of vibrations to the telescope during observations, whether through movements generated in the dome or in other parts of the building, the pier will be isolated from the rest of the building; its foundations will be laid independently of the rest of the base of the building, any coupling via the ground being avoided where possible. Furthermore, the provision of a polystyrene screen between the foundations of this structure is foreseen.

Access routes for maintenance and for cables and ducts through the walls of the pier will also be taken into account. All pipes, cables and ducts that pass through the pier will need to be appropriately isolated in order to avoid transmission of vibrations to the telescope. Also contemplated is a passage through the pier for the light beam to be directed to the coudé room.

6.5 Annexe building

The annexe building will adjoin the telescope enclosure and is defined as a structure of conventional construction that will consist of a single floor, level with the base of the telescope enclosure. Independently of the areas requiring special thermal control (see Section 6.7.2), all the outer walls and the roof of the annexe will be thermally isolated.

Facilities will be made available in the annexe for the maintenance and storage of parts, as well as a comfortable working environment for telescope personnel and visiting scientists.

As can be seen in Figure 6.5, the annexe is clearly divided by the central corridor into two zones: on the left are the areas destined for continuous use by personnel working in the installation and for visitors; on the right are those areas allocated mainly for the housing of equipment, where there will not be a continuous presence of personnel.

6.5.1 Support areas included in the annexe building

The areas earmarked for installation operation and maintenance support will be distributed inside the telescope enclosure base and in the annexe. Figure 6.5 is a plan view of the installation with a provisional distribution of the support areas.

Below is a list of the support areas to be incorporated in the annexe:

- The telescope control room, which will be divided into two parts: the main control room and a smaller auxiliary room.
- The computer room for storage and processing of data obtained during observations.
- Electrical equipment area (uninterrupted power supply, electrical panels, etc.).
- Workshop area, (mechanical and electrical) where only immediate repairs will be carried out, as described in [6.6] and Section 9.3. For major maintenance operations, outside facilities will be used.
- Air-conditioning equipment area: part of the air conditioning equipment will be situated in the annexe, next to the workshop area.
- Storage area: it is intended to provide various storage areas, distributed so as to promote order and cleanliness, and to facilitate the tasks of operation and maintenance. Hence, there will be storage areas for optical components, electrical parts, instrumentation, mechanical and handling devices, etc.

- Offices: an area will be allocated for any offices whose location is deemed necessary or convenient within the installation.
- First aid room.
- Lounge: a recreation room will be provided for personnel. The room will also serve for holding meetings.
- Kitchenette–dining room.
- Toilets.
- Gangway area: the possibility of using this area as a visitors' gallery is being considered.

6.6 External installations

6.6.1 External accesses

The access road for vehicles will join the ORM roadway with the terrace of the GTC. This road will be approximately 5 m wide and 400 m long with a gradient of 6%.

The terrace will have a total surface area of 4000 m^2. The access road, parking space, paths and pavements will be surfaced to prevent erosion and keep these areas clean. Rainwater will be discharged by surface drainage, a sufficient number of covered sewers being provided to prevent erosion. Services such as electricity, telephones, network, etc., will be subterranean and will follow by the side of the access road.

The surrounding area of the enclosure will be covered with small quartz pebbles to reduce heating of the ground by solar radiation.

6.6.2 Other external installations

Away from the buildings but to be considered as part of the GTC, there will be:

- A transformer station. This is mandatory for all installations at the ORM, given that the power line from the town of Garafía that supplies the Observatory has a mean voltage of 15000 V.
- Refrigerating and heat-extraction ducts and some of the heat exchangers will be placed approximately 100 m away from the annexe, their location to be decided taking other facilities at ORM into consideration.
- Automatic power generating equipment for supplying electrical current in the case of power cuts. Fuel storage tanks also need to be taken into consideration.
- A water purification plant for the treatment of residue water.

6.6.3 Supplies and services

6.6.3.1 Water supply

There will be an underground water tank near the annexe with sufficient capacity to provide the installation with a week's water supply for the running of the kitchen, toilets, humidifiers, etc., and which will also guarantee the supply of water in case of fire. The water for this tank will be supplied by the authorized distributor for the ORM by means of water wagon. In the design of the installation the possibility of exploiting precipitation during winter will be considered.

6.6.3.2 Electricity supply

The ORM has a 15000-V power supply, so that a transformer station is required for administering the required voltages to the components of the GTC; i.e. 380 and 220 V.

The power supply in the GTC will be divided into three categories, depending on the degree of importance of non-interruption:

1. The supply to non-essential components, for which a power cut would not affect the operation of the telescope.
2. The supply to components that are essential for the operation and protection of the telescope, but that are not critical in the case of a brief power cut (less than 1 minute). The automatic generator will be used in such cases.
3. The supply to components for which any kind of power cut would be unacceptable. For these components the uninterrupted power supply in combination with the automatic generator would be used.

Which of these categories the subsystems fall under will be decided at a future design stage.

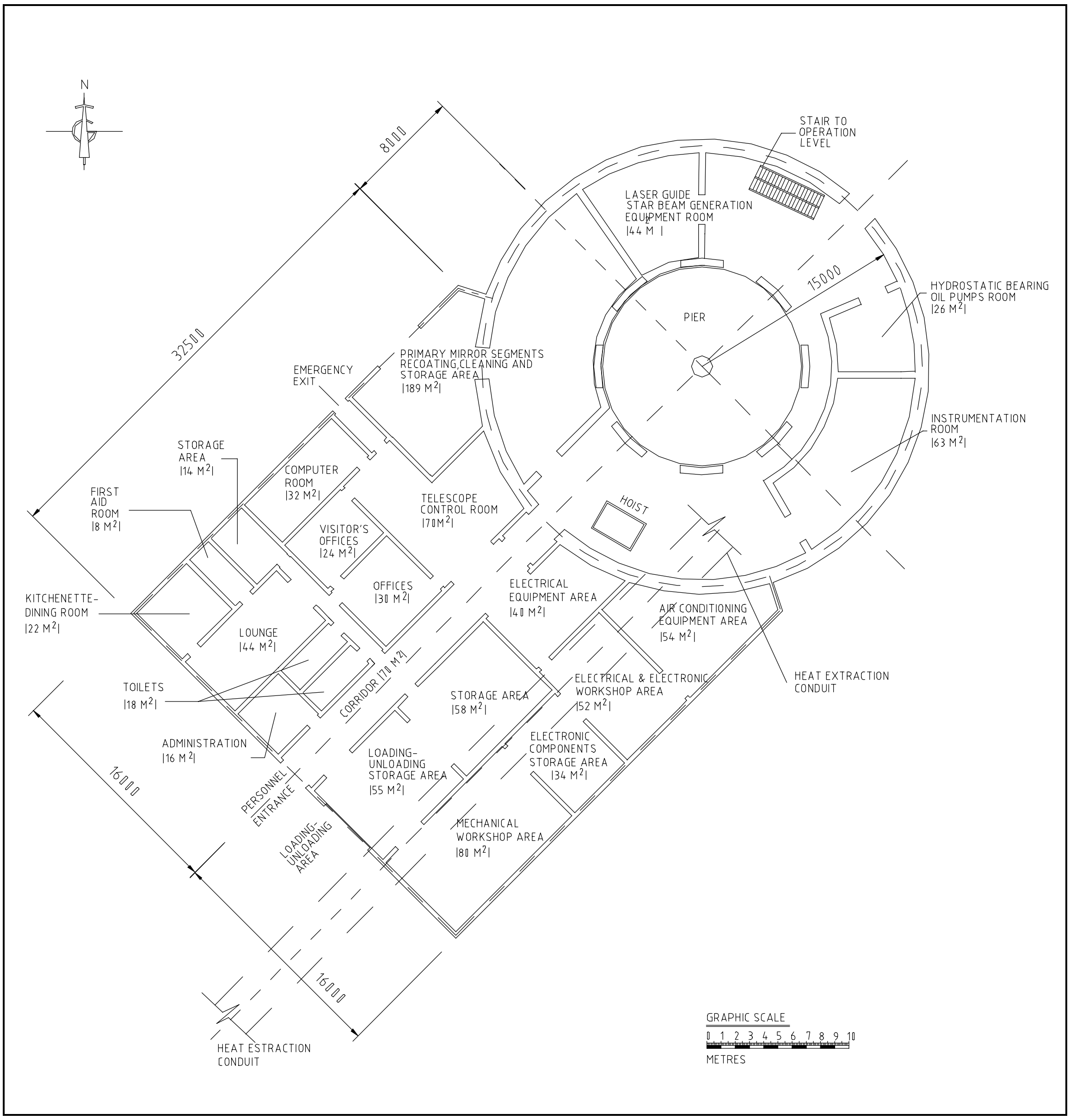


Figure 6.5: Plan view of the installation, showing a tentative distribution of the support areas.

6.6.3.3 Audio- and video-signal transmission and data transfer

The GTC will have structured cabling [6.7] which will provide support for:

- The transmission of audio signals within the installation in terms of voice communications of the users both among themselves and with the outside world, for which purposes connections will be provided for public and/or private voice transmission.
- Transfer of video signals within the installation for the purposes of monitoring and supervision.

- Transmission of service data[27], such as the interface with public and/or private data-transmission networks and the interface with the control system.

Also, provision should be made for the cabling needed for the transfer of operational data between and within subsystems.

6.6.3.4 Electrical earths

The earthing and shielding system should ideally provide an equipotential structure or framework within the installation. There will be several independent earthing systems [6.7] in the GTC. The design of these subsystems will be undertaken with a view to maximizing their conductivity and reducing the perturbations induced in signals of interest in all operational conditions, as well as guaranteeing the security of personnel and equipment by the prevention of large electrical discharges.

The poor electrical conductivity problems of the terrain on which the GTC will be built will need to be taken into account for the achievement of good earths, which may make necessary the use of a solution that guarantees the resistance requirements (e.g. a conductive gel).

6.7 Thermal control of the installation

6.7.1 Thermal control of the telescope chamber

The GTC will be located on a site of excellent astronomical quality (see Chapter 3). The presence of thermal turbulence due to the inhomogeneity of air temperature in the optical path of the telescope would degrade this quality. The GTC installation will have full thermal control for minimizing degradation of image quality.

To be able to meet this objective, the following policy will be adopted:

- Thermal loads generated by the motors and equipment located inside the telescope chamber will be kept to a minimum. For this reason the presence within the telescope chamber of such equipment will be avoided as far as possible, and power dissipation will be taken into account during the selection of such equipment.

- Any equipment which it is essential to install inside the telescope chamber (including astronomical instrumentation), and which, by virtue of its frequent use or because of the power it dissipates, generates a thermal load that is considered to be unacceptably high, will be isolated and will have a system of forced heat extraction. For some items of equipment the installation of a closed glycolated-water system will be considered.

- Materials and/or structures with low thermal inertia will be used in the telescope chamber wherever possible in order to decrease adaptation times to possible variations in outside temperature during the night.

- The telescope chamber will incorporate an air-conditioning system that will operate during the day, as well as natural- and forced-ventilation systems for use during observing periods, according to wind conditions. Furthermore, the dome will be thermally isolated from the

[27] In discussing data it is necessary to distinguish between service and operational data. By service data is understood those data relating to computer services (electronic mail, access to external information systems, other computer systems functions, etc.), and security (fire protection, access control, etc.). By operational data is meant those data relating to the primary functions of the GTC, these being defined as those proper to astronomical operations.

outside, and its external surface will be covered with special high-reflectivity paints in order to reduce the heating of the telescope chamber by solar radiation, thereby minimizing the loading on the air conditioning.

6.7.1.1 Air conditioning

To reduce the effects of heat produced inside the dome by solar radiation during the day and to minimize the effects of thermal inertia during the first hours of the night, the telescope chamber will incorporate an air-conditioning system in an effort to prepare the interior environment for observing, by adjusting the temperature to be equal to, or 1 °C below, the predicted outside temperature at the start of the night.

The GTC will have a weather-forecasting system for predicting the temperature at the start of the night at the ORM at least 8 hours in advance and with the lowest possible margin of error.

6.7.1.2 Natural ventilation

The dome will contain at least two tiers of windows in its structure to permit a continuous and controlled flow of air through the telescope chamber during observing. Experience at existing telescopes has demonstrated that natural ventilation is much more effective than forced ventilation and helps improve the quality of observations [6.8] [6.9] [6.10] [6.11].

The natural ventilation will be controlled such that the thermal requirements are met with minimum disturbance to the telescope structure, in particular from buffeting during high wind conditions. The natural-ventilation scheme to be incorporated into the GTC dome will be optimized by means of the aerodynamical studies mentioned in Section 6.4.1.

6.7.1.3 Forced ventilation

In addition to the natural-ventilation system, a system of forced ventilation will be installed in order to guarantee the renewal of air in the telescope chamber during those periods in which the use of natural ventilation would be inconvenient due to very low winds.

In periods of low wind speed[28] (< 3 m s^{-1}) natural ventilation cannot renew the air inside the telescope chamber at a sufficient rate. For these situations, the forced ventilation system will allow at least 10 complete air changes per hour.

In order to prevent sub-cooling of the external surface of the dome during the night, a set of axial fans could be installed between the external and the internal surfaces of the dome. These fans will circulate air at the outside temperature.

6.7.1.4 Thermal control of the telescope

A refrigeration system will be installed to actively cool those telescope subsystems which dissipate significant amounts of power.

6.7.2 Thermal control of support areas

[28] In the studies for optimizing the natural ventilation scheme of the telescope chamber, the minimum wind speed at which the natural ventilation is effective for different dome orientations with respect to the wind direction will be determined.

All those support areas where heat generation is foreseen to be important, especially those areas that could be in operation during the night, will be thermally isolated and will have a heat extraction system.

There are two fundamental objectives in the thermal control of the support areas: first, to prevent the heat generated in these areas from creating convective currents caused by thermal gradients inside the telescope chamber or in its immediate surroundings; secondly, to provide a conditioned environment in those areas of frequent use by personnel of the installation (e.g. the control room), as well as in those areas in which the equipment located therein requires certain environmental conditions (the computer room and the electricity control room, for example).

6.7.3 Warm-air extraction

The heat generated inside the installation will be extracted via ducts, which will carry the air to a sufficient distance, where it will be evacuated in a controlled manner. It is crucial not to affect the observations of either the GTC or of the neighbouring telescopes. In order to guarantee this, the exact location of the warm-air evacuation vents will be decided from the aerodynamical studies.

6.7.4 Control of the surface layer

Special care will be taken in the design of the entire installation in order to prevent air from the turbulent surface layer from entering the telescope chamber. In various sections of this chapter the actions being taken in this respect in the design of the GTC and the relevant aerodynamical studies have already been mentioned. Nevertheless, the following two key ideas that have been adopted in the design of the GTC for controlling the surface layer are emphasized:

1. The air entrances to the telescope chamber (ventilation windows and dome slit) will be at least 10 m above ground level to prevent surface-layer air entering. This height has been estimated as sufficient, within a reasonable safety margin, on the basis of working experience at the ORM in recent years, the site selection campaign carried out by the GTC (see Chapter 3 and [6.12]) and on reliable microthermal measurements carried out at the ORM in the past [6.13].

2. The risk of surface-layer air trampolining over the annexe building and into the telescope chamber must be avoided. For this reason, special care will be taken in the siting of the annexe in relation to the prevailing wind direction, its external geometry and its height above the ground.

Additionally, the possibility will be studied of using a wind deflector in the upper part of the telescope enclosure base in order to conduct the air flow around the geometry, while preventing part of the flow from rising towards the dome or towards the optical light path (a particularly unfavourable condition if the telescope is pointing near the horizon and facing into the wind).

6.8 Environmental impact

The ORM is located on the boundary of the Caldera de Taburiente National Park and is therefore considered as an area of ecological sensitivity. The grounds of the Observatory are classified as non-urbanizable, an exception being made to this ruling in the case of installations destined for astronomical use[29], with the prior agreement of the Park and other relevant authorities.

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[29] For more information on this topic it is worth consulting the Agreement on cooperation in the matter of Astrophysics signed by Spain and the international scientific community on 26 May 1982, and Law 4/1981 of 25 March, concerning the reclassification of the Caldera de Taburiente National Park.

The project does not need any other natural resource apart from the ground on which it is located. On the site selected for the GTC (see Chapter 3) there are no geological, archaeological or water resources that need to be protected. The project does not imply any damage to existing species of flora or fauna, nor does it favour the growth of any potentially harmful species. Given that the installations of the GTC will not be visible from “La Cumbrecita” viewpoint and other sensitive sites in the National Park, there will be no effect on the landscape.

All necessary preventive measures will be taken to minimize any possible negative effects of the installation. In this sense, noise could be produced whenever an electrical generator kicks into operations. As a preventive measure, the generator room will be sound-proofed so that the noise would be imperceptible outside the complex. None of the other installations produces any significant noise.

Similarly, gases could be generated, when the power generator is used, or during the process of cleaning and re-coating the optical components of the telescope. Given that the volume of these gases would be small, and the prevailing wind regime of the ORM would contribute to their rapid dissipation, such gas emissions are not considered as harmful to the environment.

Heat generated by different equipment will be transported to the environment in a controlled manner, in accordance with the prevailing wind direction. Special care will be taken with the generation of heat since this would in fact negatively influence astronomical observations.

Liquids generated by the installation, as in the case of the effluents from the purification plant for residue water, will be non-contaminant. The necessary precautions will be taken for the neutralization waste products arising from the periodical process of cleaning and re-coating of the telescope mirrors.

Finally, the environmental impact due to human activity in the area of the installation will be negligible.

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7. INSTRUMENTATION

7.1 Introduction

The GTC will be located at the ORM where the median seeing is about 0.6 arcsec, and values as low as 0.2 arcsec have been measured. Water-vapour measurements also indicate an appreciable fraction of the nights (27%) have values below 2 mm of precipitable water. The GTC is therefore being designed to benefit from the excellent seeing at the ORM and hence provide unique capabilities in terms of collecting power, image quality, and low intrinsic emissivity. In particular, with image-motion correction, the telescope will be able to deliver diffraction-limited images in the *M* band. The GTC will employ an AO system capable of producing a 2-arcmin corrected field in the near IR. To exploit these capabilities fully, an important requirement of the GTC project is to provide a suite of high-performance facility instruments that comply with the top-level science requirements [7.1].

However, these instruments must have a wide general appeal and not be aimed at solving one particular problem. A fundamental criterion for a facility instrument, therefore, is that it be capable of generating sufficient interest in the community for there to be a large number of good proposals for its use.

The purpose of this chapter is to explain the ideas for facility instrumentation, the sorts of instruments required, etc. This chapter will not go into detail on the instruments themselves as the Keck and various 8-m projects have demonstrated that instruments of the kind required can be successfully constructed for a 10-m telescope. Related subjects, such as data archiving, calibration and detector strategies are also discussed.

7.2 General requirements for instruments

While the instruments will be diverse there are a number of common requirements. The GTC project is to provide a suite of high-performance facility instruments that meet the following requirements:

- The instruments must be competitive with those at other facilities
- The set of facility instruments must together provide a capability for spectroscopy at various resolutions, imaging, and polarimetry between 0.3 and 15 μm.
- Several facility instruments will be simultaneously on standby to provide imaging and spectroscopy capabilities over a wide wavelength range (0.3 to 2.5 μm).
- As there will be relatively few instruments, most will have to have multiple modes of operation; for example, imaging and spectroscopy combined in the same instrument.
- All of the instruments must have high throughput.
- As far as possible all calibration processes should be automated.
- All of the instrument control systems must be integrated with the GTC control system so that the whole acts as a single unit. This is particularly important for chopping, where the detector readouts have to be synchronized with the secondary-mirror position.
- Standardized components will be used where feasible.
- Common physical, logical and user interfaces with the rest of the GTC should be used by all instruments.

- All instruments must be simple to mount/dismount and balance.

7.3 Strategic considerations

There is a top scientific requirement for the simultaneous availability of imaging and spectroscopy over a wide wavelength range, e.g. 0.3 to 2.5 μm. The main reason for this is queued service observing, so that observations can be scheduled immediately before they are actually performed in order to make optimum use of the prevailing weather conditions, the minimum requirement being that, when an instrument which requires excellent weather conditions is mounted (e.g. a 10-μm system, or an AO instrument), there must be a more general purpose instrument (e.g. an intermediate-dispersion visible imager/spectrometer) available to obtain useful data in poorer weather conditions. For queue scheduling to work efficiently in practice there needs to be a wide range of observing options simultaneously available. The implication of this is that multiple instruments must be mounted and available for use, and only a few minutes are needed to change between them. As the tertiary mirror can be removed from the light path in 5 minutes, both Cassegrain and Nasmyth foci will be available on the same night.

The two workhorse instruments will most probably be a visible intermediate-dispersion imager/spectrometer and a near-IR camera/spectrometer; so these should always be available as a minimum requirement.

The distribution of the instruments amongst the various foci will be decided finally by the Science Advisory Committee. It is clear that from emissivity considerations the thermal-infrared instruments (λ > 2.1 μm) must go on the Cassegrain focus. Hence the visible intermediate-dispersion imager/spectrometer could be located at one of the Nasmyth platforms. This would be required anyway if heavy instruments are chosen. However, visible polarization measurements are best done at Cassegrain as there is no 45-degree mirror. Clearly, a compromise must be reached but this will require a wide consultation among the community. In any event, the actual distribution of the instruments should not affect the GTC as the dimensions and weights at each focus are defined (see Figure 5.1 and Table 5.1) and the instruments must be built to these specifications.

7.4 Calibration

With many current instruments it is calibration that limits the achievable accuracy, and even when the stated S/N ratio is high, systematic effects limit the actual accuracy. The facility instruments will have strict requirements for calibration, as given below:

- Accuracy of the flat fields < 1 part in 1000.
- Accuracy in determining the bias < 1 ADU (A to D units) rms.
- Accuracy of non-linearity correction < 0.5%.
- Accuracy of wavelength calibration < 10% of the spectral resolution.
- The calibration of the instrument must be stable during the night and from night to night.

At the design stage of each instrument a calibration plan for all possible modes of operation will be produced. The time required to obtain the calibrations should be short, particularly for those taken during the actual observations.

In general the calibrations are left to the astronomer and are often performed in a haphazard manner, such that in too many cases there are insufficient calibrations to reduce the data correctly. For the facility instruments a minimum number of calibration observations will be required but, in contrast with the science observations, the astronomer will have no proprietary rights over the calibration data, which will be archived separately and so provide a history of the performance of the instrument as well as allowing easy retrieval.

7.5 Data reduction

For the majority of instruments the data reduction processes are standard. For example, when reducing CCD data, whether from an imager or spectrometer, the raw image has the bias subtracted, is flat-fielded, has bad pixels removed, etc. Each detector will have its own specific parameters, but the processes are identical and in practice astronomers with data from a specific instrument return to their home institutions and carry out the same standard reduction procedures on their data.

Part of the delivery will be an automatic reduction process which will automatically remove the bias, flat-field the images, etc., and for spectrometers will calibrate the wavelength. The aim will be to have the process running on line, using the best calibration data available, so that the astronomer can see reduced data rapidly after the exposure is taken. The process would then be run the following day, using all of the calibration data from the previous night, to produce the reduced images. The output from the process should be of sufficient quality and reliability so that many users will work from the reduced data.

7.6 Data archives

Experience with various data archives, such as *IUE* or *HST* shows that a good data archive quickly becomes an important astronomical tool in its own right. The GTC will have two data archives:

1. The calibration archive will store all bias frames, flat-fields, bad-pixel masks, wavelength calibrations and standard-star observations. As well as allowing any calibration measurement to be easily recovered, it will help with monitoring the performance of the instruments.

2. The data archive will store the raw and reduced data. This will act as a backup for all observations so that data cannot be lost; however, the primary aim is to provide an accessible astronomical database. It is expected that much of the data will find uses not initially envisaged by the proposer of the observations and hence significantly increase the scientific output of the telescope. The data will have a proprietary period; however, once this has lapsed, the data (principally the reduced data) will be made available to the community at large. Calibration data will not have a proprietary period.

7.7 Proposed instruments

The following list of instruments is really a wants list. It is not intended to be complete but rather to give an idea of the sorts of attributes that are required.

7.7.1 The 1–5 μm camera/spectrometer

As this will combine imaging and spectroscopy, and as seeing is always better in the near IR than in the visible, this is a possible first-light instrument since it will provide the best test of the imaging performance of the telescope. Its main characteristics will include:

- The largest InSb detector available (currently 1024 square), possibly double channel.

- Pixel sizes 0.15 to 0.03 arcsec per pixel. This will give a maximum field of 2.5 arcmin and on the finer scales will allow the diffraction-limited image at *K* to be oversampled.

- A number of broad- and narrow-band filters.

- Long-slit spectroscopic capabilities with resolutions from 500 up to 5000. This is sufficient for isolating the OH bands in the *H* window and will therefore reduce the background between the lines.

There are a number of extras which should be considered, namely:

- An integral field unit[30] (i.e. image slicer) with an effective spatial resolution of 0.1 arcsec. This will allow an area of about 2.3×3.5 arcsec^2 to be spectrally imaged. This has two significant advantages. As the whole field is imaged at once the seeing is the same for all sources in the image. So it will be ideal for imaging centres of galaxies where the areas of interest are at higher spatial resolution. The second advantage is that, unless the seeing is very bad, 100% of the energy from the source will be collected and the slit can be set during the data reduction to maximize the S/N ratio. In this way the integral field unit will make the instrument considerably more sensitive for point sources.
- There could possibly be a choice of image slicers giving various resolutions.
- A coronagraph will allow images to be taken close to bright sources, a necessary feature for observing planetary rings around bright stars.
- A fast shutter that allows bright objects to be observed, and possibly speckle interferometry.
- A polarimeter.

7.7.2 Intermediate-dispersion visible imager/spectrometer

This will probably turn out to be the most frequently used system on the GTC and hence should be one of the first instruments to be mounted. Its primary characteristics are:

- 2×4k CCD arrays (probably multiple).
- High throughput, particularly in the low-resolution modes.
- Resolution from a few thousand to 80000 with interchangeable gratings.
- Wavelength range from 0.3 to 1 μm.
- Variable slit sizes from 0.2 to 2 arcsec by 7 arcmin.
- Imaging over a field approaching 7 arcmin.
- Multi-slit facility.
- The ability to take the feed from fibres so that the instrument can be used as a multi-fibre or and an integral-field spectrometer.
- Polarimetry.

7.7.3 10-μm imaging spectrometer

[30] An integral field unit is a device that allows spectral imaging of a given region in the sky, normally through the use of fibre-optics bundles or an image slicer.

This will be a Cassegrain-mounted system in order to minimize the thermal backgrounds. Its basic characteristics are:

- The largest available array (currently 128 pixel square).
- A pixel size of about 0.06 arcsec per pixel.
- A spectrometer with resolutions of hundreds to a few thousand.
- An integral field unit.

7.7.4 High-resolution visible spectrometer

This will probably be mounted on one of the Nasmyth platforms. The main characteristics are:

- Spectral resolutions of 100000 to 500000.
- Wavelength range from 0.3 to 1 μm.
- Probably based on a cross-dispersed echelle grating.

7.7.5 High-resolution IR spectrometer

This instrument would probably go to one of the Nasmyth platforms. Its basic characteristics are:

- 1–5 μm wavelength range.
- Spectral resolutions of 10000 to 50000 or greater.
- Possibly a cross-dispersed mode.
- Possibly an integral-field unit for best sensitivity.

7.7.6 Instrumentation for adaptive optics

It is intended to have an adaptive optics system operating relatively soon after the telescope begins normal operation (see Section 4.6). While the 1–5 micron camera/spectrometer will be built to operate at high spatial resolutions, it is probable that a specialized high-resolution system will outperform a more general purpose instrument. Therefore, a possible adaptive optics instrument will be a high spatial resolution near-infrared camera/spectrometer. This instrument will carry pixels sized to oversample the telescope diffraction limit at *J* (0.01 arcsec) and *K* (0.03 arcsec). It should also include a coronagraph and diffraction-limited integral-field capability in the *K* band. Finally, it should also include a multi-slit capability (based on programmable micromirrors).

7.8 Parallel observing

One of the top requirements of the GTC is to maximize the scientific return. In order to reach this aim, several parallel-observing strategies to increment the science return can be pursued:

- Many of the science instruments will only use a very small part of the available FOV, and even after the needs of the A&G system are met there will still be a large part of the FOV available. One possible parallel instrument would be a visible or near-IR camera for deep off-axis imaging. The limiting magnitude (S/N ratio = 10 in 10 minutes of integration) would be about *V*=24 mag or *H*=22 mag and would hence provide a powerful tool for deep keyhole surveys which could be of particular interest for extragalactic studies. While there is little choice in the fields to be observed the advantage is that a statistically significant area of sky could be obtained relatively quickly and for little cost in terms of observing time.

- The GTC will have one or more laser projection telescopes mounted in parallel for use with AO. These telescopes will be about 50 cm in diameter. One possibility would be to mount a visible CCD on these telescopes when they are not being used for AO. With a FOV of 0.5 degrees, this would allow simultaneous absolute and relative broad-band photometry of the whole focal plane and would give a similar limiting magnitude to an intermediate-resolution spectrometer on a 10-m telescope. The availability of simultaneous photometry could significantly add to the scientific return.

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8. CONTROL SYSTEM

8.1 Introduction

The control system of the GTC will operate the telescope and its instrumentation as a single entity. It will be responsible for the operation and any computational needs of the GTC and will consist of the necessary software and hardware to provide:

- Control and monitoring of the GTC, with the aim of optimally managing the scientific observations, as well as the automatic execution of these.
- Management of astronomical data, i.e. acquisition, reduction and archiving.
- Necessary on-line processing for the calibration of the telescope and its instruments.
- Interfaces for off-line processing facilities (data analysis).

The continuous and rapid development of hardware, software and communications technology has permitted a greater complexity in control systems. In their turn, the development of active and adaptive optics, the new methods of optimizing available observing time and the continuous development programmes to maintain telescope competitiveness present new challenges in the design of control systems.

During its life-cycle, the control system of the GTC will be subject to continuous changes brought about by different factors, such as the advent of new technologies, the evolution of the requirements, the development of new instruments and fault correction. These factors must be taken on board with the minimum possible impact, not only on the project but also on the availability of the GTC once it enters into operation. This will only be possible through the selection and planning of an adequate technological framework [8.1] that enables these changes to be assimilated throughout the life-cycle of the telescope.

The ideas presented here constitute a vision of the conceptual design of the control system based on the present state of technology and on the forecasts of its evolution that can be realistically expected in the near future. This design could undergo various modifications due to possible future technological advances.

In this chapter the concept of the GTC control system design is outlined. After presenting the main design guidelines and control-system functions, the architecture is described. Finally, some important issues with respect to software engineering are discussed.

8.2 Design guidelines

The following design guidelines, deriving fundamentally from the requirements of the GTC (see Chapter 2), have been established:

- The GTC, expressly including the scientific instruments, will be controlled as a single entity in all its possible configurations and modes of operation.
- The control system will carry out the tasks of observational data management (acquisition, processing, storage and retrieval).
- The overall operation of the GTC must be as efficient as possible so as to maximize the scientific return. This will include assisting the user in the planning and performing of observations.

- The control system must be designed to allow smooth evolution.

In order to meet its requirements and objectives there are several factors [8.2] that are necessary to take into account in the design of the control system:

- *Extensibility* is the ease with which systems can be adapted to changes in specifications. The control-system software, as is usual for software supporting scientific instrumentation, will be in continuous evolution during its operating life; therefore, it must be designed to be open to extensions without affecting those parts already in operation.

- *Correctness* of the system; i.e. its facility for carrying out tasks with exactitude, as defined by the requirements and specifications. It is important that these requirements be expressed in a formal way. The control system must provide adequate mechanisms for the prevention and diagnosis of errors with the aim of maximizing available observing time and minimizing down-time.

- *Robustness* is the capacity of a system to operate in abnormal conditions. The control system must ensure that in cases where such conditions occur, there will be no catastrophic events. It must finish its execution cleanly, or enter into a mode of ‘graceful degradation’.

- *Ease of use* is the degree of simplicity with which users learn how a system is operated, prepare input data, interpret results and recover from errors. To maximize the scientific use of the GTC, one of the key objectives is to provide a system that adequately recognizes the way in which astronomers work, and that places in their hands a powerful, efficient and easy-to-use tool which will allow them to concentrate on obtaining scientific results. It is therefore fundamental that the final users of the system are fully implicated in the definition of the specifications, system use-cases and scenarios [8.3] and in the subsequent system development.

- *Reusability* is the capacity of a software product to be re-used, completely or partially, for new applications. For the project this means less code to be written and, therefore, more time available (for the same cost) for improving other factors. This factor will also be important for maintenance.

- *Compatibility* allows the combination of hardware and software components from different sources. The use of well defined interfaces and the adoption of recognized standards will be indispensable.

- *Efficiency* in the use of hardware and communication resources is an essential requirement in any software product; this should be optimized.

- *Portability* allows software products to be transferred to various hardware and software environments. For this reason, the adoption of *de facto* industrial standards, for both hardware and software, will be encouraged.

- *Verifiability* allows the development of acceptance, fault detection and diagnostic procedures during the phases of validation and acceptance. Both formal methods during software construction and continuous diagnostic techniques during operation will be used.

- *Security* considerations are obligatory given the remote-operation needs of the GTC. Moreover, the system will be continuously visited by different users, many of them having their first contact with the GTC. The integrity of the system will be guaranteed by protecting it from involuntary errors and unauthorized access.

- *Maintainability* provides the means to respond to new requirements, or to correct errors. A large part of the costs related to software are dedicated to maintenance. In accordance with recent trends the evolution and maintenance of the control system need to be considered as a phase of the development process.

The above factors describe the desired external observable properties of the whole system. From an internal perspective a series of basic principles will be applied: use of modular units, minimization of the number of interfaces, and those interfaces that are necessary will be as small and explicit as possible. This has the aim of providing a modular system that exhibits the above external properties. In general, these modules must be at the same time ‘open’ and ‘closed’, i.e. they will be simultaneously available for extension and for use by other modules. The development of object-oriented analysis, design and programming techniques, based on the above principles, convert them into indispensable tools.

8.3 General description of the control system

The GTC will consist of a set of subsystems that will work in a coordinated manner. These subsystems will be physically distributed in the installations of the GTC [8.4]. The responsibility of the control system will be to control these subsystems and provide a single homogeneous user interface.

The physical architecture of the control system will consist of a set of interconnected computers, electronic equipment, sensors and actuators. These elements will be responsible for the direct control of the different subsystems of the GTC. The central core will exhibit deterministic time behaviour, for which reason the use of mechanisms to guarantee quality of service[31] (QoS) will be important. The control system will be responsible for other tasks (e.g. planning of observations, archiving of data, analysis of data quality) for which there will exist a number of workstations connected via one or more local area networks, which will provide access to a group of centralized services (e.g. catalogues, data archives).

An open, flexible, distributed and object-oriented software architecture will be used in order to provide location-transparent access to different distributed services (see Section 8.5.2.3). These services are also required to guarantee a level of QoS. The implementation of this architecture will be simplified through the use of a distributed middleware[32]. This middleware will ensure, by suitable planning policies, that all tasks will have the necessary resources. It will provide a ‘plug&play’ skeleton where the different software components of the control system will be connected. This architecture will provide a homogeneous environment so that the time and cost of development of the different components will be reduced.

8.4 Main functions of the control system

8.4.1 Management of observations

The control system will be responsible for all aspects related to the planning and execution of observations. In order to maximize the scientific return of the GTC, various forms of operation will be provided.

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[31] QoS enables a service to be carried out in accordance with certain specific yield requirements.

[32] A distributed middleware provides a series of programming abstractions independent of the communications networks.

8.4.1.1 Modes of operation

The GTC will have three basic modes of operation (Section 2.5.1.1), which are summarized here. The fundamental differences between these modes are the level of interaction possible with the telescope and who is responsible for the operation of the telescope during the assigned period.

1. *Queued service observing:* Many astronomical projects can be attempted only when the observing conditions (e.g. meteorology, seeing) are excellent. These factors can only be determined immediately before the observations take place. Hence a mode of operation is required that allows each observing programme be carried out in optimum circumstances. Astronomers will be required to submit complete and correct observing programme specifications well in advance; the accepted programmes will be then queued. A scheduler, which takes into account the meteorological conditions, scientific priority and requirements of the individual programmes, will be used to decide the order of execution of queued observations under the monitoring of the support staff of the GTC. The astronomers will be able to 'listen in' remotely on his observations, but will not be able to influence them.

2. *Classically scheduled observing:* The time allocation committee assigns specific dates to a scientific programme. The astronomer will be responsible for the operation of the GTC during this period. Two possibilities exist:

   - *Assisted observation:* The astronomer will structure his observing programmes into blocks, which the scheduler will order to maximize efficiency. The observation will therefore take place in a similar way to queued service observing, except that the astronomer will have full control over the queue.

   - *Detailed observation:* The astronomer enters each command individually into the telescope control system and each command is acted upon as it arrives. For system safety the commands will be entered into a command sequencer so that high-level checking can be performed.

   In both cases the astronomer will be able to operate the GTC remotely.

3. *Engineering mode:* In this mode the primary goal of the time use is not science, and the operations are performed by GTC staff or persons with detailed knowledge of the subsystems. The operations include commissioning any new telescope subsystem or instrumentation, calibration and diagnostic testing. For some of these operations direct access to subsystems will be required.

8.4.1.2 Observations

An observing programme will be made up of a set of observation blocks. An observation block will contain all the information necessary for carrying out an observation (see Figure 8.1): the configuration of the GTC (focus, instrument, etc.), instrument configuration, observing parameters (position of object, exposure time, filters, diffraction grating position, etc.).These blocks can be mutually interdependent; e.g. A after B, or A, B, C sequentially and indivisibly. While in general observation blocks will be scheduled immediately before they are performed, it will be possible to have fixed-time observations. Hence an observing block is the key constituent which allows the coordination of the information required to go from the proposal, through the observations and calibrations to the final reduced data.

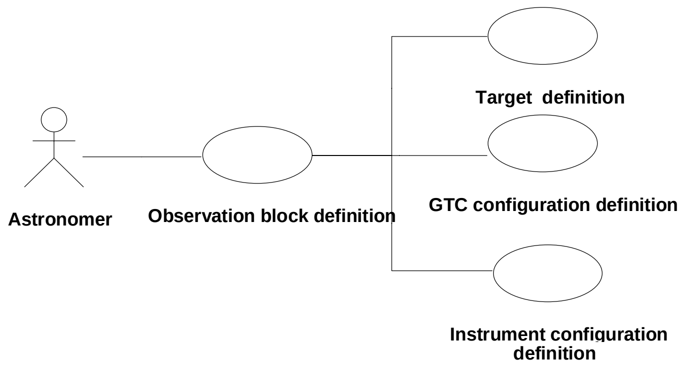

Figure 8.1: Use-case diagram of preparation of observations.

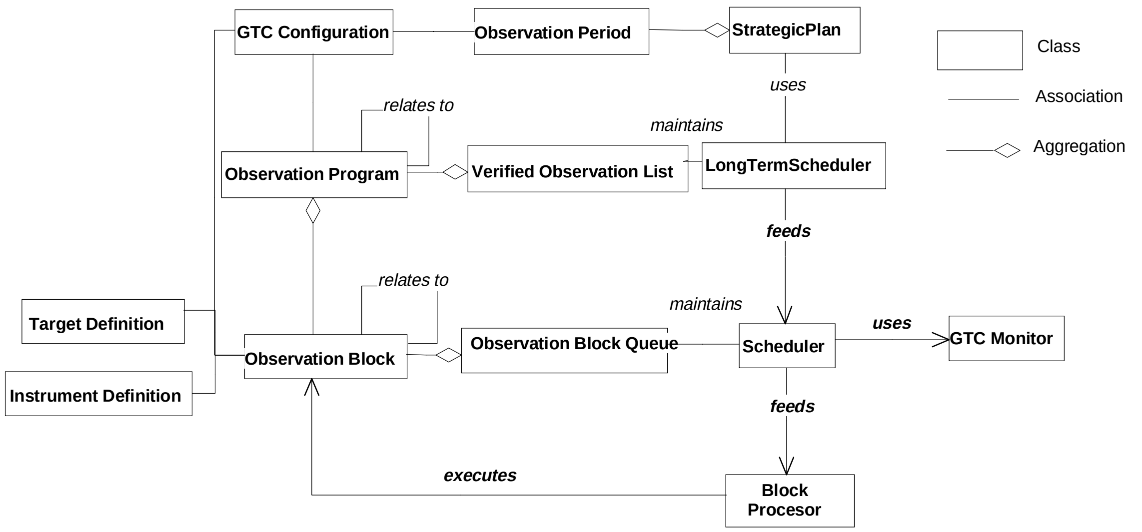

Figure 8.2: UML observation block processing class diagram.

From the observing programmes and the general calibration procedures of the instruments and telescope, the scheduler will optimize the sequence of operations with the aim of maximizing the efficiency of the system and the scientific yield. The optimization criteria could be scientific priorities, observing conditions (e.g. seeing, relative humidity), minimizing overheads (e.g. pointing time and changes of configuration), capturing the object in the most favourable tracking position, etc. Figure 8.2 shows the high-level structure for the scheduling using Unified Modeling Language (UML)[33].

There will be software to help users prepare their observations. This software will allow performance simulations and carry out checks in order to minimize errors. This procedure must be sufficiently intuitive so that inexpert users can familiarize themselves with it in the least time possible.

[33] UML is a language for specifying, constructing, visualizing and documenting the artifacts of a software-intensive system

8.4.2 Telescope control

The control system is responsible for maintaining, in real time, both the aperture of the scientific instrument on the required position on the sky and the required optical configuration of the telescope. This requires the combination of several processes: pointing, acquisition, tracking and guiding (see Figure 8.3), as well as open- and closed-loop active optics to maintain the configuration of the optics actively (Figure 8.4). Calibration procedures to create and maintain the telescope behaviour model (see Section 4.5.3) will be needed. The detailed requirements are presented in Chapters 2 and 4.

8.4.2.1 Pointing

The centre of the aperture of the active instrument is positioned at the coordinates indicated. The movement will be carried out as quickly as possible within the limits of position, velocity, acceleration and safety. Models will be used for determining the target position and trajectory, behaviour of the telescope, atmospheric refraction, etc.

8.4.2.2 Target acquisition

Using a celestial reference, normally an image, the desired position within the aperture of the active instrument is located at the specified target coordinates. This has a far higher precision than pointing. If the position of the object is known with high precision, the acquisition will be carried out automatically. For other cases (e.g. comets, high proper motion objects) the acquisition will be confirmed interactively. The possible kinds of acquisition will depend on the observing technique:

1. *Off-axis sensor*: The off-axis A&G guide camera will not image an on-axis object during scientific observations; however, if the offset between a suitable off-axis guide star and the object is known, then the position of guide star in the camera can be used to determine accurately the position on the sky relative to the aperture of the scientific instrument.

2. *On-axis sensors*: When making infrared observations a dichroic will be used to split the infrared light, which is passed to the scientific instrument, from the visible light, which is passed to a guide camera. Hence, the guide image can be used to position the aperture accurately. A further possibility is that long-slit spectrometers may have a slit-viewing camera mounted so that an image of the sky surrounding the slit is produced.

3. *Using the science instrument*: If the instrument has an imaging capability, then a test image can be obtained to confirm the position of the object on the detector. If there is no imaging capability, for example an aperture photometer, then beam profiles can be obtained to locate the position of the aperture.

8.4.2.3 Open-loop tracking

The defined position in the aperture of the active instrument will be maintained relative to the object of interest during the period specified and while it remains accessible. During open-loop tracking no celestial position reference is available so the motion of the telescope mount and rotators are determined by models. These models will allow tracking at sidereal or non-sidereal rates, or will allow specific telescope calibration test (e.g. constant velocity, constant acceleration). In order to fulfil the tracking requirements detailed models of the behaviour of the system will be needed (e.g. telescope flexure).

If the field rotator is active then the orientation of the image is fixed relative to the science instrument, whereas if the rotator is not active then the image will rotate. In the latter case it should be possible to position the apparent axis of rotation anywhere within the FOV of the telescope. Hence if the centre of the instrument aperture is not exactly aligned with the mechanical axis a point source can be maintained within the aperture.

8.4.2.4 Slow closed-loop guiding

Measurements of a guide star will be used to maintain the position of the aperture of the active instrument relative to the specified coordinates. These measurements are used to correct the non-modellable errors in the tracking and hence the guiding accuracy is greatly improved, particularly over long periods.

The aim of slow closed-loop guiding is only to correct the low-frequency position errors. Hence the frequency at which the guide errors are passed to the mount control will be low, well below the resonant frequency of the telescope structure. The star will be sampled at a frequency of at least five times that at which the position error is passed to the mount control subsystem.

Normally a field rotator will be used; hence the relationship between the instrument aperture and the guide probe remains fixed on the sky. However, there are situations when field derotation is not used, and the control system should track the guide star as it moves across the FOV of the guide camera.

8.4.2.5 Image-motion correction

In order to correct the higher-frequency position errors outside the range of the slow guide system a fast tip-tilt motion of the secondary will be used to steer the image in the focal plane. A fast guide sensor will be used to measure the position of the guide star in the focal plane and hence to derive the necessary corrections. The frequency of the control loop could reach 40 Hz, in which case the readout of the sensor will be carried out at at least 200 Hz.

Image-motion correction will attempt to correct two kinds of effects, windshake (all wavelengths) and atmospheric image motion (this will obtain diffraction-limited images for observations carried out at $\lambda > 3.5$ μm in good seeing conditions). In any case, the guide star must be within the isokinetic patch (~ 2 arcmin, see Section 4.6.1).

Additionally, if fast focus correction is implemented (Section 4.8.2), this will require fast piston motion of the secondary and a fast wavefront sensor to detect the error.

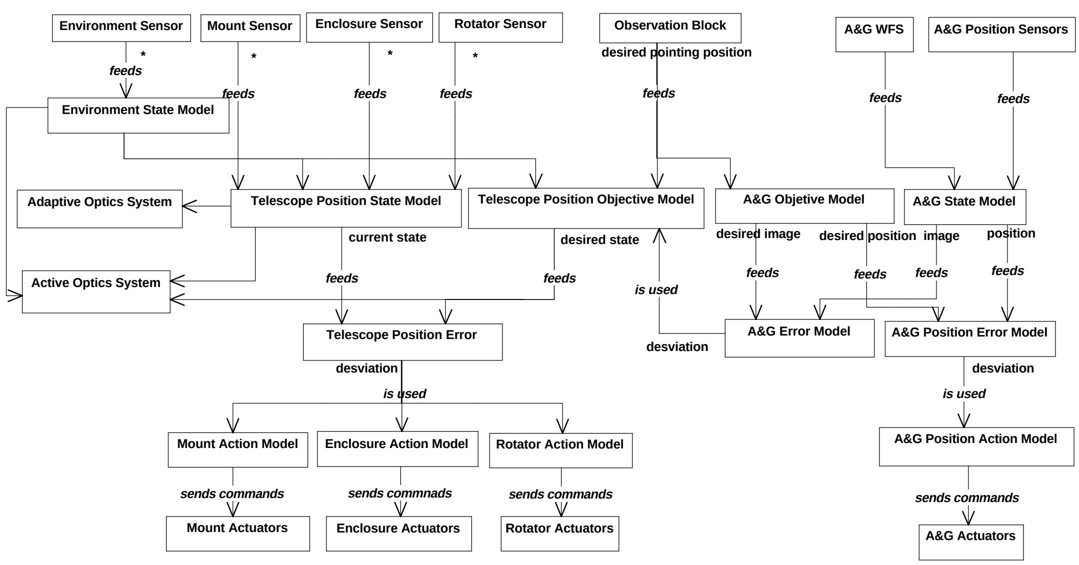

Figure 8.3: Telescope position control class diagram. An explanation of the different models used to represent the domain of the problem can be found in Section 8.5.2.2.

8.4.2.6 Open-loop active optics

Open-loop active optics actively maintains the real optical configuration as close as possible to the requested configuration, using models to correct the thermal and gravitational distortions of the system. Various sensors will be used to measure the relative position of the segments with respect to one another, the absolute positions of the segment in relation to the cell, and the position of the secondary mirror. Using the telescope behaviour model, this information will be used to correct the errors in the optical alignment.

8.4.2.7 Closed-loop active optics

A wavefront sensor will be operated in the focal plane simultaneously with the active science instrument. The aim is to measure and correct continuously two aspects of the optical configuration, tip-tilt errors between the segments, and the alignment of the primary and secondary mirrors. These measurements will be used to update the optical state model. This is compared with the desired optical configuration to obtain the errors needed to correct the optical system by feeding the desired electronic-sensor objective model. To obtain sufficient precision, long integration times are required (> 30 s) in order to average out the effects of seeing. Hence the time for closure of the loop will be slow (> 2 min).

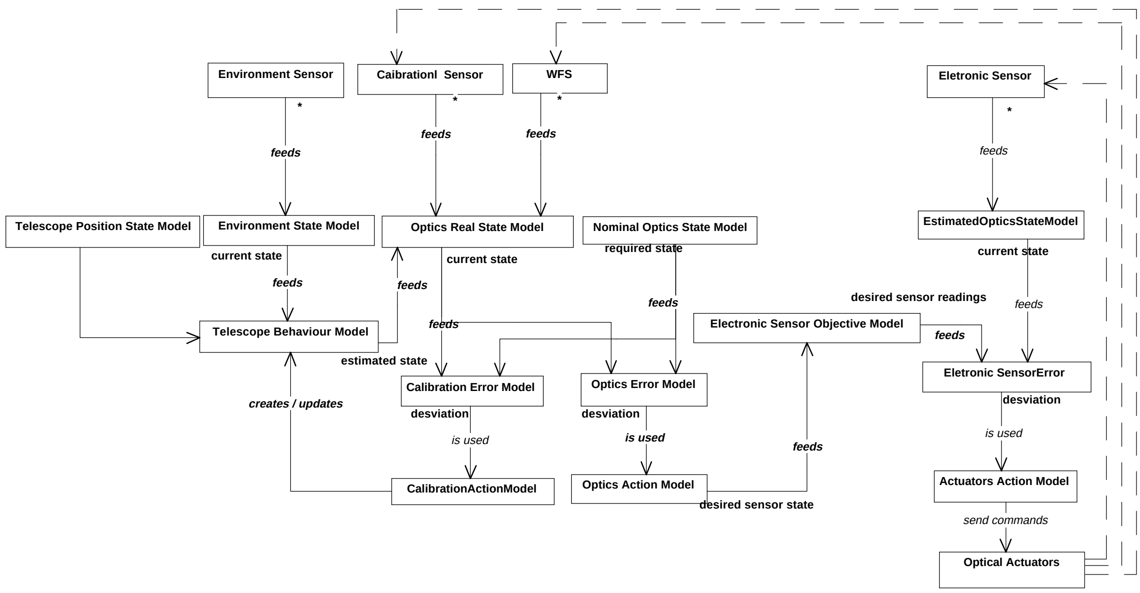

Figure 8.4: Active-optics object diagram.

8.4.2.8 Calibration

The aim of the calibration is to provide the information needed to update the telescope behaviour model. This model will include different environmental conditions and telescope attitudes. Specialized strategies and instrumentation will be developed for the various calibration procedures. These procedures must be as efficient and automatic as possible. The calibration process requires the following measurements to be taken:

- The figure of each individual segment.
- The relative alignment (tip-tilt) between the segments.
- The relative phase (piston) between the segments.
- The relative alignment between the primary and secondary mirrors.
- The pointing accuracy of the telescope.

The calibration procedures adopted by the GTC will allow the measurements to be spread over time to profit from the best conditions when they are available. As well as having scheduled blocks of time specifically for calibration, there will be measurements taken on a nightly basis and possibly even during the night (e.g. using measurements taken from the closed-loop active optics sensors). The telescope behaviour model will be updated whenever the measurements are known to improve it.

8.4.2.9 Adaptive optics

The control system must anticipate the requirements for high-order AO (see Section 4.6.2), including the control of the laser guide star. A high-speed wavefront sensor will be used to measure the errors in the wavefront which will be corrected using a deformable mirror.

8.4.3 Instrument control

The control of the scientific instrumentation will be coordinated by the control system of the GTC. Standardized interfaces (user, electronic and software) will be used at several levels between the control system and instruments.

8.4.3.1 High-precision synchronization

There will be situations in which a precise synchronization between the various components of the GTC will be necessary. For example:

- *Chopping:* The exposures have to be precisely synchronized with the position of the secondary mirror at the highest frequencies. This will require a precision of a few milliseconds.
- *High temporal resolution photometry:* These observations must be carried out with a high absolute time precision.

8.4.4 Enclosure control

Various subsystems of the enclosure will be controlled. The dome, shutter and wind screen movements will be synchronized with the telescope position during observations.

Based on measurements of the temperature within the telescope chamber and external meteorological conditions, the control system will optimize the air flow through and around the telescope. When the wind speed allows natural ventilation, the apertures of the windows and the positions of the louvres will regulate the air flow entering the chamber (Section 6.7.1). With low wind speeds forced ventilation will be used.

8.4.5 Observation and data management

The control system will coordinate the data acquisition, reduction and archiving procedures.

8.4.5.1 Observation

The control system will coordinate the operation of the telescope and instrumentation. The raw data will be read from the instrument. A series of basic data-reduction functions will be provided to transform the raw data into a form useful to the user. Three levels will be considered:

1. *Pre-reduction:* This is required if the quantity of raw data is too large to be handled efficiently (for example, in thermal-IR observations as many as 1000 images could be taken each second). In this case a process will be carried out that averages the data. Only the pre-reduced data will be preserved.

2. *On-line reduction:* The raw data (or the output from the pre-reduction process where applicable) will be taken automatically and a series of reduction processes will be applied to them. This will allow the user to see the reduced images rapidly and begin preliminary scientific analysis. The most usual processes will be bias subtraction, elimination of bad pixels, dark-current subtraction, flat-fielding, etc. The best available calibration data will be used.

3. *Off-line reduction:* The reduction process will be repeated once the night's observations have finished, but this time taking the whole night's calibration data into account.

The reduction processes will be determined by the instrument configuration. There will also be interfaces for the off-line data-processing facilities.

8.4.5.2 Instrument calibration

The control system will be responsible for managing the basic instrument calibration required for the reduction of the scientific observations. There will be various kinds of calibrations:

- *Standard calibrations:* Certain standard measurements will be taken (bias, dark-current and flat-field exposures) for each of the possible configurations of the instruments that are to be used during the night. These calibrations will be carried out at the beginning and end of each night. There will be a pre-defined calibration block for each possible configuration.

- *Flux calibration:* Observations of standard stars are taken several times during the night to calibrate the response of the detector.

- Some calibrations will automatically be executed as part of an observation block; for example, obtaining an arc spectrum for calibrating grating positions.

8.4.5.3 Data archive

Observational and calibration data will be archived to produce an accessible astronomical database. Raw data and reduced data will always be kept. The necessary mechanisms for safely storing these data and retrieving them quickly will be provided. Therefore, the storage media used must be sufficiently stable and economical.

It will also be important to keep those data related to the functioning of the GTC. The performance of the GTC will be improved through the analysis of these data.

8.4.6 Monitoring

Continuous monitoring of all aspects of the GTC will be provided.

8.4.6.1 Monitoring the state of the GTC

The state of all the components of the GTC will be monitored to confirm their safe and correct operation. The most relevant parameters will be displayed. These parameters will be stored for later analysis.

8.4.6.2 Monitoring the quality of observations

The quality of the scientific data will be monitored. This will provide information on possible saturation of detectors, noise, image size, diffraction-grating precision, etc. This information will be presented to the user, highlighting any possible problems in the data set.

8.4.6.3 Monitoring of observing conditions

Measurements of meteorological conditions and seeing will be taken. These will be used in planning the observations and recognizing conditions that put the integrity of the GTC at risk. The control system must automatically take any necessary actions to safeguard the GTC (e.g. to close the dome when there are excessively high wind speeds or high humidity).

8.4.6.4 Monitoring of alarms

Alarms will be used for informing of the occurrence of different faults in the GTC. These alarms will specify the origin and nature of the problem. There will be various levels of severity, the most important having acoustic and visual warnings. There will be various levels of detail in the alarms, with the aim of helping the diagnosis of problems.

8.4.7 Other subsystems

The control system will also be responsible for controlling the tertiary mirror, the electrical subsystems, the thermal control of installations, the rotation of cables, the primary-mirror protection subsystems, the telescope counterbalancing, the atmospheric dispersion correctors, etc.

8.5 Architecture of the control system

Although the architecture of the control system will in general be similar to that of some of the designs for other large telescopes such as the VLT [8.5], Gemini [8.6] or Subaru [8.7], it will incorporate the technological advances made since the start of these projects. These advances include the strengthening and wide diffusion of object-oriented technology, the consolidation of object-oriented middleware for distributed systems and their availability in real-time environments [8.8], the World Wide Web explosion, the advent of platform-independent languages such as Java and the consolidation of the use of high-speed real-time networks in control applications. The employment of these technologies will permit the adoption of a more flexible and modular design that will fulfil the architectural requirements of the control system.

A critical aspect of any complex system is the design of its architecture [8.9] [8.10] [8.11]. From the point of view of the architecture, a system is typically described as a collection of components that interact among themselves. After outlining the main requirements of the control-system architecture, the solution proposed for the GTC is described from different perspectives [8.12].

8.5.1 Architecture requirements

From what has been seen in Section 8.2, a series of requirements for the control system architecture can be derived:

- It must be organized in logical units, which are independent of who carries out the implementation or operation.
- Functional duplications in the system will be eliminated.
- Recognized standards will be adopted.
- Automation will be introduced where appropriate in order to minimize repetitive and routine procedures and in order to increase efficiency.
- Continuous self-diagnostic techniques will be implemented.
- The average time of fault recovery will be minimized.
- There will be a backup policy for improving fault tolerance repair.
- It will be modular; any hardware or software modifications can be carried out in parallel, with minimum interference to the telescope operation.
- Each subsystem will have a standalone capability.
- The software will be as hardware independent as possible.
- Commercial products will be used whenever possible.

8.5.2 Software architecture

The software architecture can be seen from a number of different perspectives. Each perspective addresses a specific set of concerns.

8.5.2.1 Development view

In this section the static distribution of the software is shown in its development environment. This view is centred on the organization of the software modules. The software is grouped into subsystems that can be developed by one or more persons or entities. The organization of subsystems will be hierarchical, each layer providing a narrow and well-defined interface to those above. The specific internal criteria of the software [8.2] are taken into account in this breakdown. These criteria are related to the ease of development, software management and reuse of commonality. This view can be used for the allocation of requirements and work packages, and also supports cost evaluation, project planning, monitoring of project progress, as well as for reasoning about software reuse, portability and security.

Any canonical object-oriented architecture [8.35] must consider the following components:

- *Base operating system:* Comprises real-time and conventional operating systems. These must fulfil those standards that are considered to be relevant (e.g. POSIX and its real-time extensions).
- *Networking:* Local area network protocols with the necessary bandwidth, such as asynchronous transfer mode (ATM), Fast Ethernet, Gigabit Ethernet, Scalable Coherent Interface (SCI) will be used.
- *Persistence object store:* This constitutes the database of the applications. An object-oriented storage system constitutes a somewhat superior level since it jointly encompasses the properties of a database and the behaviour common to these objects. Several commercial options exist at present, and further evaluations need to be carried out.

- *Distributed object management:* This provides abstractions for the administration of the distribution, such as the mobility of data in a communications network.
- *Domain-independent framework:* These provide domain-independent abstractions (e.g. generic container or numerical methods libraries).
- *Application environment:* These provide regular services to clients, such as printing facilities.
- *GUI desktop environment:* This provides primitive abstractions for the construction of graphics interfaces.
- *Domain model:* This embraces all classes of objects that form part of the vocabulary of the domain of the problem, including abstractions such as sensors, actuators, etc.
- *Domain-specific framework:* This provides all the collaborations that are common among the objects of the previous model that are specific to our domain.

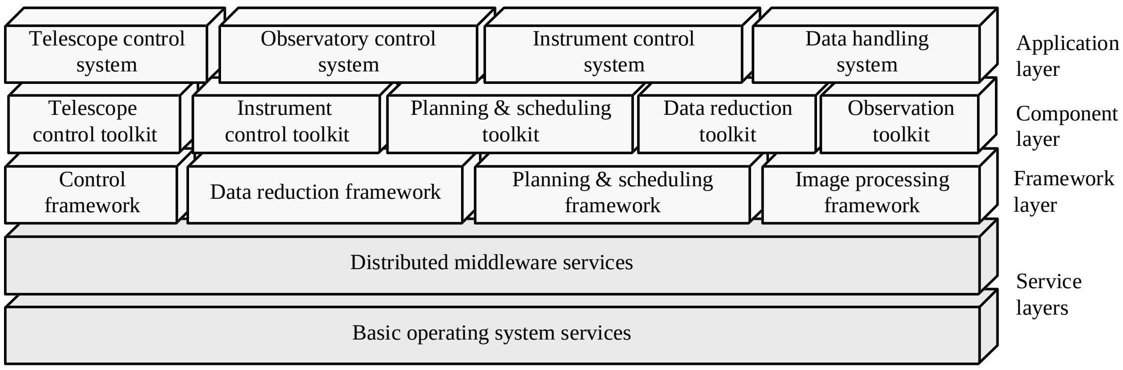

Figure 8.5: Development view.

The adopted hierarchical structure will consists of five layers (see Figure 8.5); the service layers (base operating and middleware services) provide the application domain independent infrastructure which is common to all the components of the control system. These layers isolate the application from modifications of the hardware platforms, operating systems and commercial off-the-shelf products (e.g. database management systems). To this infrastructure, the framework layer adds a set of specific domain frameworks[34], control, planning and scheduling and data processing forming the basis of a domain-specific software architecture. These frameworks will provide adequate 'hot-spots' [8.14] for adaptation. The component layer adds highest-level reusable components grouped into toolkits (e.g. FITS viewer). The application layer contains the final applications (mainly built by the composition of the underlying components) and the majority of the user interfaces and interfaces with external systems.

8.5.2.2 Object-oriented control framework

A framework abstracts the essential entities, state and behaviour in the domain of a problem. It includes key mechanisms, provides interaction protocols for key scenarios and encapsulates the fundamental invariants. A control framework will provide the common mechanisms to all control-

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[34] A framework is a semi-complete and reusable application that can be specialized for making applications to measure.

system applications. Combined with the distributed middleware it will form the skeleton of the control system. The fundamental abstractions of this framework will be devices (e.g. sensors, actuators) and models (e.g. objective models, action models, state models and error models; see Figure 8.6).

Devices are abstractions which provide a logical representation of the physical elements controlled by the control system. Some devices will be able to play the role of hardware wrappers[35]. Device services will provide location-transparent access to the different subsystems of the GTC via standardized interfaces.

State models will be determined from two forces: some in the downward sense, derived from the information necessary for controlling the actuators, and others in the upward sense, derived from the need to update the models from the values derived from the sensors and other sources. These abstractions (state vectors) will be based on values (e.g. azimuth velocity, temperature and altitude position) represented on a determined scale that can be understood in terms of physical laws.

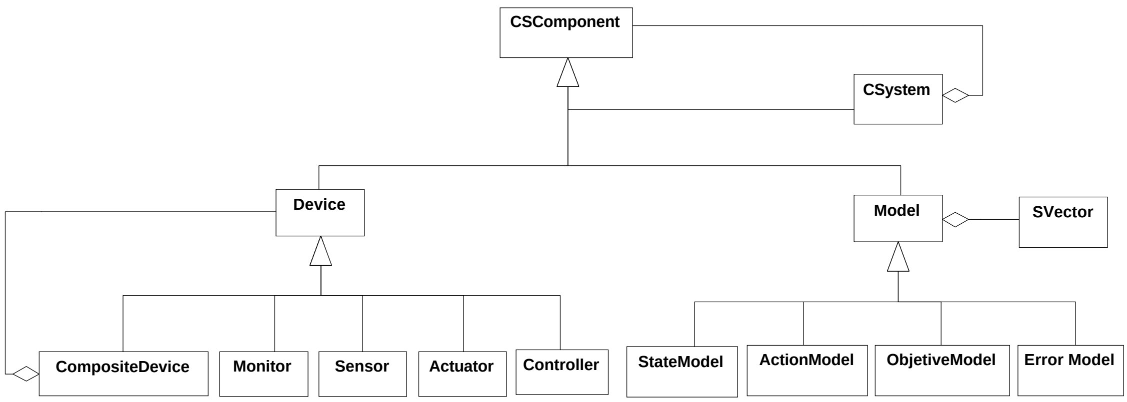

Figure 8.6: Device hierarchy.

Device controllers will build, initialize, activate, deactivate and reset the components of the control system. They will form the supervisory structure of the control system, which will have a hierarchical architecture.

8.5.2.3 Distributed architecture

The architecture of the control system will consist of a set of highly integrated systems distributed by means of networks in a hierarchical organization. This hierarchy will be organized by following the client-server model. The control system will operate in quasi-real time, with a hierarchy of control layers and interprocessor communications. There will be a large number of control points and, therefore, of processors necessary for managing them. Present plans contemplate various front-end processors, processors, workstations and various servers.

As in other applications domains (avionics, telecommunications, multimedia), real-time guarantees are required of the control system in the communication networks, as well as in the operating systems and underlying middleware components, with the aim of satisfying their QoS requirements. Applications in these domains must be flexible and reusable with the object of providing point-to-point QoS guarantees. These flexibility and reusability requirements drive the

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[35] A hardware wrapper encapsulates a physical device.

use of object-oriented middleware like CORBA, MidART [8.15] ACE (Associative Computing Environment) [8.16], ILU or DCOM (Distributed Common Object Model). Although some operating systems, networks and protocols at present support real-time scheduling, they do not provide an integrated solution. At present, there are various projects [8.15] [8.17] [8.18] working on the adaptation of this object-oriented middleware to hard real-time systems (e.g. avionics) or systems with restricted latency (e.g. teleconferences).

The processing elements of the control system can use a real-time implementation [8.17] of the CORBA (Common Object Request Broker Architecture) [8.19] standard for communications between objects via the network. The adoption of this client-server model, together with the CORBA/IDL (Interface Definition Language) interfaces and C++ and Java programming, will be in accordance with recent developments in programming languages and distributed architecture design.

Moreover, the specification of interfaces will be very important for sustaining and preserving investment in the face of rapid technological change. For this purpose open standards, such as RT POSIX or ATM, as well as CORBA itself, will be used.

Figure 8.7 shows an overview of the distributed structure of the software designed for the control system, which is based on the reference Object Management Architecture (OMA) of the Object Management Group (OMG). The basic mechanism consists in providing connections and interoperability among different objects that reside in different processors. This will be achieved by means of the implementation of different distributed services:

- *Object Services* are interfaces for general services that are likely to be used in any program based on distributed objects.
- *Common Facilities* are interfaces for horizontal end-user-oriented facilities applicable to most application domains.
- *Domain Interfaces* are application domain-specific interfaces.
- *Application Interfaces* are non-standardized application-specific interfaces.

The above object frameworks (see previous section) can be implemented as collections of cooperating objects categorized into Application, Domain, Facility, and Service Objects. Each object in the framework will support, or will make use of, some combination of Application, Domain, Common Facility, and Object Service interfaces (e.g. via interface inheritance or client requests).

The possibility will be considered of providing server interfaces to other systems, e.g. access to Experimental Physics and Industrial Control System (EPICS) [8.20] via the channel access mechanism or CDEV [8.21]. In this case, EPICS devices can be represented as CORBA-compliant devices services.

Access from the user interfaces to the distributed services could be effected by means of stand-alone applications or through the Internet Inter-ORB Protocol (IIOP) already incorporated into some browsers. This will permit the execution of user interfaces from any remote platform.

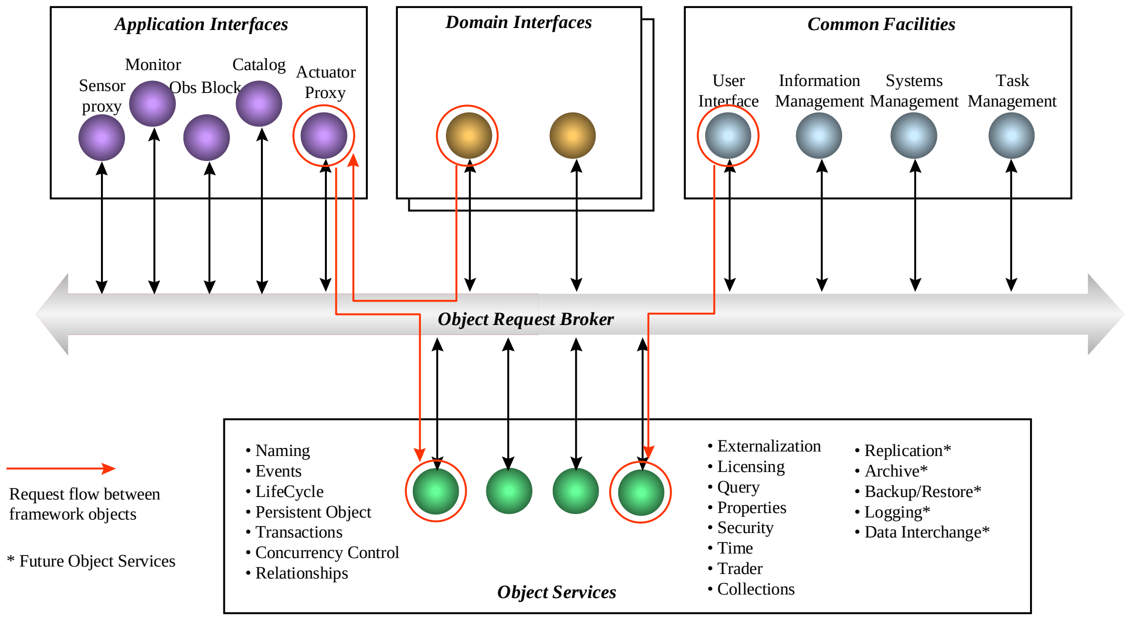

Figure 8.7: Distributed architecture.

8.5.3 Hardware architecture

The hardware architecture of the control system will be totally distributed (see Figure 8.8). It will consist of VME nodes called local control units (LCUs) with real-time processing capacity connected directly to the physical devices of the GTC. These connections will be able to use a varied set of control buses (e.g. CAN bus, GPIB, Bitbus). Other higher-level nodes will carry out coordination functions and will offer critical services to the remaining nodes (e.g. event dispatching, logging, monitoring, scheduling). Both the LCUs and the coordination units will be connected by means of one or more high-performance ATM switches to form the so-called control network. This architecture will allow the dynamical configuration of traffic so that each node has an adequate bandwidth for its needs. In those circumstances in which the required bandwidth is very large, other interfaces such as SCI or Fibre Channel will be used. However, when bandwidth is not an issue, cheaper interfaces such as Ethernet or Fast-Ethernet could be used.

ATM technology provides a series of important features: wide bandwidth, end-to-end individual QoS, virtual connections and flexible topology. These features will allow the building of a system based on an open standard with integrated communication services (data, images, audio and video). This can lead to a reduction in costs, greater flexibility and more dynamical applications. Although Ethernet technology continues to evolve rapidly (Gigabit Ethernet), it is still inadequate for real-time traffic due to its unpredictable delays and the lack of support to guarantee QoS. Moreover, ATM constitutes a scalable technology (possibility of widening bandwidths without modifying the topology of the network) from 1.5 Mbps (DS-1) to 10 Gbps (OC-192c). At present, there are products available from various manufacturers working with speeds starting from 25Mbps, 155 Mbps (OC-3c) and 622 Mbps (OC-12c). This will allow the adoption of a homogeneous and scalable solution for all the data-transmission needs of the GTC. The use of physical fibre-optics interfaces will be equally important, since these will provide protection against many of the possible sources of electromagnetic interference, as well as a large bandwidth.

Although the cost of ATM is at present higher than that of other solutions (although not by much in comparison with switched Ethernet), the benefits in terms of simplicity and architecture scalability permit a simpler system and therefore cheaper software. Scalability allows solutions to be found for all needs, avoiding the use of different protocols for each need and the use of gateways that can give rise to bottlenecks in the system.

The control system will have an absolute time reference system supplied by a GPS (Global Positioning System) receiver. This signal will also be distributed to the other workstations of the GTC installation.

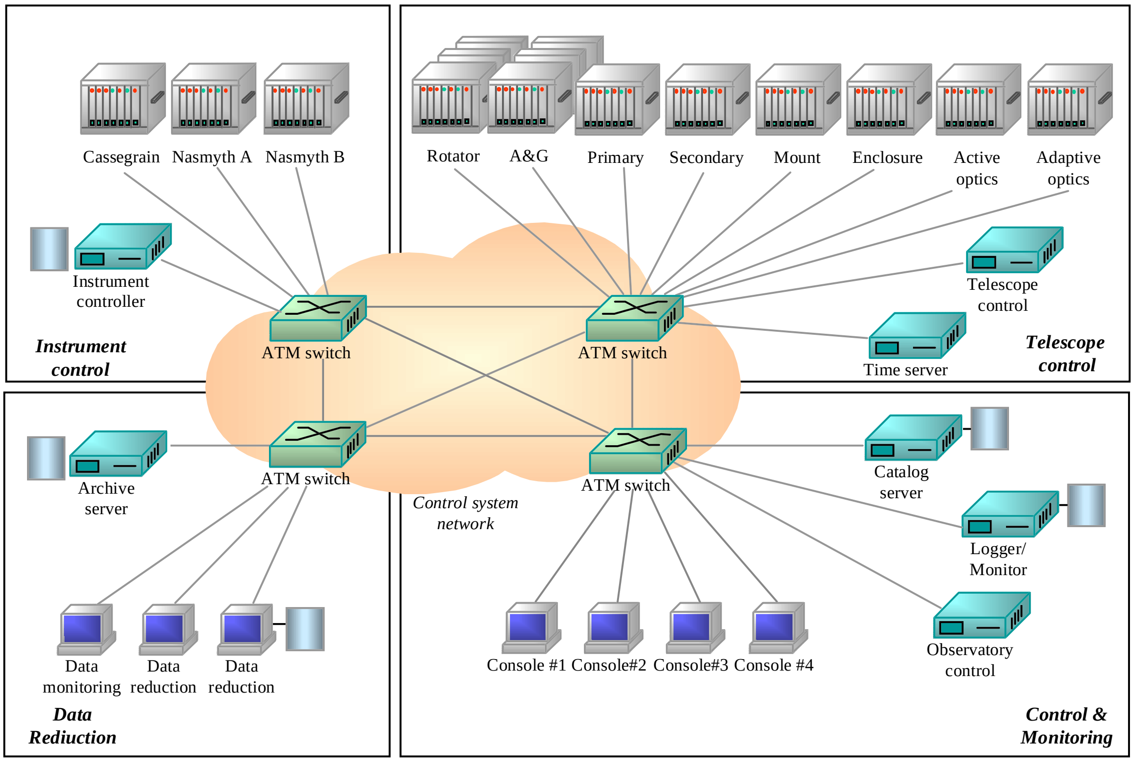

Figure 8.8: Hardware architecture.

8.6 Software engineering aspects

During its life-cycle, the control system of the GTC will be subject to a continuous flow of changes driven by various factors (new technologies, evolving requirements, development of new instruments, faults corrections, etc.). These must be assimilated with the minimum impact on the execution of the project and on the availability of the GTC. This will only be possible by the choice and planning of an adequate technological framework that allows these changes to be absorbed during the life-cycle of the GTC.

The options that form the technological framework of the control system encompass a very wide field; therefore, it is useful to split it up in order to simplify its study. The following categories of products [8.22] [8.23] will be considered: concepts, processes, methods and tools. In this classification the choices at a given level will restrict or provide a context for the lower levels. This structure will allow the planning of the adoption of families of interrelated and mutually coherent products. This can be done either top–down or bottom–up.

Using this classification as a reference frame, it is possible to study existing options in each of the categories and carry out a process of selection. The basic options that are being considered in each of these categories are outlined below.

8.6.1 Software engineering best practices

Some of the concepts that have recently influenced the development of software systems are described here. These concepts constitute well established practices that have shown their efficacy in numerous projects and hence, they will be widely used in the GTC control-system development.

- *Analysis, design and object-oriented programming:* These techniques replace traditional data-directed methods and functional decomposition (analysis and structured design) by an integrated approach to the analysis, design and implementation based on an object model. These methods, when they are applied correctly, produce systems that exhibit the properties outlined in Section 8.2.

- *Fast prototyping and iterative development:* In a fast-prototyping and iterative-development process [8.24] an initial version of the system is rapidly constructed (prototype pattern [8.25]) with an emphasis on the areas of greatest risk. The objective is to stabilize the basic architecture and refine the requirements with direct input from the users. The development continues with a series of iterations on the core of the architecture until the desired level of functionality, capability and robustness has been reached. The risk is reduced in the early stages of the project through a process of continuous integration so that any surprises that appear at the later stages due to integration are minimized.

- *Architecture-directed development:* In an architecture-directed process, the objective is to achieve an architecture that is resilient to changes in the requirements, within reasonable limits.

- *Large-scale reuse:* Object-oriented design and architecture-directed development implicitly support reuse [8.26]; this is more effective when reasonably large components are reused, such as subsystems and class categories. Therefore, the analysis, design, integration and testing of these components will also be reused.

- *Improvement and control of the software process:* Experience with real-world large projects shows that a highly integrated environment is necessary in order to facilitate and reinforce the control of the management of the process. For this purpose, various standards are being studied (ISO-9000-3 [8.27], CMM [8.28], SPICE [8.29]).

- *Software first focus:* The use of standards for open systems will allow the postponement, until the optimum moment in the project cycle, of the choice of technologies (hardware platforms, operating systems, network protocols and topology). This is crucial if it is required to achieve an effective compromise between functions, capabilities, costs and planning in an area where technology can change dramatically over the lifetime of the project.

- *Object-oriented frameworks:* An object-oriented framework [8.30] [8.31] is the skeleton of the architecture for a problem in a given domain and provides opportunities for the reuse of designs and code on a large scale, reducing the time and cost needed for building an application.

- *Design patterns:* A design pattern [8.32] [8.14] describes a set of cooperating objects united by certain relationships which are repeatedly encountered in the solution of similar problems. One of the main interests of patterns is that they allow the representation of knowledge of design decisions in a domain; therefore, these can be reused.

8.6.2 Development process

The adoption of a development process will allow the implementation of the control system software within the time and budget assigned and the verification of the required specifications. The advantages of a well-established procedure are that it will:

- Provide guides that allow the ordering of the activities of a team.
- Specify which artifacts are to be developed at each moment.
- Direct the tasks of the individual developers and of the team as a whole.
- Offer criteria for monitoring and measuring the products and activities of a project.

The nature of the GTC project and the continuous evolution of technology make an evolutionary life-cycle model [8.33] preferable to other options such as the cascade or incremental models. The evolutionary model is characterized by a planned development in deliveries. All the phases of a cycle are executed to obtain a delivery, so that each one incorporates the experience gained in the previous deliveries.

In evolutionary development, the priorities of the users must be taken into account. Software parts that are at the same time important for the user and can be achieved with the fewest technical problems and delays must be produced.

8.6.3 Analysis and design methodologies

Authors of the software development methods with the most widespread implementation (Booch, OMT, OOSE) have recently joined forces with the aim of defining the UML [8.34] for use in analysis and design methods. Additionally to the three main methodologists (Booch, Rumbaugh and Jacobson), some of the most influential companies have joined together in the presentation of UML, which means that there is a strong possibility that UML will be the standard notation for the visual representation of object-oriented models. Therefore, UML will be used as the standard visual modelling language. This will provide an important tool allowing the communication between software engineers and scientists. UML supports (but does not require) a use-case driven, architecture-centric, iterative and incremental process. This is in accordance with the concept mentioned in Section 8.6.1.

8.6.4 Tools

The selection of tools for a project is very important; they help in carrying out tedious and repetitive development tasks and provide support for other activities:

- Analysis and design tools are necessary to allow the discussion of the problem and its implementation architecture at an appropriately abstract level.
- Configuration management support tools need to be used for projects of significant scale.
- Testing is an important aspect in any project. Some form of automated regression testing will guarantee that no incremental release invalidates any of the features of the product under development.
- Other tools, such as browsers, requirements management support tools, documentation generation tools, intelligent debuggers and metrics tools, will have an important role to play as the project grows.

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9. SCHEDULING, COSTING AND MANAGEMENT OF THE PROJECT

9.1 Introduction

In the life-cycle of a facility such as the GTC three major activities can be clearly differentiated:

1. The design, construction and setting up of the facility (execution phase of the project).
2. Providing the maintenance and services necessary for the scientific use of the GTC (also known as the operation of the facility).
3. Improvements to and extensions of the GTC, and the development of new instruments.

Each of these activities has different objectives, procedures, costs, dates and timescales, hence the groups responsible for their development and the organizations under whose control the work is carried out must be varied and suited to the needs of each activity. Therefore, in order to execute the GTC project a non-profit commercial company was decided upon as the most viable option for providing the necessary agility and executive capacity. The formulas to be adopted for operational activities or subsequent developments have yet to be decided.

Over and above these formulas, however, there must exist an organization of wider scope capable of directing and coordinating the activities in each of these aspects of the life-cycle of the facility. There are strong arguments for the creation of a foundation possessing final ownership of the installation and directing the aforementioned activities. This foundation would be the appropriate body for accommodating the interests of the various partners in the GTC project and for defining the level of participation of each. This matter is beyond the scope of this document and will not considered further here.

The scheduling, estimated cost, management organization and methods to be applied during the execution of the GTC project are detailed in this chapter. An economic assessment of the subsequent operational and development activities is made at the end of the chapter.

9.2 Execution of the GTC project

For the smooth management of the project, a complex system like the GTC has to be logically broken down into work packages (subsystems and activities). A work breakdown structure (WBS) provides a structured view of project’s scope. Different levels of the WBS offer a view of the project in varying degrees of detail. In terms of budget allocation and planning, the WBS is a useful management tool for clearly defining responsibilities, following the progress of the project and providing a means of early detection of time or budget overruns. The WBS also provides a stable and comprehensive view of the project for senior management, thereby simplifying their supervisory activities.

The first- and second-level WBS used in this section is shown in Table 9.1. This WBS will be used for presenting the cost estimates and the project schedule.

```
1.      Enclosure and services
    1.1.    Civil engineering work and service installations
    1.2.    Dome
2.      Optics
    2.1.    Primary mirror
    2.2.    Secondary mirror
    2.3.    Tertiary mirror
    2.4.    Mirror-coating and cleaning system
3.      Telescope
```

```
    3.1.   Mechanical structure
    3.2.   Bearing, encoder and drive systems and auxiliary equipment
4.     Control system
5.     Instrumentation
    5.1.   Calibration, acquisition and guiding system
    5.2.   Instrument 1
    5.3.   Instrument 2
6.     Project management
```

Table 9.1: First and second level of the GTC project work breakdown structure.

The instrumentation work package includes two scientific instruments for Day 1, the calibration and A&G system. This package is really a focal-plane systems package and will be developed in close contact with research consortia, as will be seen in more detail later. On Day 1 only one focus will be fully equipped with an A&G system and rotator.

9.2.1 Cost estimates

Table 9.2 shows the estimated cost of the project obtained from the evaluation of each work package into which the project is broken down using the WBS. The costs of the large subsystems can be evaluated by working upwards. This cost estimation is based mainly on information obtained directly from potential suppliers of subsystems for the GTC, some of whom have collaborated in the compilation of this document. Where such information has not been available, we have relied on the experience of other telescope projects, constructions carried out at the Canarian observatories and the experience of the IAC. All amounts are expressed in Spanish pesetas (May 1997) and have not been adjusted for inflation over the lifetime of the project. Many of the estimates are based on data in currencies other than the peseta (e.g. the American dollar, the Deutschmark and the French franc). In these cases the average exchange rate with the peseta in May 1997 has been applied.

Subsystem	MPtas. (1997)	MPtas. (1997)
Enclosure and services		**2400**
Civil engineering work and service installations	1040	
Dome	1360	
Optics		**4230**
Primary mirror	3680	
Secondary mirror	300	
Tertiary mirror	150	
Mirror-coating and cleaning system	100	
Telescope		**1570**
Mechanical structure	1145	
Bearing, encoder and drive sys. and aux. equipment	425	
Control system		**500**
Instrumentation		**2250**
Calibration, A&G system	750	
Instrument 1	750	
Instrument 2	750	
Project management		**1800**
TOTAL		**12750**
10% contingency		**1275**

TOTAL (incl. Contingency)		**14025**

Table 9.2: Estimated budget for the construction phase of the GTC project in millions of pesetas (MPtas.).

Neither personnel overheads nor the indirect costs of instrument development by the participant research centres have been included in the calculation of this budget.

The estimated cost profile for the time of execution of the project is shown in Table 9.3. This is the result of the combination of the previous budget outlined in Table 9.2 and the schedule shown in Figure 9.1 (Section 9.2.2).

Year	MPtas. (1997)
1996	199.7
1997	375.0
1998	804.5
1999	2701.7
2000	3860.4
2001	2579.8
2002	1631.6
2003	567.2
2004	30.1
TOTAL	12750.0

Table 9.3: Estimated cost profile for the time of execution of the GTC project. The 1996 figure is given in real pesetas.

9.2.2 Schedule

The work schedule for the GTC project is shown in Figure 9.1. This schedule has also been organized by means of the WBS in Table 9.1 and represents the execution plans for the various main subsystems. Also shown for reference are the activities carried out over the last few years.

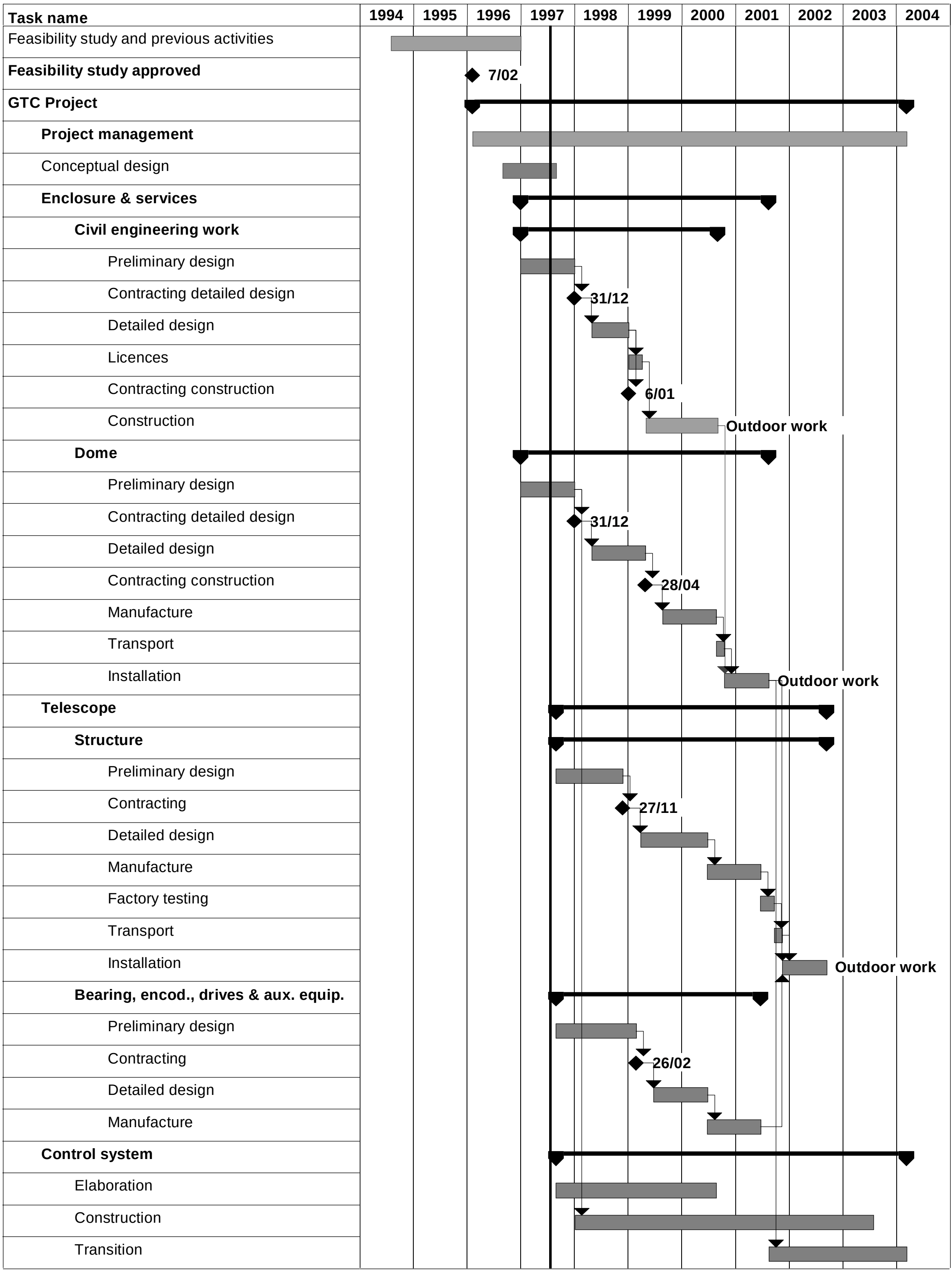

Figure 9.1: GTC project schedule (continued on next page). Outdoor work will cease during the winter months (December to March).

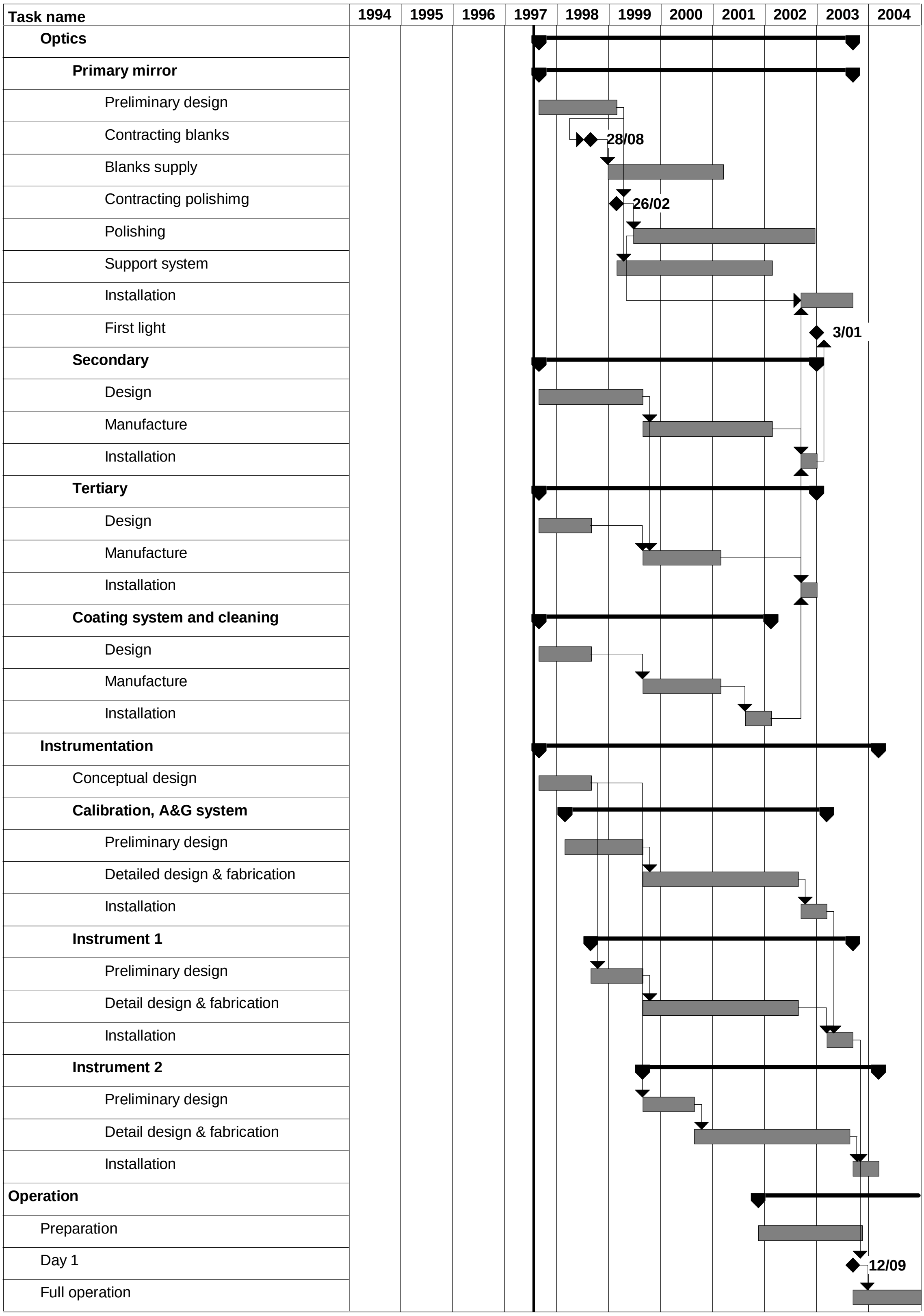

Figure 9.1: GTC project schedule (continued from previous page). Outdoor work will cease during the winter months (December to March).

The execution times shown are based on information obtained from potential suppliers. Information from similar projects in progress or already completed has also been used, as well as the experience of the technical team that has written this document.

The activities that establish the critical path of the project can be determined from an analysis of this work schedule. These are the activities related to the mechanical structure of the telescope. The high-performance requirements of this structure necessitate careful design for success to be achieved. Moreover, to minimize the risk from delays and complications that could arise from assembly at the ORM we plan to erect the structure at the factory.

In the case of the primary mirror, the total time for supplying the segments is quite prolonged. However, we intend to begin the testing of the GTC and its instrumentation with a reduced number of segments while simultaneously installing further segments as they are supplied. This is why this activity is not found on the critical path as might otherwise have been expected.

The year 2003 will see the completion of the GTC project and the beginning of routine operation. A period of overlap is convenient between these phases, both for the transfer of knowledge and skills to the support and maintenance staff and for familiarization of the latter with the installation to be supported. From the beginning of the installation of the telescope structure, towards the end of the year 2001, at least a skeleton support and maintenance staff will participate in the integration and testing stages.

9.2.3 Project management organization

The goal of a project management organization is to achieve the project's objectives within the assigned resources strictly according to schedule. A complex project like the GTC needs firm management of its scope, cost, schedule and quality of execution. The GTC management organization for the execution of the project has been designed to achieve these goals.

The management organization adopted is quite similar to those followed by other large scientific projects and is outlined in Figure 9.2.

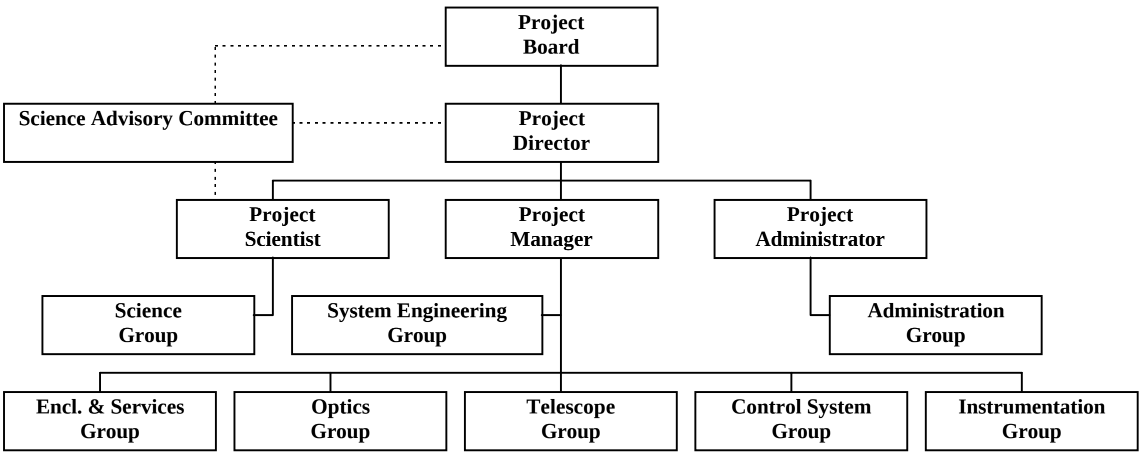

Figure 9.2: GTC project organization chart.

The *Project Board* is the body with overall control of budget and policy and is responsible for reviewing and approving annual and multi-year budgets. Only the Board can approve any proposed changes in the objectives, scheduling and overall budget of the project. Members of the Science Advisory Committee and the Senior Project Management, formed by the Project

Director, the Project Scientist, the Project Manager and the Project Administrator, are nominated by the Project Board.

The *Science Advisory Committee* will advise the Project Board and the Project Director on all aspects related to the science requirements of the project. In addition to monitoring the science requirements, the Science Advisory Committee will recommend the scientific priorities to be followed during the design, construction and commissioning, with special attention to instrumentation. Only the Science Advisory Committee can recommend changes to the science requirements. These changes must be approved by the Project Board. The Science Advisory Committee will be chaired by the Project Scientist, who will periodically inform the Committee on the progress of the project.

The *Project Director* will be responsible for the running of the project until the completion of the GTC, leading the Project Office and ensuring that the scientific goals are achieved. Within the limits established by the Project Board, he will have wide-ranging authority for managing the project. He will direct the Project Office and report to the Project Board.

The *Project Scientist* will have the responsibility of ensuring that the scientific objectives, specifications and programmes are adequately fulfilled during the design, construction and commissioning of the GTC. He will work with the scientific community to define the scientific requirements of the GTC, particularly those of its instrumentation. He will work with the other members of the Project Office throughout the construction phase of the project to evaluate the consistency of the project plans with the scientific requirements, advise on scientific priorities and identify and review specific technical approaches to meet the scientific requirements. He will provide advice and assistance to the Project Director and the other members of the project team.

The Project Scientist must be consulted on all aspects of the project that could affect the scientific performance of the GTC. All major actions, documents, and plans of the project will require the agreement of the Project Scientist.

The Project Scientist will chair the Science Advisory Committee and report on the project’s progress at meetings of that Committee.

In consultation with the Science Advisory Committee, he will take special responsibility for setting the scientific direction and priorities for instrumentation. He will maintain close contacts with the scientists responsible for specific instruments to ensure that these meet the expected scientific specifications. He will have the assistance of a Deputy Project Scientist. The Project Scientist will report to the Project Director.

The *Project Administrator* is responsible for the accounts, procurement and contract administration of the project. He will give support on these matters to the project team. The archiving and circulation of appropriate documents, inside and outside the Project Office, and providing computing support for the project staff will also be the responsibility of the Project Administrator. A small group of persons will work with him to support these activities. The Project Administrator will report to the Project Director.

The *Project Manager* will be responsible for managing the project to achieve the science specifications within the approved schedule and budget. He will direct the activities of several engineering groups that in charge of different aspects of the project. He will work closely with the Project Scientist in all aspects of the project that might significantly affect the scientific performance of the GTC. He will report to the Project Director.

Reporting to the Project Manager will be various groups involved in the engineering of different GTC subsystems (see Figure 9.2). Each group will be headed by a group leader. These groups will carry out the work-package activities to deliver the subsystems under their responsibility within budget and on schedule.

The *Systems Engineering Group* will be responsible for systems-engineering activities and for the integration and testing of the GTC at the ORM. Systems-engineering activities include the configuration and documentation management and interface management. Also included, and of especial importance, are the control of specifications at system level and their assignation to the different subsystems, as well as performance analysis. Regarding the integration and testing, the other engineering groups will follow the plans developed by the systems engineering group. These plans will particularly take safety aspects into account during integration.

This group will develop the plans to be followed for the correct operation and maintenance of the GTC, including safety guidelines (see Section 2.5). Consequently, the logistic support analysis and guidelines to be followed during the design and construction for an integrated logistic support of the GTC will also be this group's area of responsibility.

Finally, the systems engineering group must ensure quality in the Project Office by establishing guidelines and giving support in these matters to other teams in their dealings with subcontractors.

The strategy adopted for instrument development (see Section 9.2.4) will limit the responsibilities of the *Instrumentation Group* to negotiating the supply of instruments by outside consortia and giving them adequate support and communication with the Project Office. The intense engineering activity associated with the other project groups will not, therefore, be expected of this group. Its goal will be the procurement of instruments on time, within budget and according to established specifications.

The *Project Office* will be a team formed by the Project Director, the Project Scientist, the Project Administrator, the Project Manager, the engineering groups, the administration group and the support for the Project Scientist. The estimated manpower needed in the Project Office to manage the activities of the GTC Project is evaluated at a mean value of 25 per year during the lifetime of the project, until the end of the year 2003. This is the assumption made in evaluating the cost of the project management package presented in Table 9.2.

9.2.4 Project management policy

The management policy concerning the design and construction of the GTC is to maximize the participation of industry. Many GTC Project activities are quite common practice in industry, which will be better able than the Project Office to carry out such tasks. Industry has the necessary expertise, infrastructure and optimized procedures. Manufacturing is an obvious example, but detailed design will also be better handled by industry. Contracting these activities out to industry will give the project full advantage of this expertise. Other project activities are less common in industry and these will be undertaken by the Project Office.

During the conceptual and preliminary design the science requirements will be transformed into technical specifications. These activities will need close contact with the scientists, and an analysis of the cost effectiveness and performance of alternatives will need to be made. These will be the responsibility of the Project Office, which will act as the prime contractor. Systems engineering, integration and set-up will also be Project Office activities, as will be establishing contracts and controlling procurement.

Instrumentation design and manufacture is an area where the intensive participation of scientists will be vital if the final instrument is to be attractive to the scientific community. This is an area where the expertise of research institutions is unrivalled. Hence the Project Office will have a very limited scientific staff, and instruments will be provided through signed contracts with selected consortia of research centres.

A procedure is under study [9.1] to follow up the definition and procurement of the instruments by the Project Office. The objective of this procedure is to encourage and stimulate the competitive participation of research institutions. The Science Advisory Committee, the Project Scientist and the Instrumentation Group will play key roles in this procedure to ensure scientifically competitive and well engineered instruments.

9.2.5 Project management methodology

For the sound development of the project a set of methods and control and follow-up mechanisms has been adopted. These are the principal management tools that will be used in directing the project in order to guarantee the successful fulfilment of its objectives. The most important of these areas are now briefly described.

9.2.5.1 Scope management

Throughout all the complexities of the project, the fulfilment of the scientific requirements must always be held firmly in view. For this reason, error budgets (see Appendix B) will be established and adhered to for the main requirements (image quality, pointing, open-loop tracking, emissivity and telescope availability). Baselines[36] and procedures for their modification will also be established, and critical revisions of design, both internal and external, will be undertaken.

9.2.5.2 Time management

All activities at the bottom level of the WBS will be scheduled. This will provide a useful and sufficiently detailed control of the progress of the project. This tool will ensure early detection of any deviations from the planned schedule and provided the necessary corrective actions. A formal procedure to be followed by the Project Office will be established. Also, frequent and periodic management meetings will provide communication between the members of the Project Office to ensure joint identification of such deviations and effective corrective action.

9.2.5.3 Cost management

The division of the budget into the different work packages that make up the WBS will enable the expenditure of the project to be easily monitored. By tracing each of the individual work packages any deviations will be detected at an early stage and corrective actions promptly taken. An appropriate use of the contingency fund will guarantee the prevention of unexpected budget overruns. Comparison between the planned and actual costs of every WBS item will provide early estimates of potential future incursions into the contingency fund. This fund will represent the maximum deviation permitted between the projected and real costs. It will act as an amber warning light to alert to the Project Board at its periodic review meetings.

To minimize the risk of budgetary overruns the preferred contract policy will be to invite international open tenders. This will ensure the cost effectiveness of contracts. Firm fixed-price contracts will be preferred as these will reduce cost-related risks. To minimize the extra cost of this type of contract, specifications will have to be well defined and the scope of the work well

[36] Baselines define the configuration of the GTC, i.e. its physical and functional characteristics, after each phase of the project. The baselines are subject to a strict change control since they provide a reference for the Project Office during each phase.

identified in order to avoid any changes. Where this is not possible, high costs can be expected. In such cases, small contracts with a high level of control and participation by the Project Office must be established until such time as the specifications and scope are fixed for the main contract to proceed.

9.2.5.4 Configuration management

The development of a complex system like the GTC, with so many people and firms involved, runs the risk that not everybody concerned has an identical view of the system, and this could give rise to costly mistakes. It is essential to keep correct and permanently up-to-date documentation that reflects the state of the system under development at all times. This will promote a common view of the system during the construction phase and will produce useful documentation for the future operation of the GTC. The techniques outlined for controlling the requirements, particularly the baselines, will form part of this configuration control.

9.2.5.5 Interface management

Control of changes required in configuration-control procedures will be effected by means of interfaces, which will simplify the determination of the effects that changes in one subsystem will have on another subsystem. The identification and definition of interfaces and their maintenance is therefore necessary.

These interfaces will also help to identify the responsibilities of different groups and contractors in the construction of the various subsystems and ensure compatibility among them.

9.2.5.6 System integration and safety management

One of the most complex activities that will devolve entirely upon the Project Office is the setting up and putting into operation of the GTC at the ORM. To this effect, a detailed plan of the activities and procedures to be followed during the setting up of the system will need to be developed from the start. This plan must encompass the activities of the different suppliers at the ORM and must serve as a framework for all kinds of activities at the Observatory, where special attention must be given to all aspects of personal safety.

9.2.5.7 Integrated logistic support

Large systems have traditionally been planned and developed with scant regard to logistical support, all efforts being concentrated into the fulfilment of requirements deriving from the main function of the system concerned. Questions relating to logistic support were taken into account *a posteriori*. This practice has often resulted in costs that greatly exceeded those initially foreseen over the lifetime of the project. The reasons for this are twofold. The costs of supporting the system:

1. Generally constitute a substantial part of the total cost of the life-cycle.
2. Depend critically on the decisions taken during the initial phases of the life-cycle.

This problem is further exacerbated as the complexity of the system increases.

In the light of these considerations, it is obvious that the development of the GTC has to considered as an integral concept that takes into account not only the scientific but also the logistic-support requirements. Such a compromise requires logistic support to be considered at all the phases of the life-cycle of the system, especially in those design stages in which the main decisions affecting the configuration of the system are taken.

An ILS methodology will be followed to design the GTC in such a way as to make it easily and economically supportable, as well as to develop the means for supporting it. At all times, the primary aim is to reach an optimum compromise between the cost of designing the GTC, including the means for its support, and the cost of the support itself [9.2]. Logistic-support analysis will lead to such a plan for the operation and maintenance of the GTC.

9.2.5.8 Risk management

During the execution of the project, many uncertainties will arise that might affect it negatively. The project management will need to take these uncertainties or risks into account in order to control them. Any potential risks that could negatively affect the project will need to be identified and assessed. Furthermore, plans must be devised for managing such risks and establishing the methods of tracing the effects of such plans. Risk management will allow such risks to be accommodated in the project within acceptable limits, and in accordance with such other interrelated parameters as time, technical performance and cost.

9.3 Operation of the GTC

The details of the operational phase of the GTC Project will be defined throughout its execution phase. In this way (see Section 9.2.5.7) detailed planning of the operational and maintenance tasks of the facility will be undertaken. Also, the functions to be served, the most appropriate organizational structure for carrying them out and the detailed budget entailed will be defined. However, rough estimates of present needs can already be made.

An important fact to bear in mind when analysing the operation and maintenance of the GTC is its proximity to a centre of excellence in astrophysical research like the IAC. This must be used to full advantage in order to simplify and minimize the cost of the organization responsible for bringing the GTC into operation. This will be possible by making full use of existing infrastructure and not duplicating any means that can be shared. The organization responsible for the operation of the GTC should establish an agreement with the IAC that will enable the latter's technical and laboratory facilities to be used for second-level maintenance. Also, the IAC will provide an attractive and stimulating research environment in which support astronomers can keep up an active participation in research. For this reason, an agreement with the IAC could benefit both institutions.

In this way, the organization in charge of running the GTC would establish a three-tier system of maintenance:

1. First level: on-site maintenance staff at the ORM.
2. Second level: maintenance staff at sea level on La Palma or Tenerife, with use of the means and capacity of the IAC in La Laguna.
3. Third level: suppliers of the different elements of the GTC.

Intensive contracting of outside services is also planned. This would enable staffing levels to be kept to a minimum, which would result in a cost-effective operating service. These basic concepts of the maintenance of the GTC are described in more detail in [9.2].

The reduced staffing levels inherent in this approach are in sharp contrast to those of other organizations, which, being dependent on remote research centres, have had to create *ab initio* their own infrastructure and an adequate research environment in order to satisfy the needs of their more highly qualified personnel and visitors.

Although the previously mentioned logistic-support analysis must determine these needs with greater accuracy, on the basis of these arguments the group of persons needed for support tasks will need to number between 20 and 25. This figure includes the head of the group, the equivalent to a minimum of 5 full-time support astronomers, between 8 and 10 engineers and/or technicians, four night assistants and some administrative and secretarial support. This group would guarantee the running and maintenance of the installation once it is brought into operation. Activities related to the development of new instrumentation or to the improvement of existing instrumentation, will be discussed in Section 9.4. An estimate of the operational costs of the GTC from the year 2004 is presented in Table 9.4 on the basis of this scenario.

Item	Year 2002 MPtas. (1997)	Year 2003 MPtas. (1997)	Year 2004 onwards MPtas. (1997)
Personnel & gen. expenditure	100	175	250
Archives	0	0	20
Purchase	0	0	100
Maintenance contracts	0	0	100
Contracting of services	0	0	75
TOTAL	100	175	545

Table 9.4: Estimated costs for the operational phase of the GTC.

So that the more technical members of this group can acquire the necessary experience, it is desirable that they begin their activities when the GTC is being assembled at the Observatory during the years 2002 and 2003 (see Section 9.2.2). In this way, knowledge and skills are transferred from the Project Office to the group in charge of operation. Also shown in Table 9.4 is the cost of these activities prior to the operational phase.

9.4 Continuous development programme for new instruments and system upgrades

In order to keep pace with rapidly developing technology and to keep the facility competitive, continuous development of new instruments and improvements to the GTC itself are necessary. Important items to be considered in this programme are the "not Day 1 instruments", the set-up of other foci such as the prime focus or the adaptive secondary. At a conservative estimate, a new instrument or system upgrade will be required every two years (although annually would be better). A development programme of one new instrument every two years would need a yearly funding of 375 MPtas. (1997) assuming an average of 4.5 years for developing a new instrument and a mean cost of 750 MPtas. (1997). As an additional bonus, the manpower involved in this continuous development programme could give additional support to the operational activities.

This continuous-development programme could also start before the GTC comes into operation. These new instruments and updates are essential in order to have upgrades soon after the GTC begins normal operation. It is proposed to start from year 2001 at the moderate rate of one new instrument or GTC upgrade every two years in order to have new instruments by year 2005–2006, just two years after the start of normal operation. In this case, a budget of 175 MPtas (1997) for year 2001 and 375 MPtas (1997) for year 2002 onwards will be necessary. Table 9.5 summarizes these estimates.

Item	Year 2001 MPtas (1997)	Year 2002 MPtas (1997)	Year 2003 onwards MPtas (1997)
Continuous-development prog.	175	375	375

Table 9.5: Estimated costs of continuous development of new instrumentation and system upgrades.

As mentioned earlier, the development of instruments will need to be carried out with the active participation of university departments and research centres. It is therefore proposed that this continuous development programme be carried out in collaboration with these institutions in combination with industry to produce the engineering parts. The estimated budget needed for this continuous development programme can be provided by the current budgets for scientific infrastructure of the funding agencies and through international collaboration.

References

[9.1] Rodríguez-Espinosa, J. M., Hammersley, P. L. 1997. 'General requirements for the GTCiInstrumentation', *GTC Project Document ESP/CCIA/0009-L.*

[9.2] González, J. C. 1997. 'Análisis de soporte logístico de alto nivel', *GTC Project Document RPT/STMA/0015-R.*

APPENDIX A. GTC REQUIREMENTS

The top-level science requirements are the following:

- A major improvement in limiting magnitude between 0.3 and 15 μm beyond what is currently possible on a 4-m class telescope.
- Excellent image quality over a reasonable field of view.
- The simultaneous availability of imaging and spectroscopic capabilities over a wide wavelength range (0.3 to 2.5 μm).
- High operational efficiency.
- High reliability.

Furthermore, the GTC should be located at a high and dry mountain site, enjoying a high number of photometric nights per year.

The detailed requirements, derived from these top-level requirements, are summarized in Table A.1.

	Requirement	Goal
Telescope entrance pupil equivalent circular aperture diameter	10 m	
Spectral range	0.3 to 15 μm	
Image quality		
FWHM on axis at visible wavelengths	0.18 arcsec	
SR on axis at 4.8 μm (0.5-arcsec seeing) with image-motion correction	0.33	
SR on axis at 2.2 μm (0.5-arcsec seeing) with adaptive optics and natural guide star	0.8	
SR on axis at 2.2 μm (0.5-arcsec seeing) with adaptive optics and laser guide star	0.5	
Foci		
Cassegrain		
Maximum weight	6000 kg	
Available space (diameter/length)	2 m x 3.5 m	
Nasmyth (2 foci)		
Maximum weight	10000 kg	
Available floor area	6 m x 6 m	
Folded Cassegrain (4 foci)		
Maximum weight	1000 Kg	
Prime		
Maximum weight	2000 kg	
Available space (diameter/ length)	1.3 m x 2 m	
Maximum time to insert/remove the tertiary mirror	5 min	
Field of view		
Cassegrain visible–NIR		
Unvignetted	8 arcmin	20 arcmin
Vignetted on mirrors	25 arcmin	30 arcmin
Nasmyth visible–NIR		
Unvignetted on tertiary mirror	15 arcmin	20 arcmin
Vignetted on tertiary mirror	unvignetted+5 arcmin	
Thermal IR		
Unvignetted	7 arcmin	

Table A.1: Summary of GTC requirements. If not otherwise indicated, the values represent the minimum requirements (continued on next page).

	Requirement	Goal
Background performance		
Stray light at λ < 2.1 μm (maximum on axis at the instrument detector over the natural background)	10%	
Telescope emissivity at 3.8 μm (maximum at Cassegrain)	5%	3%
Optics emissivity maximum degradation respect to clean state	3%	
Secondary mirror		
Chopping		
Range at 2.5 Hz (on the sky)	±1 arcmin	
Range at 10 Hz (on the sky)	±7.5 arcsec	
Duty cycle	80%	
Repeatability (on the sky)	0.03 arcsec	
Fast image-motion correction		
Maximum frequency	40 Hz	
Range (on the sky)	3 arcsec	
Precision (on the sky)	0.01 arcsec rms	
Fast focus maximum frequency		40 Hz
Main telescope axis movement range		
Elevation	−1° to 91°	
Azimuth	513°	540°
Pointing accuracy		
5° < zenith angle < 60°	2 arcsec rms	<1 arcsec rms
Zenith angle ≥ 60°	3 arcsec rms	<1 arcsec rms
Tracking		
Elevation limit	15°	0°
Speed limit relative to the sidereal rate	1 arcsec s^{-1}	
Open-loop tracking accuracy (sidereal rate)		
In 10 min	0.1 arcsec rms	
In 1 hour	0.5 arcsec rms	
Closed-loop guiding jitter without image-motion correction averaged over 5 to 10 s	0.038 arcsec rms	
Offsetting accuracy		
Up to 30 arcmin	0.1 arcsec rms	
Up to 60 arcmin	0.3 arcsec rms	
Time to point/offset and start tracking		
Up to 5 arcsec	1 sec	
Up to 5 arcmin	10 sec	5 s
Up to 10°	30 sec	20 s
To any position in sky	5 min	3 min
Diameter of zenith blind spot	1°	
Acquisition and guiding		
Field of view	1 arcmin	
Frame rate		
Slow guiding system	0.01 to 10 Hz	
Image-motion correction system	200 Hz	
Camera position tolerance with respect to the science instrument aperture	0.015 arcsec	
Enclosure		
Dome slit horizon limit	15°	
Telescope azimuthal movements without rotating the dome	2°	
Maximum time to close the dome shutter	3 min	
Maximum downtime due to failures	2%	
Lifetime	50 yr	

Table A.1: Summary of GTC requirements. If not otherwise indicated, the values represent the minimum requirements (continued from previous page).

The environmental specifications at the selected site to locate the GTC are established in Table A.2.

	Nominal conditions	Range of operation	Limit of operation[37]	Survival
Air temperature	−2° to +19° C	−8° to +25° C	N/A	−15° to +35° C
Relative humidity	2 to 87%	1 to 90%	90%(or dew point)	100%
Atmospheric pressure	770 to 790 mbar	720 to 800 mbar	N/A	N/A
Wind speed				
Averaged over 15 min looking into the wind[38]	0 to 10 m s^{-1} [39]	0 to 16 m s^{-1}	16 m s^{-1}	55 m s^{-1}
Averaged over 15 min looking away from the wind	0 to 13 m s^{-1} [40]	0 to 22 m s^{-1} [41]	22 m s^{-1}	55 m s^{-1}
Gusts	N/A	0 to 27 m s^{-1}	27 m s^{-1}	67 m s^{-1}
Earthquakes (horizontal acceleration)	N/A	N/A	N/A	0.1 *g*

Table A.2: Environmental specifications for the GTC. Nominal conditions are those that prevail during 98% of the time in which the operation of the telescope is not impeded by weather conditions. (N/A: not applicable).

37 Conditions above which the dome must be closed.
38 The telescope pointing within ±45° of the wind direction.
39 Wind speed between 0 and 10 m s^{-1} for 92% of the useful time.
40 Wind speed between 0 and 13 m s^{-1} for 98% of the useful time.
41 Wind speed between 0 and 22 m s^{-1} for 100% of the useful time.

APPENDIX B. ERROR BUDGETS

Error budgets are an important tool for controlling the fulfilment of top-level requirements, and make it possible to split these requirements into the different elements of the GTC. Hence, error budgets are the benchmark in guaranteeing that the GTC meets the science requirements once all its elements have been integrated.

Five budgets corresponding to the main performance requirements have been identified: image quality, pointing accuracy, open-loop tracking accuracy, IR background and availability [B.1]. The following sections show a breakdown of the highest levels of the mentioned budgets.

Image quality

Concerning image quality, three error budgets are maintained corresponding to the science requirements for visible, 2.2- and 5-μm observations.

For visible observations the requirement is that the image degradation produced by the GTC should be below about 0.18 arcsec FWHM on axis. The corresponding error budget at 500 nm is shown in Table B.1. Values in the budget are the effects of each error source in the FWHM of a seeing image. This has to be taken into account in the case of the diffraction and discontinuous wavefront errors due to the segmented nature of the primary mirror.

	FWHM (arcsec)		
IMAGE QUALITY	**0.176**		
1 Image size	0.149		
1.1 Field aberrations		0.051	
1.1.1 Diffraction			0.044
1.1.2 Real configuration errors			0.025
1.2 Primary-mirror surface errors		0.112	
1.2.1 Segment figure errors			0.109
1.2.2 Segment alignment and phase errors			0.025
1.3 Secondary- and tertiary-mirror surface errors		0.065	
1.3.1 Secondary-mirror surface errors			0.042
1.3.2 Tertiary-mirror surface errors			0.050
1.4 Active optics		0.053	
1.4.1 Measurement errors			0.033
1.4.2 Active-optics residuals			0.042
2 Image motion	0.063		
2.1 Measurement errors		0.020	
2.2 Setting noise		0.033	
2.3 Perturbations		0.050	
3 Local seeing	0.069		
3.1 Dome seeing		0.055	
3.2 Telescope seeing		0.025	
3.3 Mirrors seeing		0.033	

Table B.1: Error budget for visible observations (500 nm).

For observations in the thermal IR the telescope is required to produce images with an SR of 0.33 at 4.8 µm on axis, using image-motion (fast-guiding) correction, assuming a visible seeing of 0.5 arcsec. The corresponding error budget is presented in Table B.2.

			SR
IMAGE QUALITY			**0.330**
1 Image size	w_{rms}(µm)	0.173	0.954
1.1 Field aberrations	w_{rms}(µm)	0.049	
1.1.1 Real configuration errors	w_{rms}(µm)	0.049	
1.2 Primary-mirror surface errors	w_{rms}(µm)	0.091	
1.2.1 Segment figure errors	w_{rms}(µm)	0.054	
1.2.2 Segment alignment and phase errors	w_{rms}(µm)	0.073	
1.3 Secondary- and tertiary-mirror surface errors	w_{rms}(µm)	0.057	
1.3.1 Secondary-mirror surface errors	w_{rms}(µm)	0.036	
1.3.2 Tertiary-mirror surface errors	w_{rms}(µm)	0.044	
1.4 Active optics	w_{rms}(µm)	0.126	
1.4.1 Measurement errors	w_{rms}(µm)	0.097	
1.4.2 Active-optics residuals	w_{rms}(µm)	0.081	
2 Image motion	θ_{rms}(arcsec)	0.010	0.951
3 Local seeing	w_{rms}(µm)	0.100	0.983
4 Atmospheric seeing	w_{rms}(µm)	0.762	0.370

Table B.2: Error budget for observations at 4.8 µm with image-motion correction and a visible seeing of 0.5 arcsec. w_{rms} *is the rms wavefront error and* θ_{rms} *is the rms wavefront slope.*

For observations with AO the requirement is that when using natural guide stars, the telescope and AO system should produce diffraction-limited images at 2.2 µm with an SR of 0.8 on axis in 0.5-arcsec visible seeing (see Table B.3).

			SR
IMAGE QUALITY			**0.805**
1 Adaptive-optics errors	w_{rms}(µm)		0.904
1.1 Image-motion correction error	θ_{rms}(arcsec)	0.0004	0.999
1.2 High-order correction error	w_{rms}(µm)	0.111	0.905
2 Telescope errors	w_{rms}(µm)	0.119	0.890
2.1 Primary-mirror surface errors	w_{rms}(µm)	0.091	
2.2 Secondary-mirror surface errors	w_{rms}(µm)	0.036	
2.3 Tertiary-mirror surface errors	w_{rms}(µm)	0.044	
2.4 Active optics residuals	w_{rms}(µm)	0.052	

Table B.3: Error budget for observations at 2.2 µm with adaptive optics and a visible seeing of 0.5 arcsec. w_{rms} *is the rms wavefront error and* θ_{rms} *is the rms wavefront slope.*

Pointing accuracy

The requirement for pointing accuracy is 2 arcsec rms for elevation angles between 30° and 85°. Table B.4 shows the corresponding error budget for the Cassegrain focus.

	arcsec	
POINTING ACCURACY	**1.997**	
1. Telescope-pier position errors	0.143	
1.1. Pier coordinate errors		0.020
1.2. Pier tilts		0.141
2. Telescope-structure errors	1.198	
2.1. Azimuth-axis errors		0.382
2.2. Elevation-axis errors		0.341
2.3. Primary-mirror positioning errors		0.375
2.4. Secondary-mirror positioning errors		0.477
2.5. Science-instrument positioning errors		0.897
3. Optics positioning errors	1.469	
3.1. Primary-mirror positioning errors		0.755
3.2. Secondary-mirror positioning errors		1.260
3.3. Non-common errors between A&G system and science instrument		0.010
4. Pointing-control errors	0.611	
4.1. Encoder errors		0.071
4.2. Time-base errors		0.015
4.3. Calibration errors		0.512
4.4. Atmospheric-dispersion correction errors		0.326

Table B.4: Pointing-accuracy error budget for Cassegrain focus and elevation angles between 30° and 85°.

Open-loop tracking accuracy

For open-loop tracking an accuracy of 0.1 arcsec rms over a period of 10 minutes is required. The error budget for the Cassegrain focus is presented in Table B.5.

	arcsec	
TRACKING ACCURACY	**0.100**	
1. Telescope-pier position errors	0.005	
1.1. Pier coordinate errors		0.001
1.2. Pier tilts		0.005
2. Telescope-structure errors	0.056	
2.1. Azimuth-axis errors		0.016
2.2. Elevation-axis errors		0.016
2.3. Primary-mirror positioning errors		0.018
2.4. Secondary-mirror positioning errors		0.023
2.5. Science-instrument positioning errors		0.042
3. Optics positioning errors	0.069	
3.1. Primary-mirror positioning errors		0.036
3.2. Secondary-mirror positioning errors		0.059
3.3. Non-common errors between A&G system and science instrument		0.001
4. Tracking-control errors	0.046	
4.1. Drive errors		0.024
4.2. Encoder errors		0.024
4.3. Time-base errors		0.014
4.4. Calibration errors		0.023
4.5. Atmospheric-dispersion correction errors		0.015

Table B.5: 10-minute tracking accuracy error budget for Cassegrain focus.

IR background

At wavelengths longer than about 2.1 μm, the requirement is that the emissivity at the Cassegrain focus should be below 5% at 3.8 μm. Table B.6 shows the corresponding budget.

	%
IR BACKGROUND	**5.00**
1. Primary-mirror surface	2.00
2. Secondary-mirror surface	1.30
3. Gaps between primary segments	0.70
4. Secondary-mirror outer bevel	0.25
5. Secondary-mirror inner bevel	0.05
6. Spider (in reflection)	0.50
7. Auxiliary spider (in direct emission)	0.10
8. Other sources	0.10

Table B.6: IR background budget for Cassegrain focus.

Availability

There is a top-level science requirement for high efficiency and reliability. Table B.7, which refers to the percentage of time lost with respect to the useful observing time, presents the non-availability budget on the basis of this requirement.

	%
NON-AVAILABILITY	**5.0**
1. Calibration (telescope behaviour model)	2.0
2. Night-time scheduled maintenance	1.0
3. System failures (including instrumentation)	2.0

Table B.7: Non-availability budget.

References

[B.1] González, J. C., Castro, J., Devaney, N., Sánchez, V. 1997. ‘Presupuesto de errores del sistema’, *GTC Project Document ESP/STMA/0005-R.*

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