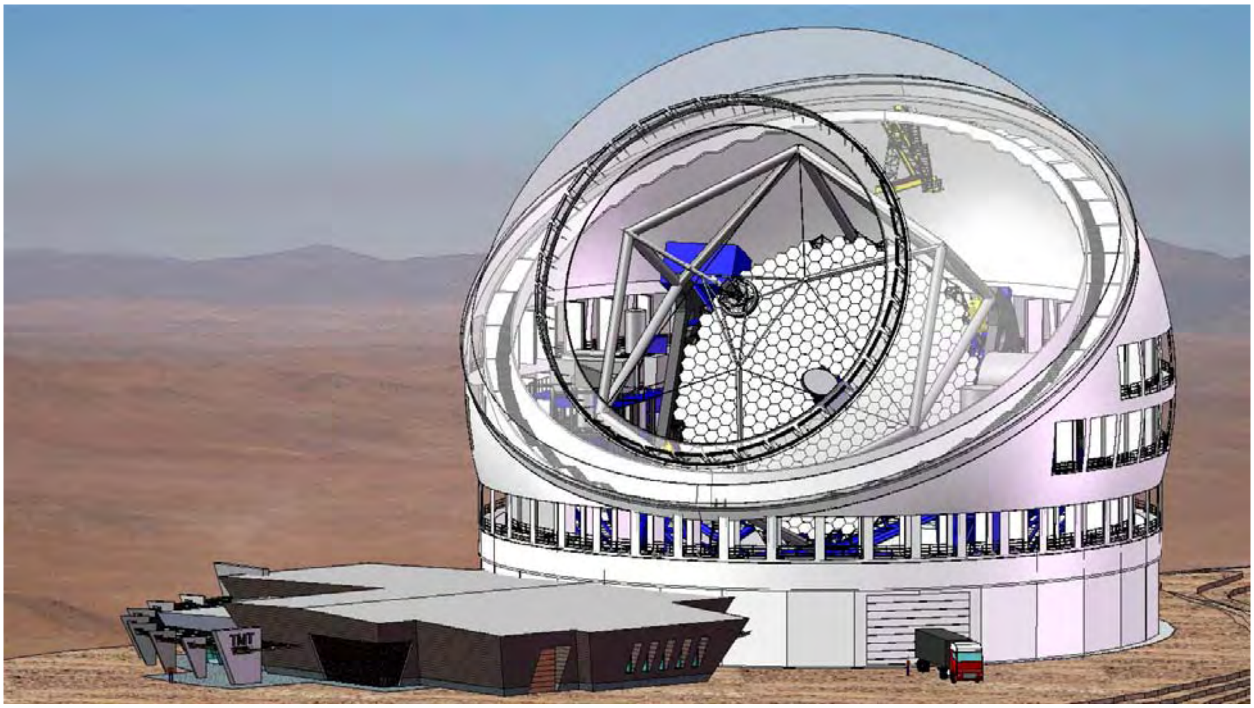
# Thirty Meter Telescope

## Construction Proposal

**September 12, 2007**



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# The Thirty Meter Telescope Construction Proposal

The TMT Board has established an External Advisory Panel (EAP) to periodically review the progress of the TMT Design and Development Program (DDP).

In June 2007, the TMT Board requested the EAP to assess the proposal to construct TMT together with the plans to achieve construction readiness and to conduct early operations of the TMT Observatory. The EAP was charged to review the science cases, science requirements, and observatory requirements. They were asked to review recent observatory design changes, and to evaluate the proposed design against the requirements, and to assess readiness for construction. They were also asked to comment on the site testing and site selection process. The panel was asked to comment on the state of operations planning and the operational model for the observatory, as well as to evaluate the plan for TMT as an upgradeable observatory. The EAP was asked to assess the state of the project management, organization, estimated construction costs and the strategy for phasing the entire TMT program from design and development, construction, through commissioning and early operations.

The TMT project prepared The Thirty Meter Telescope Construction Proposal for this review. In this document, the project summarizes work completed to date and provides an implementation roadmap. It begins with the science cases and science-driven requirements that motivate the TMT design. This is followed by high-level operational concepts, technical requirements, and observatory architecture description. Detailed descriptions of the observatory sub-systems are followed by concepts for system assembly, integration and verification followed by a description of how the observatory will be operated. The proposal concludes with an overview of how the project will be organized and a summary of project cost.

The TMT project plans to update this proposal over the next 12 – 18 months as TMT design work and implementation planning are completed.

This version of the proposal omits some information that is proprietary to the project.

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# TMT Construction Proposal

# 1 Implementing the Thirty Meter Telescope

## *1.1 Starting Points*

Since the revolution in physics at the dawn of the 20th century, the history of astronomy has been one of exploration guided by the twin beacons of physical insight and technology. Physical insight has guided the questions we ask and the answers we derive from our observational data. Technology has extended our grasp to the very dawn of time.

Those of us alive today are extraordinarily lucky to have the answers to some of the deepest questions about the universe around us. We have arrived at a moment when we can see the imprint of the Big Bang everywhere we look: from the smallest ripples in the cosmic microwave background to the filaments of galaxies stretching across the sky of the present day universe to the very water in our bodies.

But our journey of exploration is not over, not all has been revealed. The *terra incognito* ahead is just as exciting as the astronomical landscape explored in the past.

Our universe appears to be dominated by mysterious quantities we have named dark energy and dark matter – we can observe their effect but we do not understand what they are or why they exist. The discovery of planetary systems around other stars has revealed that the structure and composition of our solar system may be the exception, not the rule – our ideas about planetary formation and the origin of life have to be completely revised. Beacons of extraordinary brightness shine out across the universe – what are they and how can they be used to study the intervening universe? Galaxies in the local universe show signs of a violent and turbulent past – what will we see when we actually observe their predecessors in the high redshift universe? We have a good idea of when the first stars formed – can we capture and analyze their light?

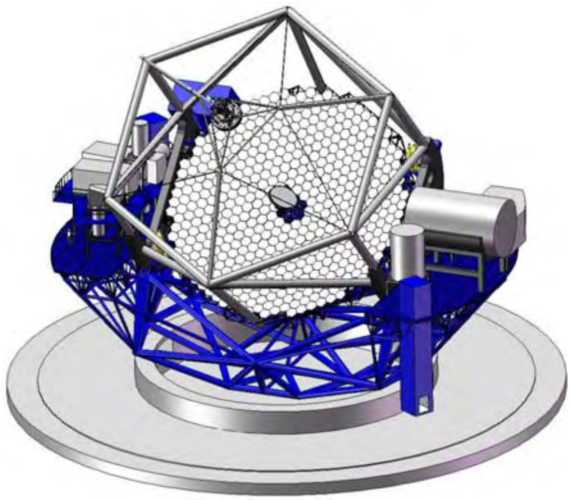
We choose to improve our understanding, to seek answers to these questions, not merely to satisfy idle curiosity but for the benefit of all humankind. The steady improvement in our understanding of the physical universe has driven the development of our technological civilization to heights that were simply unimaginable even 100 years ago. We stand on the edge of another breakthrough of inconceivable impact in our understanding of the physical universe – and astronomy will play a key role in taking us over that threshold.

And so we propose to build TMT – an exploration vehicle that takes advantage of the latest technology. To do this, we bring together the experience and knowledge of a broad, international community. Over the last 15 years, this community has been at the forefront of ground-based astronomical research and technology, having built and operated four 8 – 10m telescopes and participated in many of the most important scientific breakthroughs over this period. Our goal is to build a facility that will be exceptionally powerful in its own right while being capable of working in synergy with other planned facilities (such as the James Webb Space Telescope in space and the Atacama Large Millimeter Array on the ground) to address the key questions of 2016 as well as the new questions that will arise during following 30 years. TMT will fulfill the aspirations expressed in the 2001 decadal report for a giant segmented telescope [1].

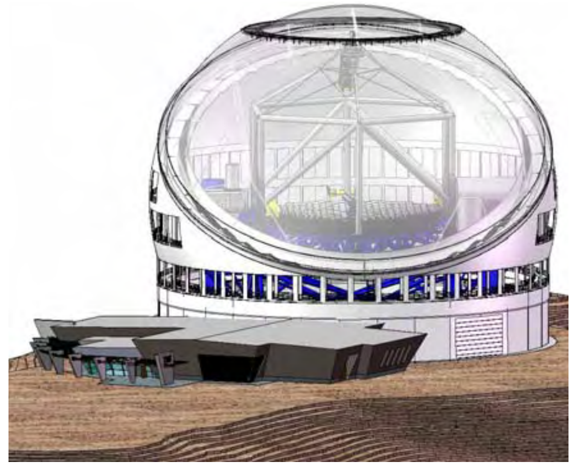
TMT construction will commence in 2009 with the goal of testing the telescope with its full primary mirror in 2016. First science observations will be carried out shortly thereafter. By following this construction schedule, TMT will be the first telescope in the next generation of extremely large telescopes, providing the TMT partner astronomers with first access to a new window on the universe, rich in scientific discovery.

## *1.2 The TMT Observatory*

The core of the TMT Observatory, see **Fig. 1-1**, will be a wide-field, alt-az Ritchey-Chretien telescope with a 492 segment, 30 meter diameter primary mirror, a fully active secondary mirror and an articulated tertiary mirror. The optical beam of this telescope will feed a constellation of adaptive optics (AO) systems and science instruments mounted on large Nasmyth platforms surrounding the telescope azimuth structure. These platforms will be large enough to support at least eight different AO/instrument combinations (depending on exact volume and mass parameters) covering a broad range of spatial and spectral resolution. To support and maintain these technical systems, a comprehensive set of support facilities is included in the basic observatory design.



**(a)**



**(b)**

**Fig 1-1: The telescope design (a), and the entire observatory system (b).**

TMT will couple unprecedented light collection area (almost 10 times more than one of the Keck telescopes) with diffraction-limited spatial resolution that exceeds by Keck by a factor of 3. Relative to the Hubble Space Telescope (arguable the most revolutionary astronomical instrument of our generation), TMT will have 144 times the collecting area and more than a factor of 10 better spatial resolution at near-infrared and longer wavelengths.

### 1.2.1 Aperture Size

Telescope primary mirror (M1) diameter (aperture size) is a key design choice – it drives the size and complexity of almost every other observatory system. From a science perspective, we know that the observations limited by atmospheric turbulence improve in sensitivity as diameter squared ($D^2$). Furthermore, AO systems allow us to remove much of the effects of turbulence, achieve diffraction-limited imaging, and gain an improvement of $D^4$. Hence, science gain motivates the largest diameter enabled by technology and cost.

Technologically, large M1 diameters are enabled by using the precision-controlled, segmented mirror techniques pioneered with great success by the W. M. Keck Observatory. The TMT M1 design team includes many of the key developers of the Keck system. In principle, arbitrarily large mirrors are possible. However, our analysis of AO technology development over the next ten years with respect to our detailed science goals (as summarized in **Chapter 2** of this proposal) suggests that D = 30 meters occupies an attractive and achievable scientific "sweet spot" at near-infrared wavelengths [2].

Obviously, cost also limits M1 diameter – how does financial pressure affect choice of aperture size? Prior to the design of the Keck telescopes, ground-based optical-IR telescope costs scaled roughly as $D^{2.7}$, reflecting the nearly volumetric dependence of observatory cost on aperture [3,4]. The advent of thinner primary mirrors with shorter focal lengths, as in the Kecek design, reduced this relationship to an estimated $D^2$; i.e., varying as the area of the aperture. A detailed cost study of key TMT design parameters (aperture, segment count, segment size, segment thickness, and enclosure diameter) for several hundred estimated elements in TMT concluded that TMT costs should scale as approximately $D^{1.15}$ relative to the Keck capital investment. Thus, we conclude that the TMT design represents an improved cost scaling and that the proposed 30 meter diameter of TMT represents a good value relative to the extraordinary science reach.

### 1.2.2 Adaptive Optics

Like all existing ground-based observatories, TMT will be capable of seeing-limited observations, i.e. observations with spatial resolution limited by the natural turbulence in the Earth's atmosphere. Since such observations improve as $D^2$, TMT will be able to observe objects nine times fainter than Keck in an equal amount of time.

However, TMT will be the first ground-based astronomy telescope designed with adaptive optics (AO) as an integral system element. AO is a general term that covers systems designed to sense atmospheric turbulence in real-time, correct the optical beam of the telescope to remove its affect, and enable true diffraction-limited imaging on the ground. For many astronomical observations, this is equivalent to observing above the Earth's atmosphere at a fraction of a cost of a space-based observatory. Gains improve from $D^2$ to $D^4$ – literally opening windows on the nearby and distant Universe inaccessible by any other observatory, on the ground or in space.

Just as the TMT primary mirror builds on the technological and operational heritage of Keck, the TMT adaptive optics design builds on the technological and operational heritage of (among others) the Gemini, Keck, and Very Large Telescope observatories. This is an area of rapid advancement and the TMT project is fortunate to have direct connections to some of the world leaders in this area (e.g. the Center for Adaptive Optics at the University of California, Santa Cruz). TMT plans are based upon an AO development roadmap that takes advantage of AO technological advances as they are being applied in astronomical observations and as they are developed.

### 1.2.3 Science Instruments

The TMT design is a response to a set of science-based requirements developed by the TMT Science Advisory Committee (SAC), a committee of scientists representing all the TMT partners and (by extension) the future TMT scientific user community. Central to these requirements are descriptions of a suite of eight instruments conceived to attack the key science problems of the first decade of TMT operations. Starting from these descriptions, detailed conceptual design studies were commissioned from instrument development teams throughout North America. These conceptual designs were reviewed by non-advocate review teams with members from North America and Europe.

Based on these studies and reviews, the SAC has selected three early light instruments: a wide-field, multi-object spectrograph working at optical wavelengths called WFOS; an integral-field unit spectrometer with imaging capability working at near-infrared wavelengths called IRIS; and a multi-slit, near-infrared spectrometer with imaging capability called IRMS. The latter two instruments will be fed by a facility AO system called NFIRAOS to achieve full diffraction-limited sensitivities and spatial resolutions in the near-infrared. These three instruments will be capable of exploring the wide astronomical terrain: from the first stars in the Universe to planets orbiting nearby stars.

The rest of the SAC suite, the first decade instruments, will be developed and deployed on a schedule paced by a combination of technological readiness and available financial resources. Naturally, TMT maintains the flexibility to investigate and deploy different instrument concepts in response to scientific and technological developments over the next decade.

### 1.2.4 Enclosure

The TMT enclosure has several key functions. By day, it must protect observatory systems, facilitate a broad range of maintenance activities, and keep the telescope temperature near the expected night time temperature. By night, it must shield the telescope from wind buffeting while allowing enough airflow to keep the interior iso-thermal to limit seeing degradation due to air turbulence in the enclosure.

TMT has selected an innovative, structurally efficient calotte enclosure design that, by its spherical shape and circular "shutter" aperture, fulfills key functional requirements with lower mass (and hence lower cost) than possible for previous enclosure designs.

### 1.2.5 Infrastructure: Summit and Support Facilities

TMT programmatic requirements have been studied to specify the needed conventional facilities and construction sequence at the summit and at a nearby support location. Minimum excavation of the summit to support the required facility footprint and construction allowances has been defined.

The summit facility supports telescope operations, control room functions, staff summit support, mirror handling, stripping, cleaning, storage and recoating, basic engineering and technical activities and other elements of operation that must be carried out close to the telescope.

Support facilities, approximately 15 minutes from the summit, include a construction camp, dormitories and dining facilities for operations staff, and workshops for maintenance and technical activities.

#### 1.2.6 Site

Ultimately, the performance of any optical-IR ground-based observatory is limited by its location. Currently, TMT is executing a multi-year site testing program on five different mountains determined from satellite imagery and meteorological data to have excellent potential. Final site selection is planned for mid-2008.

Location also has an impact on design and cost. For the purposes of detailed preliminary design, Cerro Armazones in northern Chile has been chosen as the design reference site. This choice does not unduly constrain the ultimate TMT site decision but does allow the kind of planning necessary to better define requirements and estimate cost. Cerro Armazones is a good model for the Mexican site and other Chilean sites under consideration. Relative to Armazones, the Hawaiian site under consideration is expected to have somewhat reduced infrastructure requirements and hence lower cost. However, much of this cost differential is reduced by cost rate differences in several key areas. In short, cost estimates for Cerro Armazones are expected to be broadly applicable for all sites under consideration.

## *1.3 The TMT Project*

The TMT Project was constituted to design and build the TMT Observatory as well as initiate early operations. The project is nearing completion of site-independent design and development work. During this phase, we have delivered a successfully reviewed conceptual design, a rigorous cost estimate, and carried out a value engineering study resulting in a design optimization that retains the full science capabilities consistent with the partner cost targets.

By early 2008, the project will provide the TMT Board with the information necessary to make a definitive site selection and prepare for the transition to an implementation program that consists of three, overlapping phases. First, completing site-specific facility design, industrializing production of the key TMT components, producing first articles and carrying out low-rate initial production will bring all elements of the project to full construction readiness. Second, construction will consist of full production of the serial elements of the primary mirror (mirror segments, supports and controls, actuators, edge sensors and incidental components), fabrication of all other technical elements, civil construction of summit and support facilities, erection of the telescope enclosure and structure, and assembly, integration and verification of the complete system at the observatory site. Finally, early operations will overlap construction as facilities are progressively delivered to routine operations and as science capabilities are fully commissioned. Completion of these three phases will enable full scientific operation of the TMT observatory.

## *1.4 The TMT Construction Proposal*

In this document, we summarize work completed to date and provide an implementation roadmap. We start with the science cases and science-driven requirements that motivate the TMT design. This is followed by high-level operational concepts, technical requirements, and observatory architecture description. Detailed descriptions of the observatory sub-systems are followed by concepts for system assembly, integration and verification followed by a description of how the observatory will be operated. We conclude with an overview of how the project will be organized and a summary of project cost.

We intend to update this proposal over the next 12 – 18 months as TMT design work and implementation planning are completed.

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# 2 Science Motivation

## 2.1 Introduction

TMT will enable ground-breaking advances in a wide range of scientific areas, from the most distant reaches of the Universe to our own Solar System. We can look ahead and imagine what the most vital scientific questions of the coming decades might be, but history has shown that the most important discoveries were often unexpected. Powerful new facilities can reveal stunning new realms of research. There is no doubt that TMT will make revolutionary discoveries in areas that we cannot today predict.

### 2.1.1 The big picture

Decades of advances with ground and space-based facilities have provided a clear and convincing picture of the overall history of our Universe. We now know that the observable Universe began some 13.6 billion years ago when a small region of empty space became unstable and began to expand, rapidly increasing in size by some twenty or thirty orders of magnitude. This period of expansion, called inflation, lasted only a fraction of a second, yet it resulted in the production of all matter and energy in our Universe. When inflation ended, an exceedingly hot mixture of elementary particles of all varieties pervaded space. At the same time, tiny "quantum" fluctuations in the distribution of this energy were stretched to macroscopic scales by inflation. These fluctuations formed the seeds for the galaxies and clusters of galaxies that we see today.

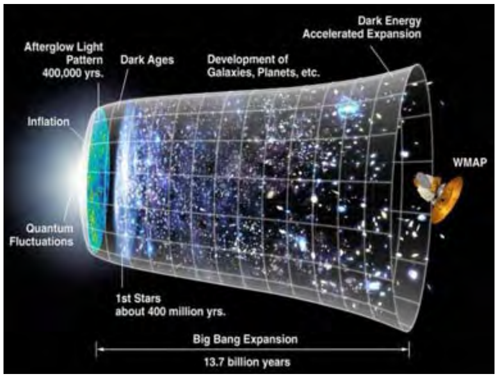


**Fig 2-1: Schematic history of the Universe (WMAP team).**

Following inflation, the Universe continued to expand, but at a slower rate. This expansion resulted in cooling of the plasma allowing the elementary particles to combine to form the familiar protons, neutrons, electrons, photons, neutrinos and ultimately hydrogen and helium nuclei. Also present were large quantities of what we now refer to as dark matter and dark energy. During this expansion, the gravitational attraction of the small energy fluctuations resulted in the growth of dark matter density fluctuations.

Some 400,000 years after inflation, the nuclei and electrons combined to form neutral atoms and the Universe became transparent to the photons remaining from the Big Bang. Today we see those photons as the cosmic microwave background. Once freed from the drag produced by interactions with those Big Bang photons, the neutral gas began to fall into the denser pockets of dark matter. In a complex process of gravitational accretion and radiative cooling, the first stars formed. The intense radiation produced by this first generation of massive stars heated the surrounding gas, creating bubbles of ionized gas. Initially, the light from these first stars was trapped in these bubbles; but as more and more of the surrounding gas was re-ionized, this first light began to propagate throughout the universe.

As star formation continued and dark matter halos merged due to gravitational attraction, the first galaxies were formed. These first galaxies – relatively small collections of stars, gas, and dust caught within the gravitational potential of dark matter halos – merged to form larger more massive galaxies. The end products of this process (known as hierarchical structure formation) surround us today – from the most massive clusters of galaxies, to our home galaxy the Milky Way, and down to its dwarf galaxy neighbors.

Within many galaxies, star formation continues as clouds of gas cool and contract. Dense clouds of molecular gas form stellar nurseries that harbor infant stars. These nascent stars are surrounded by disks of gas and dust within which planets develop. We now know that many, perhaps most, stars have planetary systems and we have begun to explore the closest examples. We can presently detect only the largest planets, similar to those in the outer Solar System, but suspect that smaller Earth-like planets are also present. Some of these systems should have conditions favorable for the development of life.

### 2.1.2 The big questions

TMT will allow astronomers to explore virtually every aspect of this picture, from inflation to exoplanets. The resolution and sensitivity provided by its large aperture and AO systems, combined with a flexible and powerful suite of instruments, will enable us to address many of the most fundamental questions of the coming decades.

***What is the nature and composition of the Universe?***
Ordinary matter can generally be detected directly, from the light emitted by stars, from radiation emitted by hot gas in galaxies and clusters, and by absorption of light from background luminous sources. We can infer the presence of dark matter from its gravitational attraction, which affects the motion of galaxies and the propagation of light. In contrast, the gravitational effect of dark energy is repulsive, manifested by an increase in the rate of expansion of the Universe. A census of these components reveals the surprising result that normal matter accounts for only a small fraction of the composition of the Universe– the rest is dominated by dark energy and dark matter. Closely related to the question of the composition of the Universe, is its dynamical history. The inflationary period that produced the observable Universe is believed to have been driven by a form of dark energy – a scalar field. Incredibly, the earliest moments of the Big Bang, involving physics on the smallest scales, can be probed by observations of the large scale structure of the Universe.

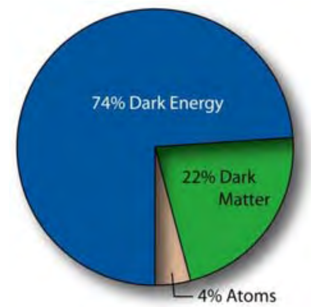


**Fig 2-2: Composition of the Universe.**

***When did the first galaxies form and how did they evolve?***
By looking into space to greater and greater distances, we are able, thanks to the finite speed of light, to see further and further back into the past. To see the very first stars and galaxies we must look over enormous distances, some 13 billion light years. So far these objects remain beyond the reach of present telescopes. At lesser distances, moving forward in time, we see galaxies interacting dynamically and forming stars. But it is not yet clear how this produces the diversity of galaxy types that are seen today.

***What is the relationship between black holes and galaxies?***
There is now overwhelming evidence that black holes exist, and that black holes with as much as a billion times the mass of the Sun occupy the centers of galaxies. But, we don't know when or how these supermassive black holes formed, or how they fit into the overall picture of galaxy formation and evolution.

***How do stars and planets form?***
Stars form within molecular clouds, by a combination of complex physical processes. What determines when these clouds form stars? What determines the masses of these stars? What fraction have planetary systems? There are many questions we are just beginning to explore.

***What is the nature of extra-solar planets?***
The exoplanets detected so far are gas giants like Jupiter and Neptune. They were discovered because their large mass noticeably perturbs the motion of the host star. Surprisingly, many are found very close to their host star. As the higher temperatures from near proximity would prevent such planets from forming, it seems they must have migrated inward after first forming at greater distances. We believe that smaller terrestrial planets exist, but these cannot be detected with present telescopes. Are such planets common? Can they survive the disruption that would result from migration of the massive planets? Do they have atmospheres like Earth?

***Is there life elsewhere in the Universe?***
If terrestrial planets exist, are conditions conducive to the development of life? Each star has a habitable zone, where a planet would have a surface temperature comparable to Earth's. If, as expected, exoplanetary systems have populations of small icy bodies like comets, it is possible that water and organic molecules could have been delivered to such planets by impacts. If life then develops, it might be detected by signatures of biological activity in planetary atmospheres.

### 2.1.3 The required tools

To answer these and many other questions, advances in technology are needed. The greatest progress will come from combined studies at many different wavelengths using ground and space-based facilities. Several major new telescopes will begin operation in the next decade, including the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA). Soon to follow will be the Square Kilometer Array (SKA). By providing powerful new capabilities at optical, infrared, microwave and radio wavelengths, these facilities will open new frontiers. Yet they alone will not be sufficient. Much as the resolution of the Hubble Space Telescope was complemented by the greater light gathering power of the Keck 10-meter telescopes, these upcoming facilities will require a complementary large-aperture ground-based telescope to provide high spatial and spectral resolution observations in the optical and infrared. In fact, a revolution in technical capability now makes ground-based telescopes even more effective. Adaptive optics (AO) systems allow the largest optical-infrared telescopes on Earth to achieve higher resolution than telescopes in space, which necessarily have smaller apertures. By compensating atmospheric turbulence, AO allows telescopes to reach the diffraction limit, in which the angular resolution achieved is proportional to the diameter of the telescope aperture.

A useful figure of merit for telescope performance is the time required to achieve a given signal-to-noise ratio for a particular science program or object. The reciprocal of this time is a measure of the sensitivity or productivity of the telescope. Because larger telescopes collect more light, their sensitivity typically increases in proportion to the square of the aperture diameter. But, in the important case of observations of faint point-like objects, the smaller angular size results in less contamination by background or foreground light from the sky, Solar System and galaxy, so the sensitivity increases in proportion to the fourth power of the diameter. This is an enormous factor, making a thirty-meter telescope a hundred times more sensitive than a ten-meter telescope.

To take advantage of these huge gains in light collection and spatial resolution, TMT must be equipped with a suite of powerful science instruments. The TMT Science Advisory Committee has developed recommendations for the instruments and their performance requirements based on a careful consideration of the science programs. These instruments will be discussed in detail in subsequent sections. Here we briefly outline the main capabilities.

**IRIS (Infrared Imaging Spectrometer)**
A flagship instrument that will be available when the telescope first begins operation, IRIS combines a high-resolution imager and an integral-field spectrometer. It provides a capability to acquire imaging and spatially-resolved spectroscopy of the faintest objects at the diffraction-limit of the telescope. IRIS will achieve this by means of a powerful adaptive optics (AO) system, NFIRAOS. Designed to provide diffraction-limited images over a 30 arcsec diameter field of view to three instruments, NFIRAOS will employ laser guide stars and two deformable mirrors that allow it to compensate for both high-level and low-level turbulence and will operate over the near-infrared (1.0 – 2.5 um) wavelength range.

**IRMS (Infrared Multislit Spectrometer)**
Also a first-light instrument, IRMS provides the capability to obtain near-infrared spectra of as many as 46 objects at a time, by means of deployable slits. IRMS will employ the NFIRAOS adaptive optics system that will allow it to achieve very high spatial resolution and sensitivity.

**WFOS (Wide-Field Optical Spectrometer)**
WFOS provides a multi-object spectroscopic capability in the optical wavelength region (0.31 – 1 um). Using multiple slits that can be deployed over a large field of view, it can observe several hundred objects at a time at moderate spectral resolution. It is the third of the three first-light instruments recommended by the TMT Science Advisory Committee (SAC).

**MIRES (Mid-Infrared Echelle Spectrometer)**
MIRES is a diffraction-limited high-resolution spectrometer and imager operating at mid-infrared wavelengths (5 – 28 um). It will employ a separate AO system, MIRAO, optimized for the mid-infrared.

**NIRES (Near-Infrared Echelle Spectrometer)**
This is a diffraction-limited high-resolution spectrometer operating at near-infrared wavelengths using the TMT NFIRAOS AO system.

**IRMOS (Infrared Multiobject Spectrometer)**
IRMOS is a very ambitious instrument that will use deployable integral-field units to provide a capability for spatially-resolved spectroscopy of multiple targets simultaneously. It will employ an advanced multi-object AO (MOAO) that can provide good atmospheric correction over a 5-arcmin field of view.

**HROS (High-Resolution Optical Spectrometer)**
HROS is a high-spectral-resolution long-slit spectrometer operating at optical wavelengths. It does not employ AO and can be used in all atmospheric conditions, whenever the sky is reasonably clear.

**PFI (Planet Formation Instrument)**
Perhaps the most technically challenging instrument, PFI will have the capability to image, and obtain spectra of, faint planets close to bright stars. It will employ a unique extreme AO system (EXAO) and advanced systems for the suppression of starlight.

## 2.2 Cosmology and fundamental physics

### 2.2.1 Baryonic power spectrum

Studies of the distribution of matter have provided amazing details about the early inflationary period of the Universe. The power spectrum of density fluctuations is predicted by theory to have arisen from a "scale invariant" primordial spectrum that is a power law with a slope of -1. Small deviations from this slope are expected and are related to the degree by which the Universe expanded during its period of inflation. By measuring the distribution of matter over a wide range of scales, one can constrain both the slope and possible deviations to high precision. Measurement of the power spectrum on large scales is limited by "cosmic variance" (there is only one Universe)—the most precise measurements will necessarily come from measures on small physical scales. Unfortunately, regions of space containing large visible structures such as galaxies have evolved through gravity to the point that the initial conditions are erased. But by using the details of the distribution of diffuse hydrogen gas in the intergalactic medium, it is possible to measure the so-called "primordial" power spectrum. TMT will allow for the first time the study of the 3-dimensional distribution of diffuse hydrogen in the intergalactic medium, which is directly related to matter density, thereby increasing the precision of cosmological measurements by an order of magnitude over that possible with current telescopes. TMT, using WFOS and HROS, will probe the distribution and composition of gas along the lines of sight to distant quasars and galaxies, providing unique high-quality data essential to an understanding of these processes.

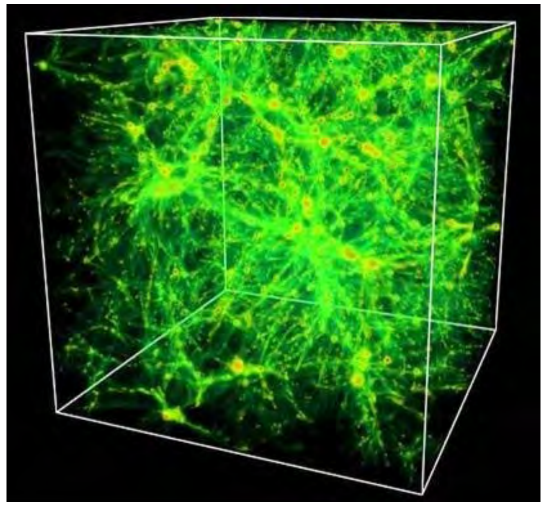

**Fig 2-3: Simulation of the dark matter structure at a redshift z = 3 (R. Cen, Princeton Univ.).**

### 2.2.2 Fundamental constants

One of the great mysteries of our time concerns the nature of the dark matter and dark energy. These dominate the mass density of the Universe, but we have no idea what they are. Theory provides ample possibilities, but we do not know if any of these correctly represent nature. Many of these theories predict that so called fundamental constants, such as the mass of the electron, should have been slightly different in the past. It is possible to search for variations of the constants by accurate measurement of wavelengths of absorption lines seen in the spectra of quasars. More than a decade of study using 8 and 10-meter telescopes has yielded the first tantalizing evidence for such variation. However, the signal-to-noise ratio of these measurements is low. In the same time period, TMT with HROS would provide three times the signal-to-noise ratio, providing a definitive result.

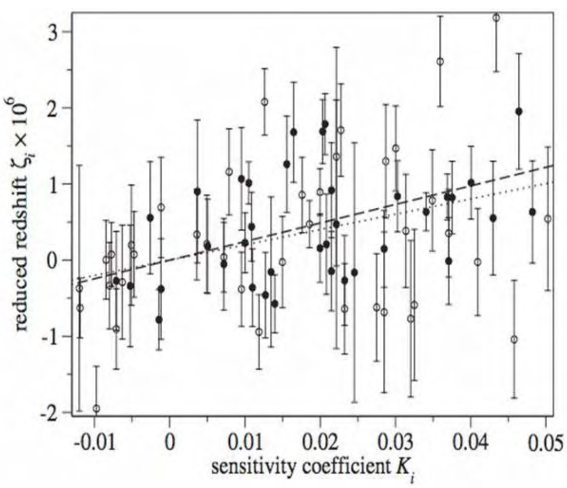


**Fig 2-4: Wavelength residuals seen in QSO spectra vs sensitivity coefficient. A positive slope indicates a variation of the ratio of the masses of the proton and electron (Reinhold et al. 2006).**

### 2.2.3 Physics in extreme environments

The most energetic explosions in the Universe produce gamma-ray bursts visible at great distances. These are believed to be caused by the collapse of massive stars that generates an intense outflow of highly-relativistic particles having energies beyond anything achievable with particle accelerators on Earth. Because these gamma-ray bursts are very rare events, one must look over cosmic distances to find them. Follow-up observations to analyze their properties require large telescopes. TMT will allow us to study the mechanism that generates the intense radiation beam, and better understand the physical conditions that produce them.

## 2.3 *The early Universe*

The expansion of the Universe stretches the wavelengths of photons, causing spectral lines to shift to longer (redder) wavelengths. The redshift of a source is thus a measure of its distance, and its age at the time that the light was emitted. It is thought that the first stars formed at a time corresponding to a redshift of 15 – 20, just a few million years after the Big Bang. So far no objects have been seen with a redshift greater than 7, corresponding to a time when the Universe was about one billion years old.

### 2.3.1 The first stars

The first luminous objects are expected to be giant stars, beyond 300 times more massive than the Sun, forming within clouds of primordial gas. Radiation from these stars ionizes the surrounding gas creating a diffuse glow. The number and brightness of these sources is uncertain, in part because it is not known how much of the light will penetrate the intergalactic medium. Nevertheless it is believed that JWST will be able to detect the brightest of these sources. TMT, with adaptive optics, will be able to detect objects an order of magnitude fainter that this. Also, the spectroscopic capabilities of IRIS and IRMS will allow us to determine if these are in fact the first objects. Models predict that the first stars will have high surface temperatures and radiation fields intense enough to ionize the primordial helium gas. The characteristic emission lines produced by this gas serve as an indicator that can be detected with TMT. In addition, TMT will be able to study the flux distribution of the sources, the size and topology of the ionized region, and track the development of the reionization of the Universe.

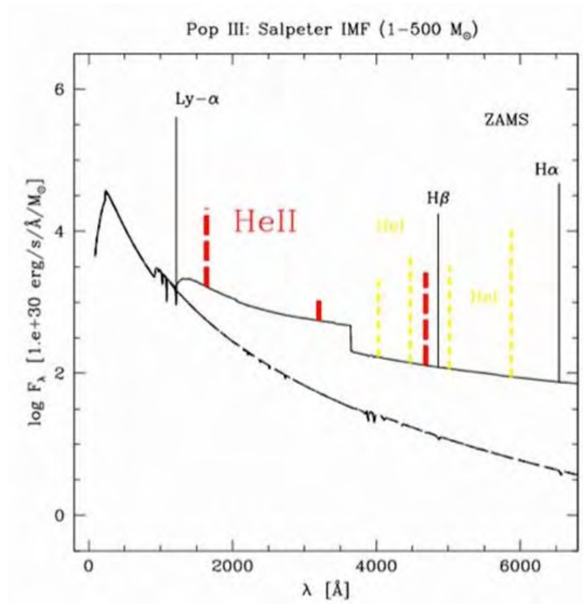


**Fig 2-5: Predicted spectrum of the first luminous objects. The He II lines are indicative of an intense ionizing radiation field produced by very massive stars (Schaerer 2002).**

### 2.3.2 The first galaxies

The first galaxies are expected to be strong sources of Lyman-α emission, originating from the gas within them. Searches for these objects, using ground-based telescopes, have detected Lyman-α emitters with redshifts as high as z = 6.6. TMT will be able to detect such objects at greater distances, hence earlier times, to redshifts as high as 18 In addition, it should be possible to go beyond even this limit by employing gravitational lenses to magnify the light of these distant galaxies. Such lenses are formed by the gravity of large clusters of galaxies that is sufficiently strong to bend and focus the light that passes through them from distant sources, making them appear larger and brighter.

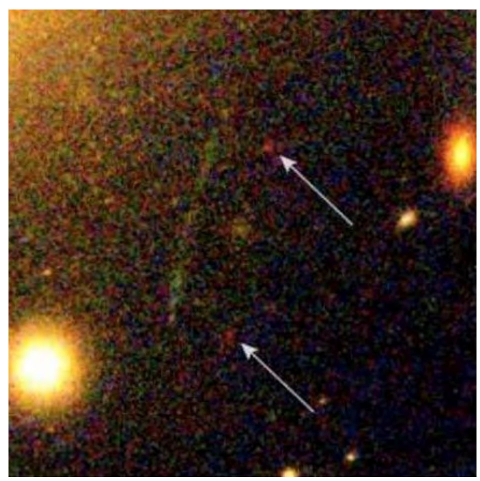

**Fig 2-6: Distant galaxies, with redshift z = 5.6, amplified by gravitational lensing by a foreground galaxy cluster (R. Ellis, CIT).**

## 2.4 *The epoch of galaxy formation*

As time progressed, the early galaxies began to interact gravitationally and merge, building up larger galaxies. During this process, large amounts of gas within the galaxies were compressed, triggering the formation of stars. It is thought that the bulk of the stars in the Universe were formed during this epoch, with most of the activity occurring over the redshift range z = 2 – 7, a period of time when the Universe was between 1 and 4 billion years old.

### 2.4.1 Physical properties of high-redshift galaxies

Just how did the galaxies form and evolve? Why are some spiral and some elliptical, and why are some forming stars while others are not? How does the distribution of dark matter relate to the luminous stars and gas that we see? Answers to these questions will come from detailed studies of galaxies at high redshift. One needs to measure the gas composition, star formation rate and internal structure, and relate this to the mass and dynamical state of the galaxy and to its environment. TMT, with the IRIS and IRMOS integral-field unit (IFU) spectrometers is perfectly suited to this task. By placing the IFUs at the locations of galaxy images, spectra will be obtained for every element within the galaxy image. From this, one can derive the distribution of velocities and physical parameters throughout the galaxy.

TMT will "dissect" forming galaxies with ten times greater sensitivity and five times the spatial resolution compared to JWST. With IRMOS, many galaxies can be observed simultaneously allowing statistically significant samples to be studied. Complementary data, at longer wavelengths, will come from ALMA.

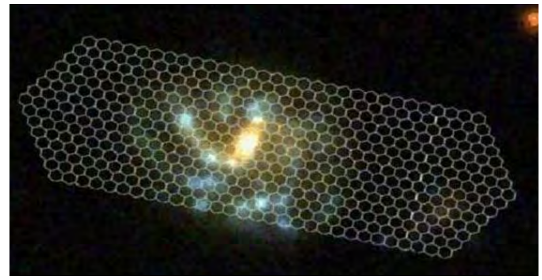

**Fig 2-7: Image of a distant galaxy superimposed on a TMT integral field unit. Individual spectra are produced for every hexagonal element, allowing an in-depth study of the physical properties of the galaxy with a spatial resolution of about 100 pc (J. Larkin).**

## *2.5 The intergalactic gas*

Most baryonic matter, particularly during the early history of the Universe, is actually outside of galaxies. Intergalactic space is filled with a tenuous gas that provides "fuel" for forming galaxies, and is a repository for material expelled by galaxies by energetic processes such as supernova explosions and accretion onto supermassive black holes. The interplay between the galaxies and the intergalactic medium is of prime importance for understanding the history of normal matter in the universe, the process of galaxy formation, and the effects of the "feedback" of energy produced by forming galaxies.

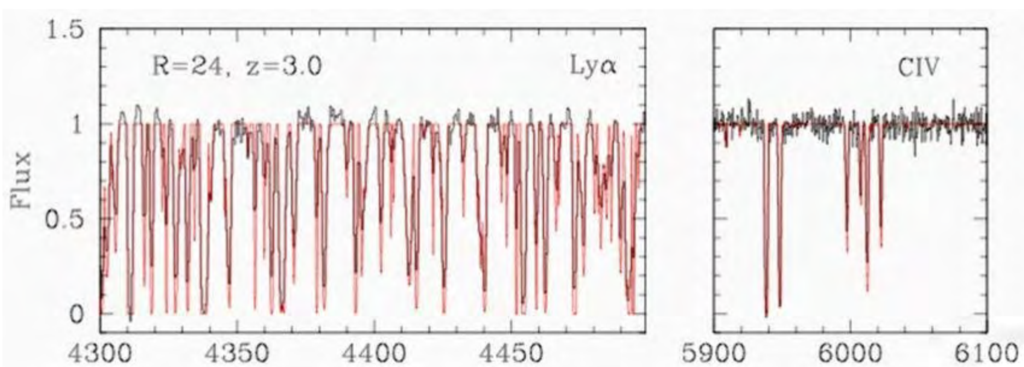


**Fig 2-8: Simulated spectrum of an R = 24 galaxy observed with WFOS on TMT (WFOS-NRC/HIA team).**

### 2.5.1 Structure of the intergalactic medium

The intergalactic medium (IGM) leaves its signature on the light received from distant luminous sources such as quasars. Elements in the gas absorb light at characteristic wavelengths, producing absorption lines in the quasar spectra. The lines produced by clouds at different distances along the line of sight to the quasar have different redshifts, so analysis of the absorption line wavelengths can reveal the spatial distribution of the gas as well as its composition, density and temperature.

Work in this area has been limited by the relatively small number of quasars, particularly at high redshift. TMT will enable an enormous advance in this field since its large light gathering power will allow background *galaxies* to be used as sources in addition to quasars. While fainter, these galaxies are far more numerous than quasars, allowing a hundred-fold increase in the number of lines of sight that can be probed. With WFOS, it will be possible to simultaneously map the distribution of galaxies and the diffuse material between them, in “3-D” providing the most complete possible census of all normal matter, and its relationship to dark matter.

### 2.5.2 The intergalactic medium at high redshift

Studies of the IGM have been limited to redshifts of at most $z \sim 6$, as no quasars of higher redshift have been found. Certainly stars and galaxies exist at higher redshift, but these are not sufficiently luminous. With TMT, we will have the potential to use more exotic objects such as gamma-ray bursts as sources with which to probe the IGM at very high redshifts and thereby study the epoch of reionization of the Universe.

## *2.6 Exploration of nearby galaxies*

Detailed studies of nearby galaxies provide an alternative approach to the study of the history and evolution of these

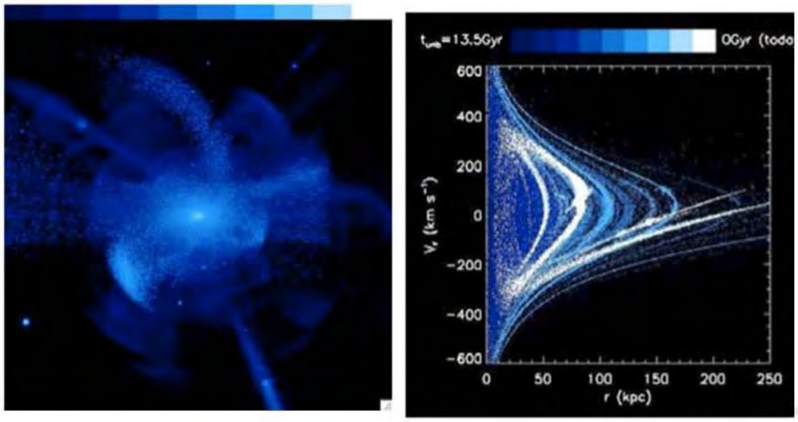


**Fig 2-9: Simulation showing the positions of populations of stars (left) and the radial velocity as a function of radius (right). The distinct components that can be seen arise from smaller galaxies that have been captured and accreted (Bullock & Johnstone 2005).**

systems, which is complementary to studies of galaxies at high redshift. The stars in galaxies retain information about the time that they were born, the composition of the gas from which they formed, and its dynamical state.

### 2.6.1 Dynamical states of stellar populations

The orbits of stars in present-day galaxies are determined in part by the past dynamical history of the galaxy. When smaller galaxies are captured gravitationally and disrupted, their stars retain much of the common motion of their former host. After capture, they orbit within the galaxy as a swarm of stars following similar trajectories. TMT, with WFOS, will be able to map the velocities of thousands of stars in nearby galaxies. This will make it possible to study the dynamical history of these galaxies and test theories of structure formation on sub-galactic scales.

### 2.6.2 Star formation history of local galaxies

The stars in galaxies retain a record of when they were formed. Precise photometry can reveal distinct populations of stars that likely formed at a common time in a burst of star formation induced by a merger or interaction with a nearby galaxy. One can also infer the chemical composition of the stars and relate this to this to the star formation history.

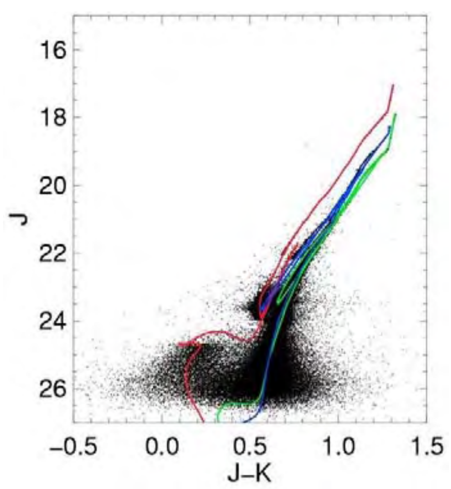


**Fig 2-10: Simulated color-magnitude diagram for stars in M32 as seen by TMT + IRIS. The red, blue and green lines represent three different input stellar populations. (K. Olsen, NOAO).**

A limiting factor in such observations is telescope resolution. In these crowded star fields, stellar images overlap making accurate photometry difficult or impossible. TMT, using adaptive optics, will have unprecedented resolution, superior to any currently planned space-based observatory operating at the same wavelengths. This will allow us photometric studies in galaxies as far as the Virgo cluster. This will open up a volume of space an order of magnitude larger than presently available, and enable investigation of a wide range of galaxy types and environments.

### 2.6.3 Stellar chemical abundances

High-resolution spectroscopy provides a complementary approach to studies of the abundances of elements in stars. With a spectral resolution $R = \lambda/\Delta\lambda$ of 30000 or more we can determine the composition in great detail, allowing studies of stellar structure, chemical evolution and nuclear astrophysics. This will allow a refinement of stellar models which form the basis for the interpretation of spectra of distant objects, and improve our understanding of how and when the elements formed. In addition, the properties of the most extreme stars, those having very low abundances of "heavy" elements (beyond hydrogen and helium), provide a direct probe of the aftermath of the first stars, which produced the first heavy elements.

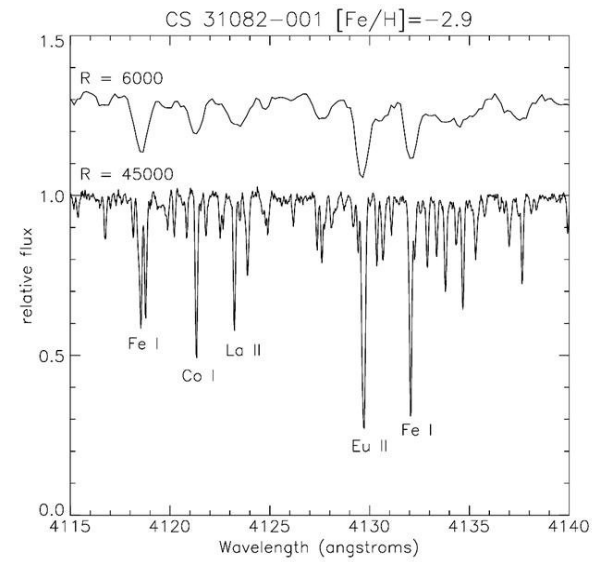


**Fig 2-11: Comparison of spectra taken at moderate resolution (upper curve) and high resolution (lower curve) of a metal-poor star (R. Gahuthakurta, UCSC).**

### 2.6.4 Dwarf galaxies in the Local Group

Dwarf galaxies are the smallest galactic systems. It is here that there is a significant discrepancy between theory and observations. Theory predicts that for every large concentration of dark matter, there should be very many smaller concentrations. Since gas collects within these dark matter "halos," we should expect to find far more dwarf galaxies than are actually observed. To resolve this issue, we need to study the mass and distribution of dark matter in dwarf galaxies directly. This can be done by studying its gravitational effect on the orbits of stars. TMT, with WFOS, will be able to measure the velocities of thousands of stars in dwarf galaxies in the Local Group (our galactic neighborhood, containing the Milky Way, the Andromeda galaxy, and about 30 other known galaxies). Since the dynamics of dwarf galaxies is dominated by dark matter it will be possible to derive the amount and three-dimensional distribution of dark matter.

## *2.7 Black holes*

The evidence is now overwhelming that black holes exist. These range from stellar-mass black holes, formed by the collapse of stars, to giant supermassive black holes that are found at the centers of galaxies, believed to have formed initially from the mergers of many stellar-mass black holes early in the Universe's history. The aim now is to understand how these black holes form and the relationship between the black hole and its host galaxy.

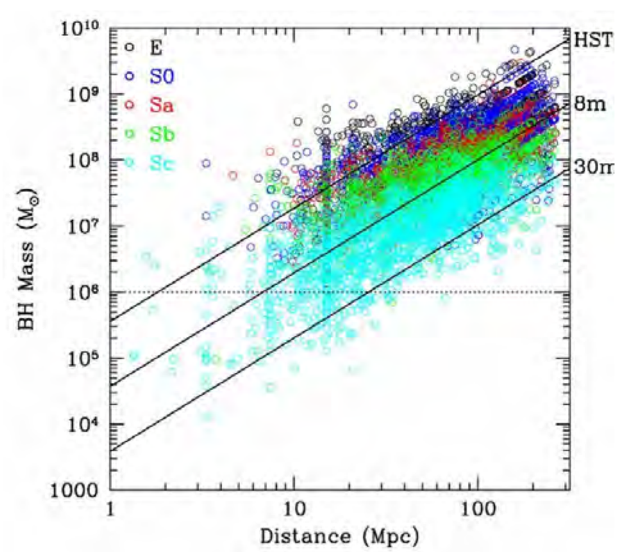


**Fig 2-12: Simulation showing black hole mass vs distance for different galaxy types. Detection limits for present telescopes and TMT are shown by diagonal lines.(TMT IRIS team). The TMT will be able to detect black holes over the full range of galaxy types (TMT IRIS team).**

### 2.7.1 Black holes in galactic nuclei

Supermassive black holes in galaxies can be detected by their gravitational influence on stars in the center of the galaxy, which must necessarily orbit at high speed around the black hole. The “region of influence” of the black hole, where the velocities are noticeably affected, is proportional to its mass. To detect the black hole and measure its mass, one needs a telescope that can resolve this small region. The TMT, with IRIS, will be able to resolve the region of influence of a billion solar mass black hole to a distance of two Giga parsec (Gpc) (about 6 billion light years), making thousands of galaxies accessible. This will allow us to explore the relationship between the black hole mass and the mass, morphology and dynamical state of the host galaxy. At present, we know that there is a symbiotic relationship between the mass of a galaxy’s “bulge” or “spheroid” and its central black hole, but we do not understand what physical processes produced the relationship observed in the present-day Universe. It is possible that the energy produced by material accreted during black hole growth may be responsible for controlling the ultimate size a galaxy can attain, or that whatever processes are responsible for terminating star formation in galaxies also shut down further growth of supermassive black holes. TMT will allow us to observe the relationships between black holes and galaxy growth as they are happening at early times.

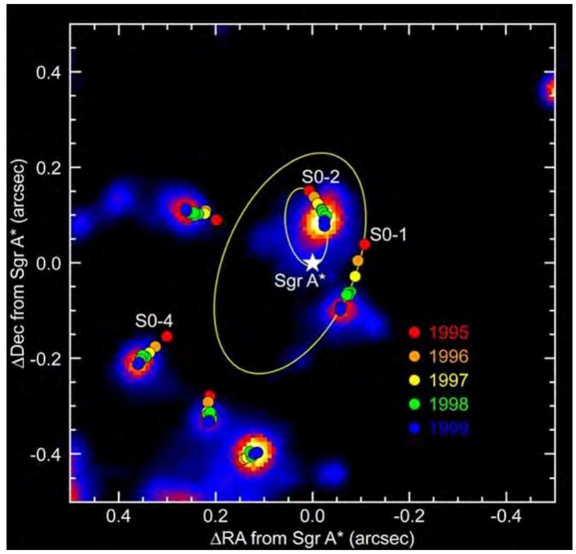


**Fig 2-13: Infrared image of the galactic center, with previous positions of stars superimposed. The position of the black hole is indicated by the star-shaped symbol at the center. Ellipses illustrate the derived orbits of two stars (A. Ghez, UCLA).**

### 2.7.2 The galactic black hole

Our own Milky Way galaxy contains a black hole with a mass about a million times that of the Sun. Its presence has been revealed by observations, using adaptive optics on 8 and 10-meter telescopes, which clearly show rapid motion of the stars orbiting the black hole.

The higher sensitivity and resolution will allow more stars to be followed, with greater accuracy in both position and velocity measurements. These data will enable precise measurements of the black hole mass and galactic parameters such as the distance of the Sun from the center of the galaxy. The exquisite precision provided by TMT will allow relativistic effects to be detected, providing new tests of general relativity.

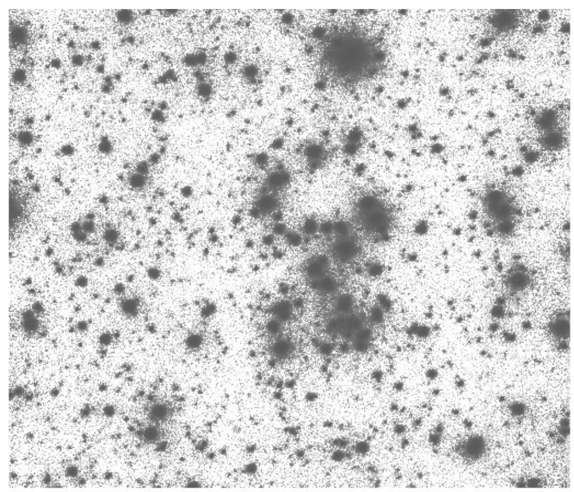

**Fig 2-14: Image of a star field in M31 obtained using the Keck 10 meter telescope laser guide star AO system. The area shown is approximately 8 x 10 arcseconds. TMT will provide 3 times sharper images and 80 times the sensitivity (J. Cohen, CIT).**

## *2.8 The formation of stars and planets*

We have a general understanding of how stars and planets form, but many details of this complex process elude us. We do not know what determines the masses of the stars, or the frequency with which planetary systems form, and cannot predict the properties of the planets. Progress in this area requires new observational capabilities, combined with sophisticated theoretical analyses.

### 2.8.1 Initial mass function in young star clusters

The distribution of masses of newly-formed stars is a key parameter that not only guides theoretical understanding but is also an essential ingredient in the interpretation of the spectra of distant galaxies. The superior resolution and sensitivity of TMT will allow individual stars to be resolved, even in crowded fields, and their masses to be determined, to a lower limit of one solar mass, over a wide range of stellar environments in nearby galaxies. In the nearest dwarf galaxies, such as the Magellanic clouds, it will be possible to probe the initial mass function to much lower masses, all the way down to the brown dwarf regime.

### 2.8.2 Physical conditions in star-forming regions

In star-forming regions we see infalling gas, which produces new stars. We also see outflows of material expelled by newly-forming stars. The competition between infall and outfall provides a feedback mechanism that regulates the star formation rate and the masses of the stars. The details of these processes are not yet understood. However, they are accessible to observation with next-generation telescopes. Infrared radiation allows us to penetrate these dust-enshrouded regions, and the large aperture of TMT will provide unprecedented spatial resolution with adaptive optics. The multiplexing capability of IRMOS will allow many outflows to be resolved, and their interaction with the interstellar medium to be studied. These studies will be complementary to studies using ALMA, which will provide information about the composition and densities of the molecular clouds.

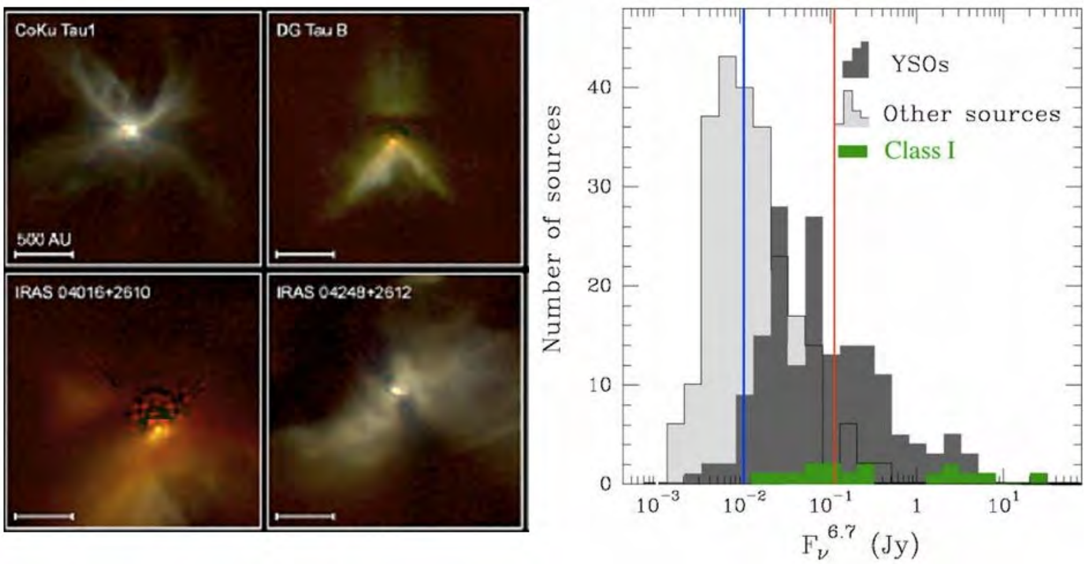


**Fig 2-15: Images of young stellar objects (left). Dusty disks can be seen obscuring the star, and bipolar outflows occur along the symmetry axis. The right panel shows the number of sources as a function of infrared flux. The two vertical lines represent the detection limits of 10-m telescopes (red) and TMT (blue). TMT will be able to detect and study virtually all YSOs in nearby star forming regions (TMT MIRES team).**

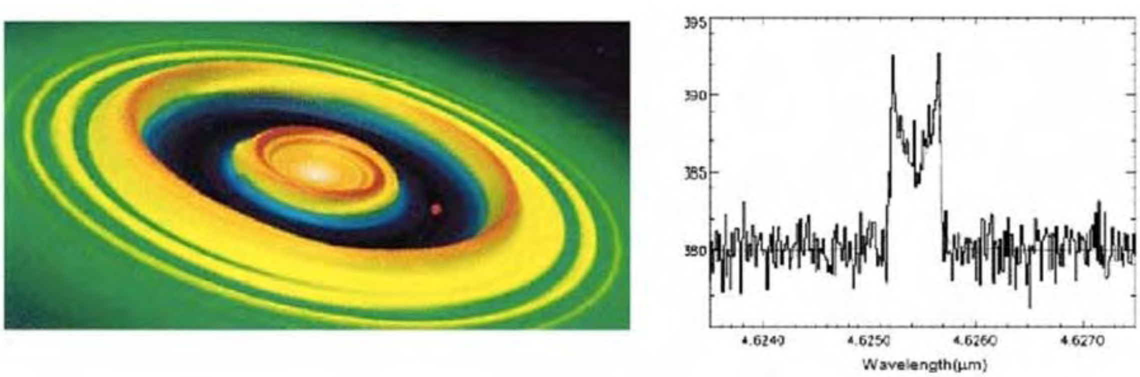


**Fig 2-16: Artist's impression of a protoplanetary disk, showing a planet orbiting within the ring that it has cleared (left). Profile of an emission line from a hypothetical spectroscopic observation (right). The double peak arises from the Doppler shift due to the rotation of the disk particles). By analyzing the spectrum, it is possible to detect the gap and thus infer the presence of the planet (G. Bryden & J. Najita, NOAO).**

### 2.8.3 Protoplanetary disks

Protoplanetary disks are flattened rotating disks of gas and dust surrounding newly-formed stars. Planets form within these disks dust particles collect and grow by accretion. As the planets gain mass they attract surrounding gas, clearing a ring in the protoplanetary disk. Interaction with the disk circularizes planetary orbits, stabilizing the planetary system.

Mid-infrared spectroscopy of these systems with MIRES on TMT will allow us to study elemental and molecular abundances, chemistry, kinematics and planet formation dynamics. TMT will provide five times the resolution of JWST, allowing us to resolve the inner regions of protoplanetary disks and detect the gaps produced by planets. It will then be possible to investigate the causes of the diversity of planetary systems.

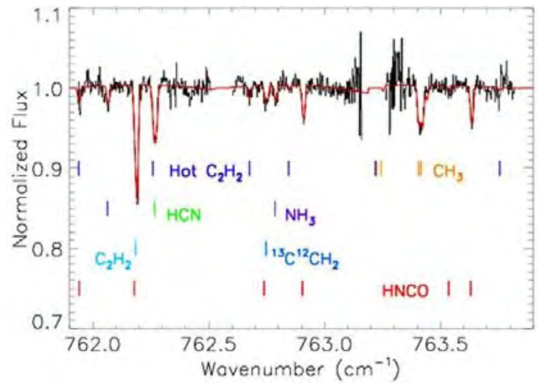


**Fig 2-17: Mid-infrared spectrum of the massive protostar NGC 7538 IRS 1 with the IRTF telescope showing absorption lines of organic molecules (Knez et al. 2005).**

### 2.8.4 Pre-biotic molecules in disks

Organic molecules have been detected in protoplanetary systems by means of mid-infrared spectroscopy. Many of these are precursors to the biogenic molecules needed for life. The high sensitivity of TMT will allow the study of many protoplanetary systems, making it possible to determine the frequency of occurrence of these molecules, and to understand how this relates to the physical environment.

## *2.9 Exoplanets*

We now know of more than 200 planetary systems beyond the solar system. The great majority of these were detected from the small periodic motion of the host star due to the gravitational perturbation of its planets. Since the perturbation is proportional to planetary mass, most of the planets so far detected are massive gas-giants like Jupiter.

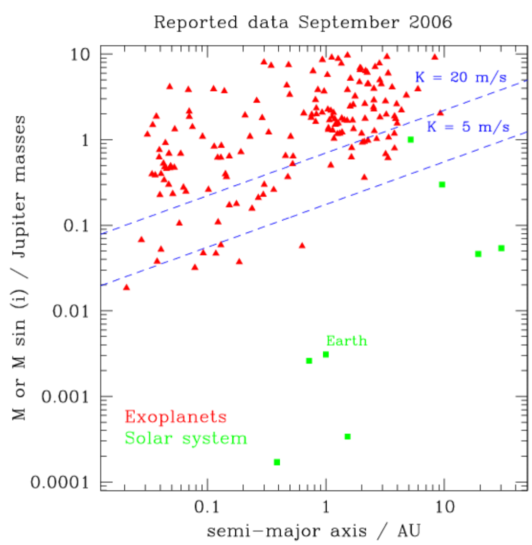


**Fig 2-18: Masses of known exoplanets plotted vs the semimajor axis of their orbits. The lines show detection limits for Doppler surveys as a function of velocity precision (P. Armitage, Univ of Colorado).**

### 2.9.1 Doppler detection of planetary systems

TMT with HROS will expand the number of host stars accessible to Doppler spectroscopy by a factor of 30 by allowing a greater volume of space to be explored. In addition, the higher sensitivity will allow observation of lower-mass stars, such as M stars – the most common stars in the galaxy. These stars are more strongly affected by gravitational perturbations so lower-mass planets can be detected. In fact, TMT will be able to detect Earth-mass planets orbiting in the habitable zone of M stars (the bitable zone is the region surrounding the star where a planet would have a temperature conducive to the formation of life).

### 2.9.2 Direct detection and characterization of exoplanets

It is now possible, using adaptive optics, to directly image giant planets. New instruments being built for 8 meter telescopes will enable us to study young planets still glowing from internal heat produced by their formation. The higher resolution provided by TMT + PFI will extend the reach of these observations to the nearest star-forming regions, making it possible to relate the properties of the planetary systems to the environment, and to observe directly large planets forming within circumstellar disks. TMT will also be able to detect planets quite near to their host star, for the first time probing scales comparable to the size of the inner Solar System. Since planets in this region intercept and reflect more light from the host star, it will be possible to image even cold Jovian planets directly by reflected starlight, and study the atmospheric composition of these planets.

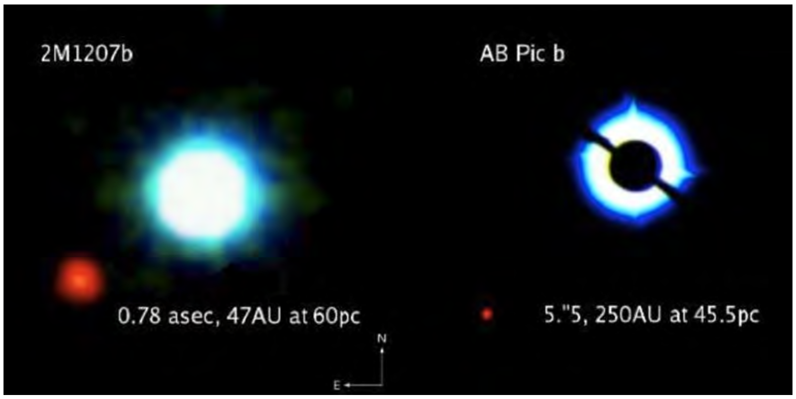


**Fig 2-19: Two giant planets imaged with adaptive optics. The red object on the left is a planet with four times the mass of Jupiter, orbiting a brown dwarf. On the right is an 80-Jupiter-mass planet orbiting a solar-type star (The black disk is an artifact of the observing technique).**

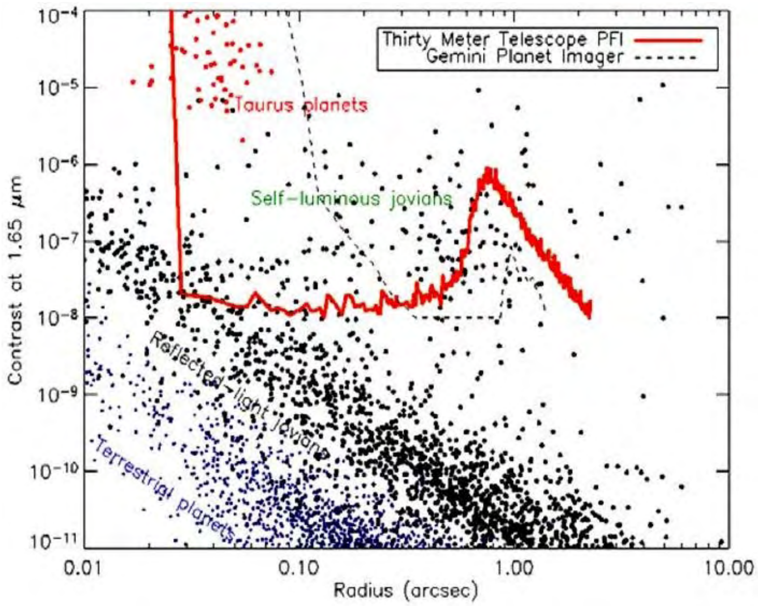


**Fig 2-20: The ratio of brightness between the planet and the host star is plotted as a function of the angular separation between the planet and star for a large number of hypothetical planets. The detection limit of TMT + PFI is shown by the red curve. TMT will be able to detect directly giant planets forming in star forming regions such as Taurus, and older planets orbiting close to their host stars (TMT PFI team).**

### 2.9.3 Atmospheres of massive planets

The light received from distant planetary systems is a combination of light from the planets and that from the host star. At optical wavelengths, the star is typically about a billion time brighter than the planets, so the light from the planets cannot be distinguished. However, at mid-infrared wavelengths, the brightness contrast between a planet and its host star is much smaller, making it possible to distinguish spectral features in the radiation emitted by the planet, superimposed up on the spectrum of the star. These features have a small wavelength shift due to the motion of the planet around the star, which makes it possible to separate them from features produced by the star itself by a process of spectral deconvolution.

### 2.9.4 Atmospheres of transiting planets

For planets that pass in front of their host star, as seen from the Earth, another technique is possible. During the transit, a small portion of the light emitted by the star passes through the atmosphere of the planet. As a result, absorption features due to molecules in the planetary atmosphere are superimposed on the spectrum of the star. These features are extremely weak since only a very small portion of the light is affected by the atmosphere. However, they can be detected with a thirty-meter telescope and high-resolution spectrometer. Simulations indicate that it should be possible to detect oxygen in the atmosphere of an Earth-like planet orbiting in the habitable zone of an M star, in about three hours with the TMT + HROS. Detection of oxygen would be highly significant since it is indicative of photosynthesis, and thus the presence of life.

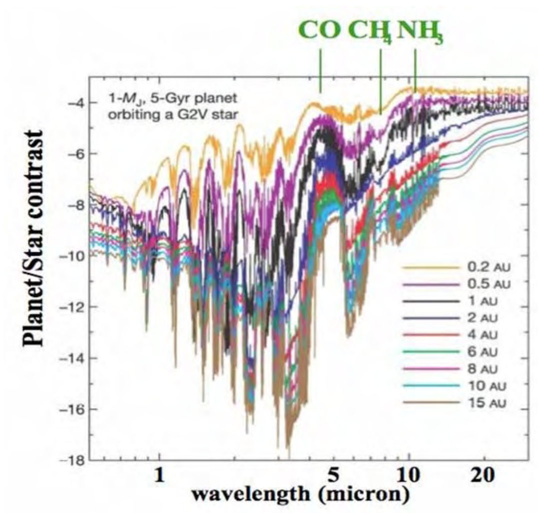


**Fig 2-21: Contrast ratio as a function of wavelength for a Jupiter-like planet orbiting a solar-type star, for a range of orbital radii. Molecular bands can be distinguished in the 5 – 20 micron region (TMT MIRES team).**

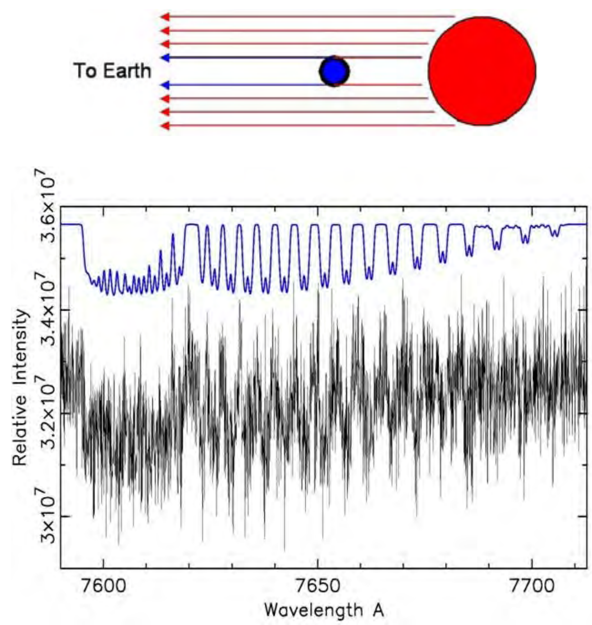


**Fig 2-22: Simulated high-resolution spectrum of the oxygen A-band absorption feature in the atmosphere of a transiting planet. The feature can be detected in a 3 hr integration by TMT + HROS (adapted from Web & Wormleaton 2001).**

## 2.10 Our Solar System

Our own Solar System is the planetary system that we can study in the most detail, and provides a reference for studies of exoplanets. TMT will contribute greatly to our knowledge, particularly of the planets, satellites, and small bodies of the outer Solar system.

**Fig 2-23: Image of Europa at the resolution of TMT + IRIS. Cracks in the icy crust, craters and surface features are clearly visible (M. Brown, CIT).**

### 2.10.1 The outer Solar System

Large populations of small bodies orbit beyond the major planets. These are relics left over from the formation of the Solar System. By studying their dynamical properties and compositions we can learn much about the physical processes by which our planetary system formed. These trans-Neptunian objects are small and extremely faint. Only the largest members, with size comparable to that of Pluto, have been detected. With adaptive optics,

TMT will be able to detect objects with diameters as small as 1 km in the Kuiper belt, beyond Neptune's orbit, in only 15 minutes exposure time.

### 2.10.2 Imaging the outer planets and their satellites

With adaptive optics, TMT will have a resolution of 7 milliarcsec at a wavelength of 1 um. This corresponds to 25 km at the distance of Jupiter, sufficient to resolve features on the surfaces of the moons of the outer planets. With TMT + IRIS it will be possible to obtain spatially-resolved spectra to study the atmospheric and surface chemistry, and monitor these objects regularly and detect changes due to weather, vulcanism and tectonic activity.

### 2.10.3 Atmospheric physics of the outer planets and satellites

High-resolution mid-infrared spectroscopy can reveal the composition of the atmospheres of the outer planets and their satellites in great detail. By combining this with physical modeling, one can study the complex chemical and photochemical reactions that produce the diversity of inorganic and organic molecules. TMT will be able to study the atmospheres of all planets and satellites in the Solar System with much higher spectral resolution than any space probe that has visited these objects.

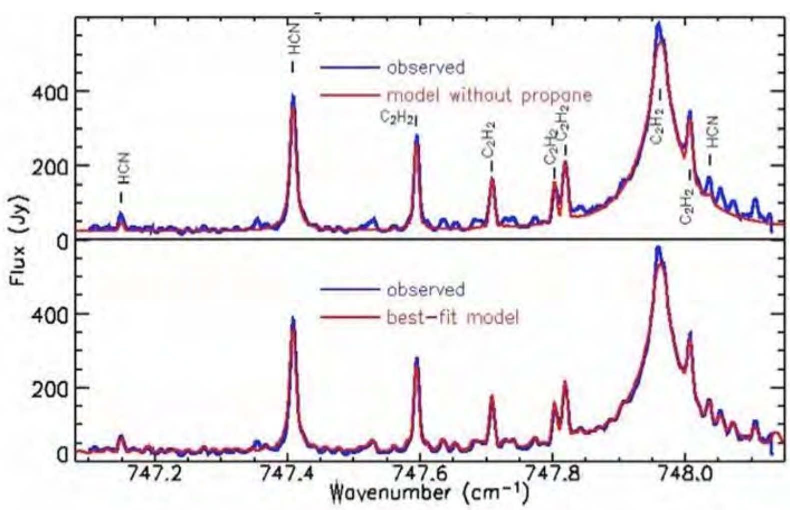


**Fig 2-24: High-resolution spectrum of Titan obtained with the Texes mid-infrared spectrometer, illustrating how high-resolution observations can give detailed information about the abundances of molecular species (Roe et al. 2003).**

# 3 Science-Based Requirements

## 3.1 Overview of Science-based Requirements

Chapter 2 has described a few of the many exciting science opportunities awaiting TMT. Yet experience shows that among astronomical facilities with 50-year lifetimes, the most important discoveries are often unexpected at the project's start. So while we can predict astonishing science opportunities in the observatory's first decade, we must also design TMT to have extremely broad capabilities, enabling future opportunities of comparable merit. The detailed Science-Based Requirements for the Observatory are given in [1].

As a ground-based telescope, the capabilities of TMT are necessarily bound by the fact that it must make its observations through the earth's atmosphere, and has to function within the atmospheric environment. Given these constraints, we want the telescope itself to have the smallest possible impact on its potential performance. This means we want:

- The largest possible collecting area
- The best possible angular resolution (diffraction limit)
- The smallest background fluxes
- The largest usable field of view
- The widest wavelength coverage
- The greatest observing time

Collecting area is expensive, and we have chosen a 30m diameter telescope to provide a great advance in science potential (9x times the world's largest telescope), while being cost-effective and technically achievable. Of course the collecting efficiency is a part of this, so we want the highest practical mirror reflectivity.

The atmosphere limits the angular resolution ("seeing-limited image quality") to about 0.5 arcsec. However, using adaptive optics (AO) a diffraction-limited angular resolution of 7 milliarcsec (mas) can be achieved at a wavelength of 1µm.

For point sources where the background flux dominates over the signal flux from the star, the time required for an observation of a given signal-to-noise ratio varies as $D^{-4}$ where D is the diameter of the mirror, if diffraction-limited imaging can be achieved. Clearly it is important to be able to achieve diffraction-limited imaging over the widest practical wavelength range. With the technical understanding we have today, achieving diffraction-limited performance appears viable for wavelengths of 1µm and longer. At shorter wavelengths, difficulties rapidly increase for a variety of technical reasons.

Science observations of faint objects frequently suffer a loss of sensitivity when there are significant background fluxes. These may be unavoidable sources such as natural astronomical backgrounds, the atmosphere itself, or potentially controllable sources such as the telescope optics and the instrument optics. As much as practical, we seek to control the latter two effects. This requires minimizing the thermal emissivity of the optics and minimizing their temperatures. Colder sites are thus advantageous.

For many science programs the observations of multiple targets is advantageous. Thus larger fields of view can be valuable. Experience has shown that as the telescope becomes larger, the science instruments become more difficult and in practice limit the useful field of view. The telescope optics also introduce aberrations that limit the field of view. For a two mirror telescope (either Ritchey-Chretien or Aplanatic Gregorian) the typical limit is about 20 arcmin diameter, before astigmatism becomes larger than the atmosphere-limited image quality of about 0.5 arcsec.

Scientific interest spans all wavelengths. However the Earth's atmosphere is opaque below about 0.3µm and above about 28µm once again the atmosphere is essentially opaque. In this region (0.3 to 28µm) there are a variety of useful atmospheric windows. These windows are influenced by the amount of atmosphere (altitude of the site) and the amount of precipitable water vapor (site altitude and temperature). Typical atmospheric transmission for a high site is shown in **Figure 3-1**.

Since science productivity is proportional to the observing time, we want the smallest practical down time. This requires use of extremely reliable systems and rapid telescope motions to move to and acquire targets as quickly as possible.

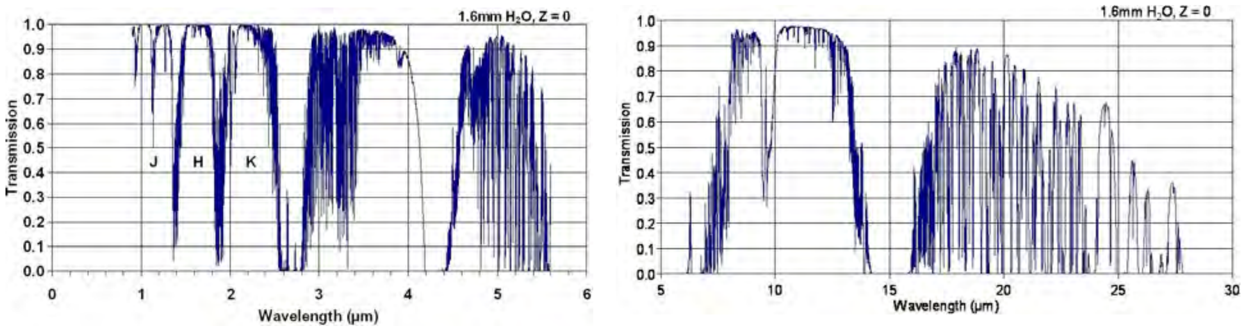


**Fig 3-1: Atmospheric transmission for a high altitude site (Mauna Kea).**

## *3.2 Telescope*

The telescope itself is the key to achieving our science goals. In this section we will describe the performance desired for the broad science objectives of this facility. The telescope is foremost an optical system, but it must also move to point to science targets, and it must provide suitable support of the science instruments that attach to it.

### 3.2.1 Optical

The telescope optics limit observations in a variety of ways and we describe the desired performance for the major categories.

#### 3.2.1.1 Optical Configuration

The circumscribing circle around the primary is 30.0 m, and the useful collecting area is about 655 $m^2$. The primary mirror (M1) is the entrance pupil of the telescope.

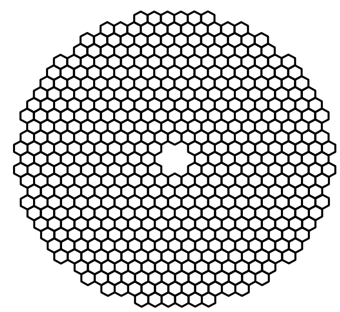

**Fig 3-2: Pattern of 492 segments of the primary mirror.**

We want a closely filled aperture to produce diffraction-limited images with the strongest central concentration of the light. When the starlight is faint compared to the background, the noise under the star image dictates the sensitivity. The time needed to reach a given S/N is proportional to b*(equivalent-noise area) where b is the background/unit area and the equivalent-noise area is the area that multiplies the background b to yield the variance in the estimate of a star intensity [2]. This is directly proportional to the needed observing time. The equivalent-noise area is

$\alpha = 1/\int PSF^2 dA$, where the PSF is normalized so $\int PSF dA = 1$

where PSF is the point spread function. For a given collecting area but with different configurations, α is the reciprocal of the observing efficiency. We indicate α for diffraction-limited observations with two configurations: a filled circular aperture and the segmented, TMT primary mirror (as shown in **Fig. 3-2**).

| aperture | equivalent-noise area for 1 μm (relative integration time) | |
|---|---|---|
| Filled aperture | 1.31e-4 $arcsec^2$ | (1.00) |
| TMT | 1.36e-4 $arcsec^2$ | (1.04) |

The TMT primary mirror configuration is shown in **Figure 3-2**. The diffraction pattern profile of this mirror is shown in **Figure 3-3**.

Experience with large telescopes has shown us that a single mirror (M1) giving images at prime focus is limiting for science instruments. A two-mirror telescope (M1+M2) giving a final focus at the Cassegrain focus (typically behind the primary) is more useful. An even more useful system employs an additional third fold flat (M3) that allows the Cassegrain focus to be folded over to the Nasmyth platforms. This design lets the telescope accommodate multiple science instruments with more room.

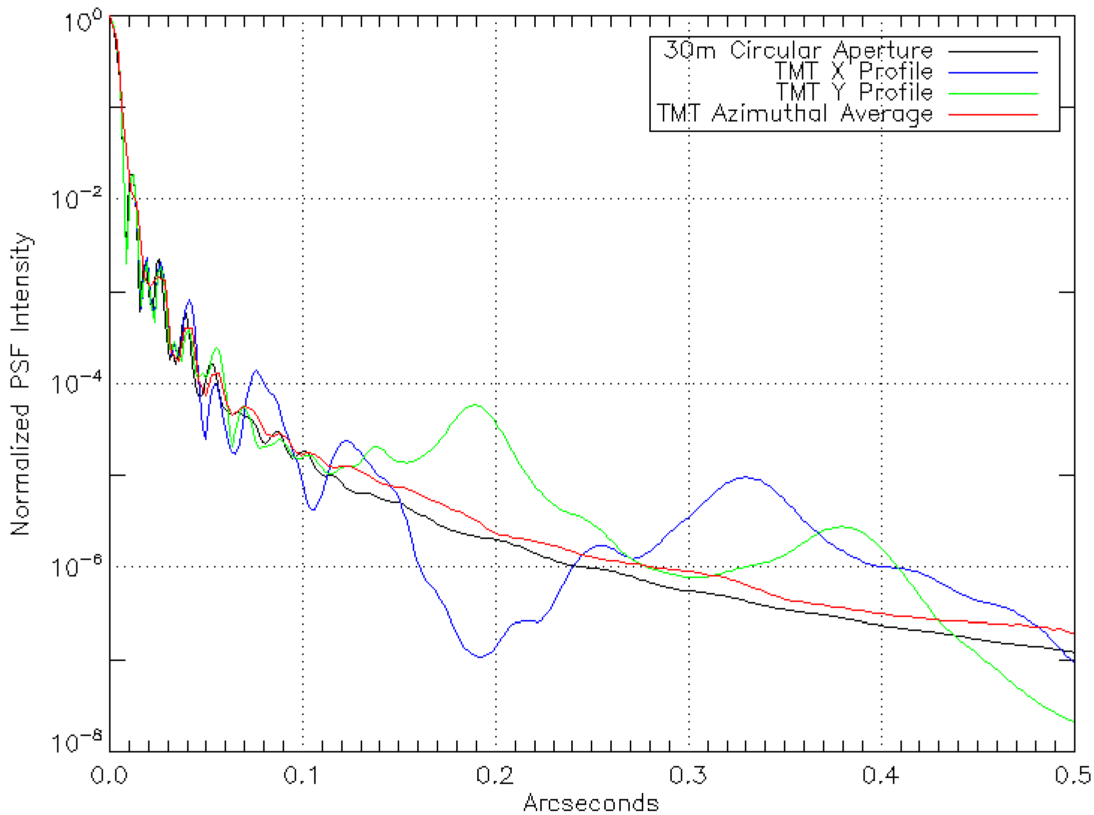


**Fig 3-3: The PSF of a 30m circular aperture is shown (black line), the azimuth average of the TMT aperture (red line) and the cuts of the TMT PSF in X (blue line) and Y (green line). In order to smooth out some of the high frequency fluctuations, these curves are the average over a wavelength range of 10%. At the larger angular scales this does more smoothing. Perhaps the two most interesting features are that the TMT azimuthally averaged PSF is very close to that of a circular aperture, and that there are very small but real variations in azimuth as indicated by the X and Y profiles.**

An innovation for TMT is that the tertiary mirror can be rotated to allow the light beam to be directed to any of the science instruments located on either Nasmyth platform. This ability is strongly desired for our science programs. The ability to place and access all science instruments on the Nasmyth platforms (without having to reposition them) allows us to eliminate the Cassegrain focus from the telescope, a useful simplification.

The two-mirror telescope allows one to eliminate the field angle dependent coma that otherwise will strongly limit the useful field of view. We have selected the Ritchey-Chretien design over the Aplanatic Gregorian because it makes a significantly shorter telescope and thus smaller enclosure, with significant cost savings. This gives a well corrected field of view of 20 arcmin. Because of the difficulty of making sufficiently large instruments to take advantage of this full field, and the added cost of making the tertiary mirror large enough, we only require that the unvignetted field of view is 15 arcmin. At the edge of the 20 arcmin field of view the vignetting is only about 10%.

Optical baffles on the telescope can simplify the design of some science instruments, as moonlight, for example, can be eliminated before the science instrument. However baffles can also entail significant additional wind cross section that shake the telescope in high winds. Additionally, for infrared work, baffles can add background to the focal plane. For our purposes then, baffles would need to be deployable, a complication. To overcome this, we have simplified the telescope by avoiding optical baffles entirely, requiring instead that science instruments in need of baffling do so internal to the science instrument.

To reduce the locally generated seeing, the telescope mass should be as small as practical. This will allow the telescope to more closely approach the changing ambient air temperature, thus reducing thermal turbulence around the telescope that would degrade the image quality.

#### 3.2.1.2 Image and Wavefront Quality

TMT is required to deliver image quality that does not appreciably reduce its science potential. Since the quality of optics is sensitive to cost, it is important to choose requirements that satisfy science needs while being technically possible and affordable.

Science capability is degraded when the telescope-generated image is blurred. There are two wavelength regimes we need to understand. For wavelengths shorter than 1µm, we predominantly expect to make seeing-limited observations. Seeing-limited observations accept the blur caused by the atmosphere and then add as little additional blur as practical from the telescope optics, local thermal degradations, and wind buffeting. For wavelengths longer than 1µm, we expect to use AO to largely correct any wavefront errors.

**Seeing–limited image quality**
Since most science observations are of faint objects, sky background flux is important. The larger the image, the more background one must accept. In this circumstance the time it takes to reach a given signal-to-noise ratio is proportional to $1/\theta^2$, where $\theta$ is the image size. There are a variety of ways to define $\theta$. We have chosen to define it as the image diameter that encloses 80% of the light from a point source. Another equivalent approach is to require the telescope to introduce errors that are no worse than that of a hypothetical atmosphere. If this atmosphere has $r_0$ = 0.8m we can achieve a 10% science reduction compared to our best sites. Using 80% enclosed energy is a practical approximation to an equivalent atmosphere requirement.

Our image quality goal is that the science productivity is reduced by no more than about 10%, due to the imperfect telescope, averaged over the site conditions. For these discussions we assume a wavelength of 500 nm.

$$\text{Real Productivity} = \int_{\text{all site conditions}} \frac{P(\theta_{\text{atm}}, v_{\text{wind}})\, d\theta_{\text{atm}}\, dv_{\text{wind}}}{\theta_{\text{tel}}^2 + \theta_{\text{atm}}^2 + \theta_{\text{wind shake}}^2(v_{\text{wind}})}$$

$$\text{Maximum Productivity} = \int_{\text{all site conditions}} \frac{P(\theta_{\text{atm}}, v_{\text{wind}})\, d\theta_{\text{atm}}\, dv_{\text{wind}}}{\theta_{\text{atm}}^2}$$

We require that real productivity/maximum productivity >0.9. For our reference site conditions, the degradations from wind shake, using a specific dynamic model of the telescope, is about 1.1%. When $\theta_{tel}$ =0.22 arcsec we achieve our overall goal of 10% reduction. The "telescope" image blur can be usefully decomposed into a part from the optics and a part from the seeing degradation due to thermal imbalances of M1 and the enclosure interior. The thermal part is currently under study, but it is estimated that with attention to the environment we can achieve about 0.07 arcsec. For the telescope proper (optics, alignment, etc.), this leaves an allowance of 0.21 arcsec.

**Figure 3-4** shows the science degradation as a function of the telescope image quality.

For our best sites this implies that the telescope image quality should be $\theta_{tel}$ = 0.237 arcsec at the zenith. Degradation of the telescope with zenith angle should be no worse than that of the atmosphere. Seeing limited image blur degrades as $[\sec z]^{3/5}$.

It is interesting to note that the segmented primary may also influence this result in the following sense. Pure piston segment errors, if large enough, could add wave front errors that would cause the net image blur to be that of a single segment rather than the entire primary, even though no tilt errors were introduced. At a wavelength of 0.5µm, simple diffraction from a single segment produces $\theta_{80}$ = 0.14 arcsec. Hence it's necessary for seeing-limited observations that the primary mirror be well phased

**Adaptive-optics based image quality**
For the longer wavelengths where we will be using AO, a more typical language for expressing image quality is to use the Strehl ratio S, the peak intensity divided by the theoretical maximum peak intensity of a perfect telescope. Numerically $S = e^{-\sigma^2}$ where $\sigma$ is the rms wavefront error measured in radians. For background-limited point sources the science productivity varies as $S^2$.

Since the AO systems are designed to reduce all sources of wavefront error including the atmosphere and the telescope, setting a telescope optical quality requirement means making a number of assumptions about the AO system and the detailed form of the telescope wavefront error.

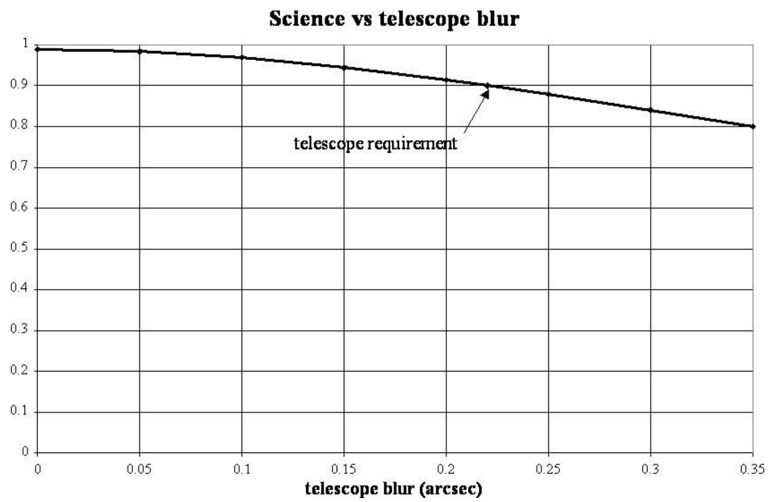


**Fig 3-4: Fractional science degradation with increasing telescope blur. Based on reference site of Armazones. Blur is an 80% enclosed energy diameter. Wind shake is included separately and accounts for the science fraction being slightly below 1 even when the telescope blur is zero.**

In keeping with the seeing-limited requirement we want the telescope to reduce $S^2$ by no more than about 10% at a wavelength of 1µm, averaging over the atmospheric conditions. Since the Strehl can be written as the product of Strehl from each component of an error budget, this requirement implies that the residual (after AO correction) wavefront error from the telescope itself must be less than 36 nm rms. Recognizing that there will be ongoing improvements in AO, we accept that with a 60x60 DM in the AO system the telescope rms residual wavefront can be as large as 45 nm. With a more capable DM, the telescope error will go down and with a 128x128 DM the allowed telescope rms residual wavefront error is 25 nm.

Because TMT has a segmented primary mirror, there are unique optical effects from the segmentation. Segment misalignment (piston-tip-tilt) may cause edge discontinuities that are difficult for the AO systems to remove. Small optical aberrations on the surfaces of each segment will also lead to edge discontinuities that are difficult for AO systems to remove.

High contrast imaging is important for planet detection experiments and this may impose additional restrictions on the optics, particularly segment aberrations and segment alignment. Planet Formation Imager (PFI) has a goal to detect planets that are $10^8$ fainter than their parent star. Detailed simulations by the PFI team [3] indicate that if the mirror segments have an rms wavefront error (before AO) of <50 nm, the speckle contrast in H band (1.65µm) will be below $2.5 \times 10^{-7}$ (5 standard deviations). Using a variety of data gathering and data reduction techniques (making multi-color observations, using field rotation, nodding back and forth to a reference star, averaging multiple data sets) should allow the noise floor from speckles to be reduced to $1 \times 10^{-8}$. We set as a requirement that the rms segment wavefront error be < 50 nm and as a goal that it be <25 nm. More certain expectations await early segment fabrication results.

#### 3.2.1.3 Atmospheric Dispersion Compensation

Atmospheric dispersion will degrade image quality for observations away from the zenith. These become smaller at longer wavelengths, but because AO image quality is so good, even in the IR, we must correct for this. ADC's will be located in instruments paths to correct for this source of blur. The fractional accuracy of correction needed (dispersion at z=45° in a standard wave band/diffraction limit) decreases with increasing wavelength, and is about 10 at 1µm. Details can be found in Appendix 9 of the SRD.

#### 3.2.1.4 Throughput

High throughput of the telescope is important and the science productivity is proportional to the throughput. In the infrared, the telescope emissivity (e=1-throughput) generates background light that can be a major source of background, so high throughput is beneficial in two ways. Most telescopes have used aluminum coatings on their mirrors. However, there are alternative coatings much better suited in some wavelength regions and some that are far more durable. Figure 3-5 shows the reflectivity/throughput through three mirrors for several coatings.

The Gemini coating is excellent everywhere except in the blue-ultraviolet, and it is our early light baseline choice. However, our science needs require high throughput all the way down to 340nm (goal 310 nm). In the future, we plan to develop or adopt coatings that will enable science in the UV while maintaining the Gemini coating performance at longer wavelengths.

It is important that the time averaged throughput is high, so we also need effective mirror cleaning procedures in place and suitably scheduled mirror recoating in order to maximize the time averaged throughput.

#### 3.2.1.5 Telescope background

The telescope background should be as low as practical. As described above, high telescope throughput leads to low emissivity, hence smaller telescope background. The actual background flux generated by the telescope depends on the temperature as well, so lower telescope temperatures are beneficial.

### 3.2.2 Telescope Motion

Motions include slewing, acquiring, pointing, guiding, zenith angle range, nodding, dithering, chopping, and offsetting.

#### 3.2.2.1 Azimuth and zenith angle range

We want to be able to observe over the entire sky. Experience at Keck shows that 99% of observations are above a zenith angle of 65°. Azimuth speeds approach infinity for targets passing through the zenith with an alt-az telescope. Thus we accept a blind spot around the zenith no larger than 1° in radius (a target passing directly over the zenith would be unavailable for 8 minutes) and the telescope should be able to do science observations down to 65° zenith angle.

We need full access to 360° of azimuth for all sky coverage. Further, since the telescope will have cable wraps with limited range, in order to minimize lost time due to unwrapping the telescope, the azimuth range of the cable wraps should be at least 540°.

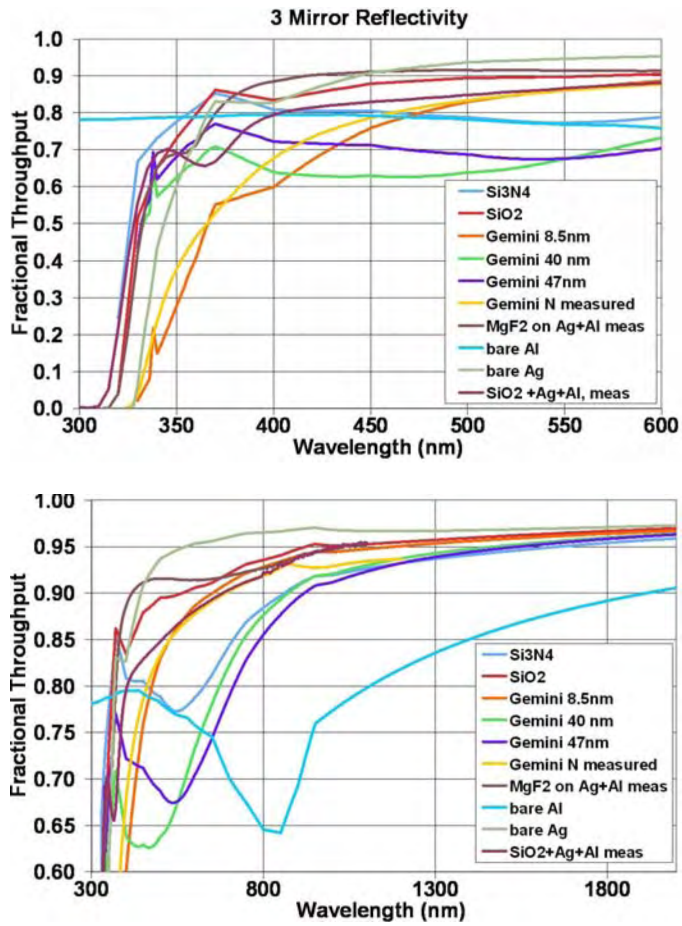


**Fig 3-5: Possible mirror coatings for TMT. The throughput including all three mirrors is shown. Some coatings are measured, most are theoretical. Durability of these coatings is not yet established.**

#### 3.2.2.2 Slewing and acquiring

Since we will typically be looking at multiple targets in an evening, it's important to minimize the time spent moving to and acquiring a science target. To get a perspective on this, Keck acquires about 40 targets per night and the rms change in elevation is 22° and the rms change in azimuth is 132°. The average motion/night is 2840° in azimuth and 450° in elevation. Some science programs can require over 150 targets per night.

To minimize the loss of night-time observing, TMT should be able to go from one target to another and acquire it in three minutes or less. Including the time needed to rotate the instrument, rotate the dome, acquire a guide star, and set up the ADC and AO system, the total time should be less than five minutes. This includes azimuth moves as large as 360°.

We also require that small moves can be made quickly; for example, we want a 1° move to be completed in under 10 s.

#### 3.2.2.3 Pointing and offsetting

When the telescope moves to a new target, it is important that the uncertainty in the final location is small enough to leave no doubt as to which object in the field is the desired target. Experience indicates that pointing errors over 5 arcsec will add significant time to target location. Errors below 1 arcsec are generally acceptable. Pointing of the TMT should be no worse than 1 arcsec rms in each direction, once a suitable pointing algorithm has been generated.

Sometimes it is necessary to offset to a known location and place this location on an instrument slit. We may need to offset from an acquired guide star up to 1° with an uncertainty of 0.05 arcsec rms. When the offsets are small enough that the guide star stays on the guide camera, we will want to offset to 0.02 arcsec rms.

When observing with AO, targets must often be positioned to much better than one arcsec. We require that once identified on the guider camera, a target can be offset to the AO instrument slit, which may be as small as 0.02 arcsec, to an accuracy of 0.002 arcsec rms.

##### 3.2.2.4 Guiding

Guiding the telescope, for seeing limited observations, should be good to a small fraction of the image size. Thus the guiding should be no worse than 0.02 arcsec rms. Guiding with AO should be correspondingly better, with rms image motion under 0.002 arcsec (small compared to the diffraction limit at 1µm of 0.007 arcsec.

##### 3.2.2.5 Nodding, dithering and chopping

Other image motions are sometimes needed to reduce background drifts and improve background subtraction with imperfect detectors. Nodding (repetitive motion of the image) should be possible with at least 80% of the time at the end points, and position variability of the end points of no more than 10% of the size of the image. Amplitudes up to 10 arcsec at periods shorter than 20 s should be possible. Chopping (repetitive motion driven by the secondary) is not believed essential for TMT, given the current state-of-the-art of modern IR detectors.

#### 3.2.3 Instrument Support

The telescope should be able to support the range of science instruments we expect it to employ during its lifetime. Some instruments will be large, with sizes up to 400 $m^3$ anticipated. The most massive instruments may weigh as much as 50 tonnes. Multiple instruments need to be supported at the Nasmyth platforms, and suitable power, cooling, signal lines and service equipment must be available.

TMT should have the flexibility to observe with any science instrument, at night, in < 10 minutes. This will facilitate queue scheduling or any program that benefits from using multiple instruments during the night.

### *3.3 Site*

A potential site must have several desirable features. TMT is measuring several interesting candidate sites, but no selection has yet been made. Broadly speaking we want a location that maximizes the science productivity. Science productivity is a function of the fraction of clear nights, the seeing probability distribution, with the wind speed distribution (that shakes the telescope), the precipitable water vapor (lower PWV reduces near IR absorption), the mean site temperature (lower reduces the thermal emission of the telescope), the rate of change of night-time temperature (smaller reduces the temperature difference between the telescope and the air temperature, hence the local seeing, particularly M1 seeing), and the temperature range (science instrument image quality degrades with larger temperature range). In addition for AO uses, the isoplanatic angle should be as large as possible to maximize sky coverage and image quality over an instrument field of view. The more slowly the atmospheric turbulence changes, the easier it is for the AO system to keep pace with the changes.

In addition to site characteristics related to science, it is important to consider the cost of construction and operation of a given site. Safety issues must be considered for high-altitude sites, and finally, there may be political issues that are site specific.

Selection of the TMT site will involve consideration of all these issues, not just the science-based performance.

### *3.4 Enclosure*

The enclosure has many functions. It must protect the telescope during severe weather, provide an opening for the telescope to look through, shield the telescope from wind-induced vibration, and provide a variety of service requirements for the optics (including handling and mirror cleaning), AO and the instruments.

The opening should not vignette the telescope over a 20-arcmin field of view. In addition, for very delicate measurements it may be desirable to halt the enclosure to minimize vibration. It should be possible to observe an on-axis object for five minutes with the enclosure fixed, without vignetting.

The enclosure motion must be rapid enough never to restrict the observations.

To the extent consistent with these shielding requirements, the enclosure should allow natural air venting of the primary mirror to reduce M1 seeing.

To minimize thermal differences that will degrade image quality, the enclosure interior should be cooled during the day so the telescope is at the expected night-time temperature.

### *3.5 Adaptive Optics*

Diffraction-limited observations are a key capability of TMT, and this will be delivered by the AO system. Ideally we would like to make diffraction-limited observations over the entire sky and for all wavelengths. Our understanding of the technology suggests this will not be available in the foreseeable future, so we have made some compromises in the required early AO capability.

We will eventually want an AO system that can deliver rms wavefront errors of ~ 130 nm with full sky coverage, corresponding to a Strehl ratio of 0.5 at 1µm. For a range of cost, schedule, and technical considerations, we will accept a first-light AO capability with 187-191 nm rms wavefront error over a 10 arcsec field of view. This corresponds to a Strehl of 0.5 at 1.36µm. The AO system must deliver this performance over a majority of the sky (e.g. 50% sky coverage at the galactic pole). This sky coverage is expected to be achieved with a multiple laser beacon system. A subsequent upgrade will reduce the AO system noise to 130 nm.

We anticipate several valuable modes of AO:

Narrow-Field, Diffraction-limited, Near IR, or narrow Field IR Adaptive Optics System (NFIRAOS) will be used for NIR spectroscopy and can feed an on-axis integral field unit (IFU) and sample the image at the diffraction limit. A small field is sufficient (10 arcsec) as long as we have close to 50% sky coverage. Image motion will degrade image size over a higher fraction of the sky. Again, we expect that a Laser Guide Star system will be needed to achieve this sky coverage. NIFIRAOS is a MCAO system with conjugates at 0 and 12km.

NFIRAOS is expected to deliver much improved image quality over a 2 arcmin field of view that will be used by an infrared multislit spectrometer. Expected AO performance over a 30 arcsec FoV and a 2 arcmin field are given in Table 3-1.. The LGS tomography is optimized for each FoV.

Wide Field, Near-Diffraction-Limited, or multiple object adaptive optics (MOAO) will involve making AO correction of a number of small discrete angular regions (1-5 arcsec) distributed throughout a 5 arcmin field of view. This will allow diffraction-limited spectroscopy of 10-20 objects at a time.

Moderate field, Diffraction-Limited, or Multi-conjugate Adaptive Optics (MCAO) which will have a well corrected 30 arcsec field of view to allow precision photometry and imaging at the diffraction limit in the near IR. This role is initially filled by NFIRAOS.

Small field diffraction-limited mid-IR (MIRAO) is the highest priority mid-IR science (5-28µm). It requires only a small field of view, as the science instrument will be an echelle spectrometer. High sky coverage is required.

Planet Detection near the parent star will require Extreme Adaptive Optics. A proposed instrument, Planet Formation Imager will provide the additional AO capabilities and a coronagraph to make high contrast imaging

**Table 3-1: Enclosed Energy Fractions using NFIRAOS, inside of selected diameters of 50, 100, 200 mas**

| Field of view | Wavelength band | Image at center of field | | | Image at edge of field | | |
|---|---|---|---|---|---|---|---|
| | | **50mas** | **100mas** | **200mas** | **50mas** | **100mas** | **200mas** |
| 30 arcsec | J (1.06-1.44µm) | 0.60 | 0.62 | 0.66 | 0.58 | 0.59 | 0.62 |
| 30 arcsec | H (1.53-1.83µm) | 0.73 | 0.74 | 0.78 | 0.70 | 0.72 | 0.76 |
| 30 arcsec | K (1.96-2.44µm) | 0.79 | 0.80 | 0.84 | 0.78 | 0.79 | 0.82 |
| | | | | | | | |
| 120 arcsec | J (1.06-1.44µm) | 0.30 | 0.38 | 0.52 | 0.15 | 0.26 | 0.46 |
| 120 arcsec | H (1.53-1.83µm) | 0.48 | 0.54 | 0.63 | 0.30 | 0.38 | 0.57 |
| 120 arcsec | K (1.96-2.44µm) | 0.61 | 0.66 | 0.72 | 0.46 | 0.51 | 0.64 |

possible on relatively bright stars.

Ground Layer Adaptive Optics (GLAO) is expected to be developed when we have an adaptive secondary mirror. This should improve image quality over a wide field of view and should be useful into the visible, not just infrared. This does not yield diffraction-limited images, but it should significantly reduce image size.

## 3.6 Instrumentation

TMT's science opportunities lie in both seeing-limited and diffraction-limited observations. Seeing-limited instruments will be spectrometers working in the 0.3-1µm region. Diffraction-limited instruments will be in the infrared, and because of the unique angular resolution we expect both imagers and spectrometers.

### 3.6.1 Seeing-limited Instruments

A wide field optical imaging spectrometer (WFOS) is our choice for an early light science instrument. Wide wavelength coverage, high multiplex advantage, and fairly high spectral resolution are important features. The spectrometer should cover 0.31-1.0µm with good sensitivity. A large solid angle of coverage enables the high multiplex advantage for a variety of classes of science targets. A minimum 50 arcmin$^2$ solid angle coverage is needed. Net slit length should be ≥ 500 arcsec to enable multi-object spectroscopy. Spectral resolution up to R=5000 is needed.

The other high priority seeing-limited instrument is the High Resolution Optical Spectrometer (HROS), an instrument with R=50,000 with a 1 arcsec slit. Maximum simultaneous wavelength coverage is also desired, monitoring the 0.3-1µm region. A slit length of 5 arcsec is needed, with this much separation between echelle orders.

### 3.6.2 AO based instruments

A wide range of AO based instruments are envisioned, and as the technology for AO evolves, this suite of instruments will surely evolve as well.

With NFIRAOS as our early-light AO facility, we will want an Infra Red Imaging Spectrometer (IRIS). This will be an integral field unit (IFU) capable of providing both images and spectra simultaneously. The IFU mode should cover an astronomically important field size, up to 2 arcsec. In imaging mode, a 10 arcsec field of view is needed. Both should be sampled at the diffraction limit. The instrument should cover the near infrared wavelength region, 0.8-2.5µm. Spectral resolution must be high enough to cause the OH bands to pollute the spectra only minimally, so R=4000 is needed.

A NIR multislit spectrometer (IRMS) is also expected as an early-light instrument that uses AO. This spectrometer will have a 2 arcmin field of view, and we expect it to be behind NFIRAOS. This instrument should have significant multiplex advantage, capable of measuring spectra up to 46 objects at a time, with a spectral resolution high enough (R=4000) to largely eliminate contamination by OH lines.

IRMOS (infrared Multiobject Spectrometer) is a very ambitious instrument that will use deployable integral-field units to provide capability for spatially-resolved spectroscopy of multiple targets simultaneously

MIRES (Mid-infrared Echelle Spectrometer) is a diffraction-limited high-resolution spectrometer and imager operating at mid-infrared wavelengths (5-28µm).

NIRES (Near Infrared Echelle Spectrometer) is a diffraction-limited high-resoluton spectrometer operating at near-infrared wavelengths.

PFI (Planet Formation Instrument) is perhaps the most challenging instrument. PFI will have the capability to image and obtain spectra of faint planets close to bright stars.

These instruments are described in some detail in **Section 8.6** and **8.7**.

## References

[1] Science Requirements Document (SRD), TMT.PSC.DRD.05.001

[2] King, Ivan, P.A.S.P. **95**, 163, 1983

[3] Macintosh et al, Planet Formation Instrument for the Thirty-Meter Telescope, 15 February 2006, TMT.IAO.CDD.006.005

# 4 Site

## 4.1 Overview

TMT needs to be built on the best available site to obtain the maximum return from its science potential. Careful site selection has therefore been extremely important to TMT from the very beginning of the project. The site selection process started in 2001/2002, in a collaboration between the Giant Segmented Mirror Telescope (GSMT) and the California Extremely Large Telescope (CELT), with the pre-selection of five candidate sites (see **Section 4.3**) to be studied in detail. On-site testing via the operation of small but complex remote site monitoring observatories has been in progress since 2003 and will continue until final selection of the TMT site. The site evaluation process employs a site ranking metric which allows for an objective comparison of the technical properties of the candidate sites and their science producing implications. Selection of the TMT site is expected in mid 2008.

Detailed descriptions of the site testing program, the requirements on this program, the candidate sites and their pre-selection, the instruments and methods used, and the results are given in the "Site Selection Requirements and Strategy Document"[1], the “Site Selection Intermediate Report”[2] and the “Site Qualification Report”[3].

## 4.2 Site requirements

The TMT site needs to be suited for producing astronomical data of superb quality and for building and operating an observatory of the size and complexity of TMT. Strict technical requirements as they apply to other parts of the project do not exist for the TMT site, because there are no hard cut-offs for the parameters entering the TMT site decision beyond which a site becomes unsuitable for TMT. Instead, the site selection process involves measuring and predicting the properties of the sites, both technical and programmatic, and balancing them so as to determine the site that best meets the TMT needs.

## 4.3 Candidate sites

Five TMT candidate sites were chosen from a list of potentially interesting sites based on existing information (previous site characterization campaigns and data from existing observatories)  and satellite data studies of cloud cover and precipitable water vapor[4,5]. The names and properties of these sites are summarized in **Table 4-1**, with photographs of each shown in **Figure 4-1.**

## 4.4 Characterization of candidate sites

The TMT site decision will be based on both technical and programmatic aspects. Technical site properties are assessed predominantly through data acquired in a multi-year study of the site conditions using identical equipment. To acquire these data, the TMT site testing team has been operating remote site monitoring observatories at each of the candidate sites. Considerable effort has gone into calibrating all equipment through side-by-side comparisons of identical instruments and, when possible, by comparison with other instruments. The instruments and methods as well as the data and results verifications are summarized in this section. This is followed by a description of the programmatic aspects being investigated. Details of all aspects of the site selection program can be found in References [1-3].


**Fig 4-1: Views of the five TMT candidate sites.**

**Table 4-1: Description of the candidate sites**

| Site | Location | Elevation | Characteristics |
|---|---|---|---|
| Cerro Tolar | Northern Chile, north of the town of Tocopilla | 2290 m | Low elevation, coastal site |
| Cerro Armazones | Northern Chile, just east of the VLT on Cerro Paranal | 3064 m | Medium elevation, coastal site |
| CerroTolonchar | Northern Chile, south of the Salar de Atacama, close to the ALMA site | 4480 m | High elevation, inland site |
| San Pedro Mártir | Northern Baja California, Mexico | 2830 m | Medium elevation, somewhat inland, between the Pacific and the Sea of Cortez |
| Mauna Kea 13 North | Hawaii, Big Island | 4050 m | High elevation, island surrounded by ocean |

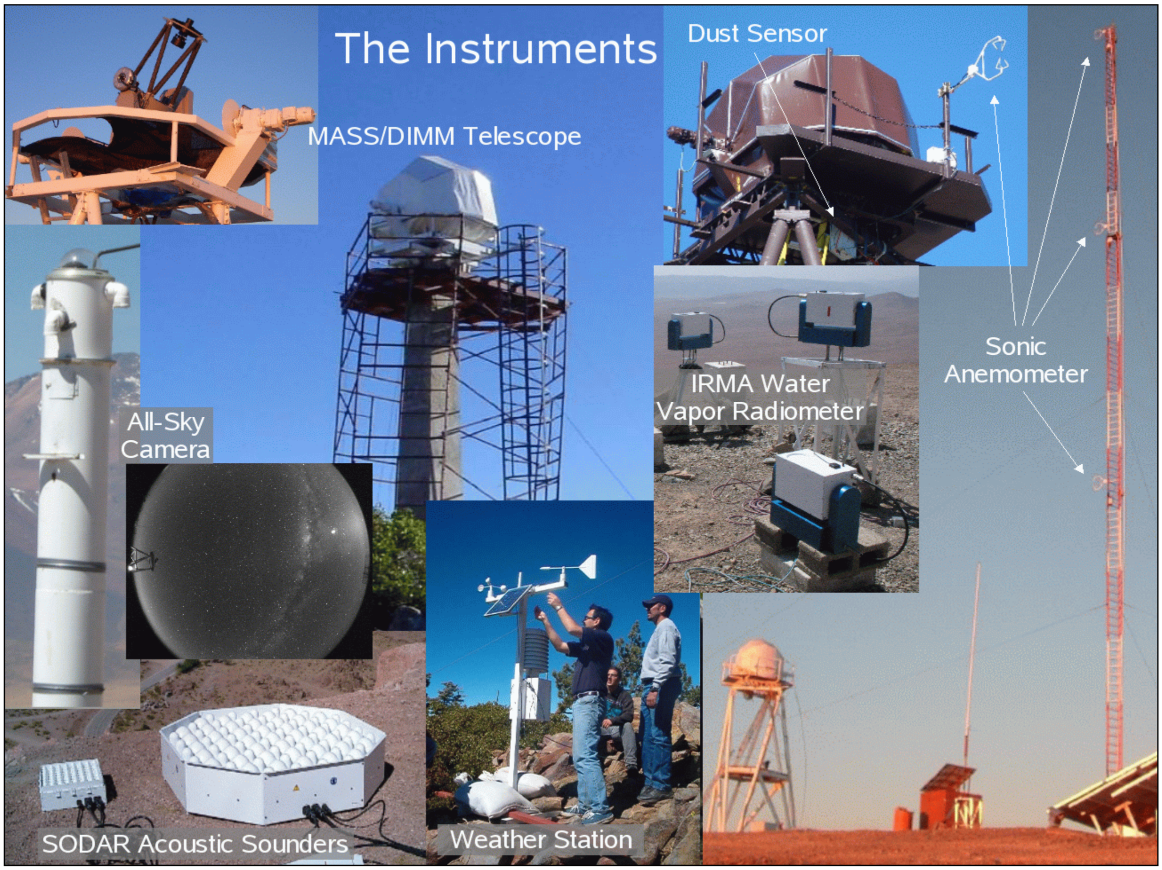


**Fig 4-2: The TMT site selection instrument suite.**

**TMT site selection instrumentation (see also Fig. 4-2):**

- **Differential Image Motion Monitors (DIMM):** The TMT DIMMs are mounted on small (35cm) but robust custom-made telescopes installed on 7m towers. A DIMM measures the integrated seeing in the air column above the telescope.
- **Multi-Aperture Scintillation Sensors (MASS):** Scintillation-based instruments, which measure 6-layer turbulence profiles and the isoplanatic angle. Can also be used for atmospheric transparency estimates.
- **Sound Detection and Ranging (SODAR) acoustic sounders:** Phased-array acoustic emitter/receiver systems, which produce low elevation (10 – 800m) turbulence and wind profiles.
- **Automatic Weather Stations (AWS):** Commercial weather stations with temperature (air and soil), wind speed and direction, humidity, barometric pressure, precipitation, solar irradiation, heat flux and net radiation sensors. Stand-alone units mounted 2m above the ground. Air temperature sensors are also installed on 30m towers on Armazones and Tolonchar.
- **Sonic Anemometers:** Mounted at the MASS/DIMM telescope level and/or at several elevations on the 30m towers. Measure wind speed and direction, an approximate temperature value, and can be used to estimate the in-situ turbulence strength.
- **All-sky cameras (ASCA):** Provide images of the entire sky in several visible and infrared filters. Used for cloud analyses, sky transparency estimates and light pollution studies.
- **Infrared Radiometers for Millimeter Astronomy (IRMA):** Measure the flux from the sky at 20 microns. The precipitable water vapor (PWV) of the atmosphere can be calculated from this using a suitable atmospheric model.
- **Dust Sensors:** Commercial particle counters mounted at the MASS/DIMM telescope level. Measure the particle density in five different channels for particle sizes of 0.3, 0.5, 1.0, 2.0 and 5.0 microns.

In addition to the on-site testing, remote methods are also used to characterize the sites:

- **Computational Fluid Dynamics (CFD) Simulations:** Used to verify results obtained at the candidate sites, to assess the impact of site preparation and construction, and to evaluate dome/mirror seeing and wind shake.

- **Satellite Studies of Cloud Cover and PWV:** Based on meteorological satellite data studies carried out by Dr. D. A. Erasmus (References [4] and [5]). Used for the pre-selection of candidate sites and to put the on-site data into a longer temporal baseline .

The relative uncertainties (differences between measurements taken at the same site under the same conditions) and absolute uncertainties (deviations of the measurements from the "absolute truth") of some of the more important parameters are given in **Table 4-2**. The relative values were determined during extensive side-by-side comparison campaigns of *identical instruments*. Absolute uncertainties are hard to measure for most parameters and are estimates based on the comparison of *different instruments*. Note that all values given here are limits for the statistical properties of these parameters, not for the individual measurements.

The original goal of the TMT site selection campaign was to take on-site measurements of all major parameters (e.g. weather, seeing) for at least 2 years, and for at least one year for all other parameters. This was achieved or exceeded for most instruments, but was not possible in all cases for practical reasons. Dates of the first deployments of all instruments are shown in **Table 4-3**. The site data will be put into context of longer-term data sets (Erasmus satellite studies; data from existing observatories) as much as possible, as well as by Computational Fluid Dynamics (CFD) simulations, to investigate whether there is reason to believe that the on-site testing period was unusual for any of the sites.

**Table 4-2: Uncertainties of the statistical properties of some of the main parameters entering the TMT site decision.**

| *Parameter* | *Relative Uncertainties* | *Absolute Uncertainties* |
|---|---|---|
| DIMM seeing | 0"02 | 0"02 – 0"04 |
| MASS seeing | 0"05 | 0"05 |
| MASS isoplanatic angle | 0"01 | «0.2" |
| SODAR seeing | 10% | 10% |
| SODAR wind profiles | 20% | 20% |
| Precipitable water vapor | 0.25 mm | tbd |
| Wind speed profile on 30m tower | <10% | <10% |
| Temperature profile on 30m tower | <0.1K | <0.1K |

In addition to being technically qualified, the TMT site must also meet programmatic needs. Obtaining legal possession and access to the site when required in the construction schedule is a primary factor, but other considerations such as labor, logistics, geological conditions and the permitting process will also be considered in the site selection. These aspects, as well as technical aspects not measured by the equipment listed above, are summarized in **Table 4-4**.

**Table 4-3: Deployment dates of the different instruments on the candidate sites.**

| | *Tolar* | *Armazones* | *Tolonchar* | *SPM* | *Mauna Kea* |
|---|---|---|---|---|---|
| **Weather station** | 3-Apr | 3-Jul | 5-Nov | 4-Oct | 5-Jun |
| **DIMM** | 3-Oct | 4-Nov | 5-Nov | 4-Oct | 5-Jun |
| **MASS** | 4-Jan | 4-Nov | 6-Jan | 4-Oct | 5-Jul |
| **SODAR** | --- | Mar 05 to Jan 06 | 6-Feb | 6-Mar | 5-Oct |
| **All-sky camera** | 5-Oct | 5-Oct | 5-Nov | 5-Jul | 6-Jun |
| **Sonic anemometer** | 6-Feb | 6-Feb | 6-Mar | 6-May | 5-Nov |
| **Dust sensor** | 6-Feb | 6-Feb | 6-Mar | 6-May | 5-Nov |
| **IRMA** | --- | 6-Mar | 7-Mar | --- | 7-Feb |

**Table 4-4: Other aspects entering the site decision**

| ***Issue*** | ***Method*** |
|---|---|
| Construction and operating cost and method | TMT cost estimate |
| Cultural, environmental and land use issues | Consultations with local groups; archaeological, fauna and flora studies; assessment of historical preservation and environmental issues |
| Labor force issues | Evaluation of labor supply, skill level, local conditions |
| Proximity to astronomers and astronomy infrastructure | Evaluation of existing observatories, organizations |
| Geological and geotechnical conditions | Geological and geotechnical studies |
| Foundation conditions | Evaluation of telescope pier and enclosure foundations |
| Vibration transmission | Evaluation of the vibration transmission through the soil from the enclosure and other equipment to the telescope structure |
| Compatibility with surrounding area | Studies of conditions and how TMT will fit in |
| Economic impact of siting TMT | Study of TMT's impact |
| Permitting, land ownership etc. | Negotiations with local authorities |
| Transportation | Evaluation of local situation |
| Customs and immigration issues | Evaluation of applicable regulations |

## *4.5 Site selection process*

It is obvious from the preceding sections that site selection is a complex process. It requires an evaluation how each of the characteristics of a site affects the obtainable science and the process of building and operating the observatory. In order to develop a method of dealing with this complexity, the following intermediate steps have been implemented:

- Quarterly reviews of the site selection process and data
- Detailed quarterly results reports
- Presentations of site results at TMT SAC and other project meetings
- Development of a site merit function (see below)
- Issue of the Site Selection Intermediate Report (1 July 2006) and Site Qualification Report (1 July 2007)

These steps serve to educate the parties involved in the site decision and to fine-tune our data analysis and site comparison methodology. They will lead to the issuing of the Site Selection Final Report in early 2008, which will first undergo an internal review. In the second quarter of 2008, the Project Manager will present a site selection recommendation to a panel of external reviewers. The results of the Site Selection Final Report and the two reviews, together with the recommendations of the Project Manager, will be presented to the TMT Board, which will make the final site decision.

## 4.6 *Site merit function*

### 4.6.1 Key Parameters

To understand the science potential of each candidate site better, we have developed a merit function [6] by which we can compare the sites. There are a number of relevant parameters for the science potential of a site. These include:

1. Fraction of clear nights
2. Seeing (image quality)
3. Wind speed
4. Precipitable water vapor
5. Isoplanatic angle
6. Mean night-time temperature
7. Annual temperature range
8. Thermal gradients at night

Other factors may also enter into the science potential of a site including variability of seeing, atmospheric time constant (for AO), latitude and proximity to other observatories.

### 4.6.2 Observing Modes

The conditions at a site may be more or less important depending on the kind of observations being conducted. We have found it useful to consider three categories: seeing limited observations (observations at wavelengths below 1µm), near IR adaptive optics observations (wavelengths 1-2.5µm), and mid IR adaptive optics observations (wavelengths 5-28µm). Our Science Advisory Committee (SAC) has estimated that in the early years about half of the observations will be seeing limited, about 40% will be near IR with adaptive optics, and about 10% will be mid IR with adaptive optics. On a longer time scale, we expect that the percentage of time devoted to adaptive optics will increase.

### 4.6.3 Science value

Our science merit function has units of science/time, so that comparisons are straightforward. Some characteristics can be quantified in unambiguous fashion, while others are more arbitrary. The actual form of the merit function is

$$M = \sum_{i=1}^{3} w_i \prod_{j=1}^{8} C_{ij}$$

where $w_i$ is the fraction of time spent in each of the three observing modes and $C_{ij}$ is the fractional science productivity for each site parameter considered. The coefficients, $C_{ij}$, may depend on the observing mode.

$C_1$ is the fraction of clear nights.

$C_2$ is the value of seeing, defined as the probability weighted sum of $1/\theta^2$ where $\theta$ is the net image size. For AO applications Strehl[2] is a better science measure, so $C_2$ is defined as the average of $S^2$ in the J, H, and K bands.

$C_3$ is defined by the degradation of image quality due to wind shake. Windier sites have a lower $C_3$ and the value depends on the structural performance of the telescope.

$C_4$ is the contribution of PWV in J, H, and K where water absorption reduces the effective transmission of the atmosphere.

$C_5$ is the impact of the isoplanatic angle. Larger isoplanatic angles increase the useful field of view of an AO system, and increase the number of viable tip-tilt stars for use with laser beacons, hence increasing the net sky coverage.

$C_6$ quantifies the beneficial impact of a cooler site, providing lower emissive background in the IR.

$C_7$ is the impact of annual temperature swing, a larger range compromising the performance of some optical instruments.

$C_8$ is the impact of temporal thermal gradients. Larger gradients cause the temperature of the primary mirror and the telescope to be further from the ambient, causing local seeing degradation.

The table shows that seeing and precipitable water vapor, in practice, have the greatest impact for discriminating between the sites. At this time, we are still gathering site data and refining the site merit function [6] so as to increase its usefulness for the final site selection.

## 4.7 Reference site

There are many cost and operations related issues that are site dependent. In order to simplify the process of developing a design and an operations model and to prepare a cost estimate, TMT has chosen Cerro Armazones as the Reference Site for the following reasons:

**Table 4-5: Shows the range of values among the sites, thus showing the relative importance of each parameter. Each number has an upper value of 1.0.**

| Mode | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| **Visible** | 0.85 | 0.77 | 0.99 | 1 | 1 | 1 | 0.95 | 0.97 |
| **Near IR** | 0.85 | 0.8 | 0.99 | 0.85 | 0.77 | 0.762 | 0.95 | 0.97 |
| **mid IR** | 0.85 | 0.9 | 0.99 | 0.53 | 0.88 | 0.825 | 0.95 | 0.97 |

- Armazones has none of the infrastructure required for TMT. All aspects of site mobilization, construction, and operations need to be studied, and costs estimated for Armazones.
- Armazones is also representative of Cerro Tolar and Cerro Toloncha in that neither of these sites has any of the infrastructure that will be required. Mauna Kea and San Pedro Mártir, on the other hand, have existing facilities (e.g. paved access roads) that will be utilized if that site is selected.
- Armazones, Tolar, and Tolonchar are all Chilean sites, representative of three of the five candidate sites.
- Based on preliminary studies, Armazones is an intermediate case in both complexity and cost.
- Current results from the on-site testing show that Armazones will likely be a qualified site.

### References


[1] Site Selection Requirements and Strategy Document, TMT.SIT.DRD.05.001

[2] Site Selection Intermediate Report, TMT.SIT.TEC.06.020.

[3] Site Qualification Report, TMT.SIT.TEC.07.009.

[4] A. Erasmus and C. A. van Staden, “A Satellite Survey of Cloud Cover and Water Vapor in Northern Chile,” internal report for AURA-O and University of Tokyo, 2001

[5] A. Erasmus and C. A. van Staden, “A Comparison of Satellite-Observed Cloud Cover and Water Vapor at Mauna Kea, and Selected Sites in Northern Chile, the Southwestern U.S.A. and northern Mexico,” internal AURA-NIO report

[6] TMT Report 78, TMT Site Merit Function, Jerry Nelson, Matthias Schoeck, TMT Report 78, TMT.PSC.TEC.07.005

# 5 Operational Concepts

In the previous section, the technical requirements that flow from the TMT science case were discussed. In this section, we discuss the operations concepts that will maximize TMT science productivity. Some of these concepts are related to operational process (i.e. how TMT will be operated). Other concepts impose additional technical requirements on TMT design and implementation. Defining operational concepts today ensures a more scientifically productive and cost-effective observatory tomorrow. The reliability of this definition process is greatly enhanced by the collective operations experience within the project team with the last generation of large ground-based astronomical facilities: Gemini, Keck, and the Very Large Telescope.

More details can be found in the Operations Concept Document [1]. The TMT operations implementation plan is discussed in **Chapter 10**.

## *5.1 Motivations*

### 5.1.1 Operations success metrics

A small number of high-level goals form the foundation for TMT Observatory operational concepts.

The fundamental TMT goal is to enable ground-breaking advances in science. So-called high-impact papers are a common measure of such advances. High-impact papers are defined to be scientific publications published in reputable, refereed journals with high (N > 100) citation counts. TMT will be operated in a manner consistent with maximizing the production of such high-impact papers.

To achieve this goal during the operations phase, the TMT Observatory must:

- Maximize the number of unique observatory capabilities – by being the first member of the next generation of ground-based observatories for as long as possible and by maintaining leadership with a steady flow of new science instruments and AO systems during the lifetime of the observatory.
- Maximize the number of available science integration hours – by keeping nightly operational overhead time, as well as scheduled and unscheduled technical downtime, as low as possible.
- Maximize user efficiency – by providing simple processes, good documentation, efficient software tools, and clear user interfaces.
- Maximize system performance – by monitoring system performance (e.g. delivered image quality, flux throughput) and restoring it to normal ranges when degraded performance is detected as well as by implementing comprehensive preventive maintenance and system improvement programs.

While striving to achieve these goals, the TMT Observatory must operate in a safe and secure manner with an environmental impact that is compliant with local, national, and international standards.

Finally, TMT operations costs must fit within the budgetary constraints defined by the TMT Board.

### 5.1.2 Physical infrastructure components

The TMT Observatory will have three generic physical components: the summit facility, a support facility no more than a two (2) hour drive from the summit, and a headquarters/office facility.

In the case of the current reference location (Cerro Armazones), the current plan is to locate the support facility roughly 10 minutes away from the summit by car and the headquarters facility in rented space in Santiago de Chile.

## *5.2 Science Operations*

### 5.2.1 Baseline services

The TMT Observatory will be a general-purpose observatory with many individual users and teams.

Each TMT partner has its own scientific community with its own sense of scientific priorities. Hence, each partner will allocate telescope time within its own community and then forward approved projects to TMT for detailed scheduling. Collaborations that cross community boundaries will be encouraged.

Each night, TMT will be run by two system operators, trained to operate all systems, including the telescope, adaptive optics, and science instruments. Technical support at night will be provided via an on-call system.

Initially, TMT will only support classical observing. In this mode, individual astronomers or teams are assigned specific time periods (usually 0.5 to 3 nights) for their approved observations. Larger time allocations are possible at the discretion of the time allocation committees. During these periods, the investigators make real-time decisions about how to execute their observation program.

At the start of TMT science operations, it is expected that most classical observers will be located in close physical proximity to the telescope. After an initial startup period, it is expected that many (if not most) classical users will observe from remote locations using hardware/software systems approved by TMT.

TMT will be a very sophisticated system. Most users will only use TMT a small number of nights per year and cannot be expected to achieve peak usage efficiency without a robust user support process. That process will include:

- a central Web portal with links to up-to-date instrument user handbooks, observation planning tools, and data processing cookbooks as well as current and historical information about observatory performance and external environmental conditions.
- a central electronic helpdesk modeled after Web-based news group system
- easy to learn and use graphical user interfaces for observation definition and status monitoring
- a staff astronomer (in addition to the system operators) on-duty every evening to assist the users scheduled for that night. These staff astronomers will typically work from 1400 – 2400 (including scheduled breaks).

All science data and associated calibration data generated by TMT will be captured and stored at the observatory for an indefinite period. Engineering telemetry data will also be captured and stored locally for at least one (1) year (and longer for selected datasets, e.g. free-air seeing measurements). At this baseline level, external access to these data via the Internet will only be provided on a best-effort basis.

Data processing software and documentation will be made available to users so that they can remove artifacts caused by the AO systems and science instruments as well as the terrestrial atmosphere. This software and documentation is expected to be part of the delivery package for each TMT instrument. At this service level, TMT will not process and/or calibrate data for users – they will be required to process and/or calibrate their own data.

### 5.2.2 Enhanced services

Baseline service planning and implementation will allow the later implementation of a number of enhanced services.

**Queue observing**

Classical observers must deal with the vagaries of weather, natural seeing, and unscheduled technical downtime. When planned observations are not well matched to atmospheric and technical conditions, individual user efficiency is often diminished, sometimes to zero. A more sophisticated approach is to collect all desired observations from all approved users a few times per year and then execute each observation under optimal environmental and technical conditions. This approach is known as queue observing and is used at least 50% of the time at the ESO Very Large Telescope (VLT) and the Gemini Observatory.

Not only may queue observing be more efficient in the mean, it also opens windows on rare atmospheric conditions such as very low precipitable water vapor or very low atmospheric turbulence (and hence very good natural seeing). During these rare conditions, otherwise impossible unique and high-impact observations can be made at the limits of TMT technical capabilities.

**Observatory-based data processing pipelines**

Unavoidable data artifacts caused by TMT AO systems and science instruments as well as the terrestrial atmosphere will have to be removed from all TMT science data. For many observations, such artifact removal is routine and independent of the science goals. Hence, in many instances, observatory-based data processing pipelines can be implemented to remove these artifacts automatically, relieving the user of that burden and shortening the time necessary to transform a set of raw observations into published papers. Successful implementation of observatory-based pipelines requires both software and process engineering – careful consideration must be given not only to algorithms but also to how science observations are structured, what calibration data need to be acquired and when they need to be acquired.

Observatory-based pipelines are now standard practice for space-based observatories and survey-oriented ground-based observatories. Semi-automatic, quick-look pipelines are a common feature at many general-purpose ground-based observatories but automatic pipelines designed for the production of science-quality data products have only recently started to gain prominence at such observatories as Gemini and the VLT.

If such pipelines become available, TMT will begin to process and/or calibrate as much science data as possible within technical and budgetary constraints.

**TMT Science Archive**
Many TMT observations may be useful for more than one project. Creating a science data archive to capture, store, and curate TMT data on a long-term basis enables such data re-use and increases the science value returned by TMT. Astronomical science data centers with broad capabilities already exist within the TMT partnership, e.g. the Infrared Processing and Analysis Center (IPAC) at Caltech and the Canadian Astronomical Data Center (CADC) at the NRC Herzberg Institute of Astrophysics. If TMT decides to create a science archive, it seems attractive to collaborate with one of these or similar existing centers rather than building a new, independent science archive.

**TMT Science Centers**
As the TMT user community grows and enhanced services are added, individual user productivity can be increased by assembling a group of scientists focused on providing user support rather than day-to-day operations. This user support group could assist users with observation planning, scheduling and execution as well as data delivery and processing.

To that end, it may be desirable to establish one or more TMT Science Centers within the TMT partner countries. Each center would have a remote observing facility. The TMT instrumentation development office (see **Section 8.7.4**) and the science data archive could be co-located with one of these centers.

## *5.3 Technical Operations*

### 5.3.1 Goals

The main goal for technical operations is to maintain and improve system performance over time.
An important related goal is to maximize the number of science integration hours by:

- Limiting time lost at night due to unscheduled technical failures to under 3% of scheduled science operations time.
- Minimizing the number of hours used at night for scheduled technical activity (e.g. M1 alignment and phasing, telescope pointing maps, M2 and M3 re-aluminization).
- Minimizing operational overheads required for target acquisition, instrument configuration, and data calibration.

A model for the potential cumulative nature of these effects for a specific set of assumptions is shown in the following table. For a more detailed discussion as well as models with different assumptions, see Section A.4 in the OCD[1].

### 5.3.2 Implementation

Achieving these goals begins during the construction phase - attention must be given to designing and implementing low-fault, easily maintained subsystems.

During operations, overall system performance will be monitored continuously and compared to established norms. Sudden changes or changes with time that are larger than predicted will be investigated promptly. As time and resources permit, the subsystem in question will be restored to the nominal performance range. Parameters related to end-to-end flux throughput, delivered image quality, and technical performance (e.g. motor current demand) will be included in this monitoring program. Measured performance relevant to astronomical observations will be made available to the community at large via the TMT Web portal.

Environmental conditions interior and exterior to the TMT enclosure will be monitored as well to provide a comparison dataset for performance problem analysis.

A multi-tier maintenance program will be implemented including:

- Preventive maintenance – to keep the system in good repair.
- Predictive maintenance – to rectify developing problems before they reduce performance or interrupt operations unduly.
- Corrective maintenance – to correct faults in a timely manner.

However, maintaining nominal performance is hardly our highest goal. It is equally important to identify technical areas where improvements can be made to enhance performance, decrease maintenance overhead, and/or decrease long-term operational costs on a continual basis. It is expected that such refinements will be most abundant in the early years of operations (as observatory performance is tuned) and then later in time as key subsystems begin to age and/or become obsolete.

**Table 5-1: Achieved science integration time model.**

| | Annual Hours | Fraction | Remarks |
|---|---|---|---|
| **Possible science integration time** | 3468 | 1.00 | 365 nights x 9.5 hrs |
| | | | |
| *Science Integration Time Reductions* | | | |
| Random weather loss | 459 | 0.13 | Site-dependent |
| Target acquisition overhead | 220 | 0.06 | 5 min per 45 min observation |
| Other scheduled technical time | 173 | 0.05 | About 1.5 nights/month |
| Commission new/upgraded instruments | 173 | 0.05 | About 1.5 nights/month |
| Night-time science calibration overhead | 150 | 0.04 | About 0.5 hr/clear science night |
| Unscheduled technical time | 104 | 0.03 | Goal: 3% (about 20 min/night) |
| Post-segment exchange optical system tuning | 60 | 0.02 | 30 per year x 2 hrs |
| **Achieved Science Integration Time** | 2129 | 0.62 | |

## *5.4 Development*

By being first in its class, the TMT Observatory will be uniquely placed to achieve world-class scientific breakthroughs. Over time, TMT will maintain world leadership through a program of continuous instrument development. The development of new instruments and new capabilities for existing instruments will be driven naturally by evolving scientific understanding and technology as well as by available resources.

As discussed elsewhere in this document, the TMT SAC has already established an instrument development roadmap for the first 5 – 10 years of operations. This roadmap will be reviewed and revised on an annual basis.

## *References*

[1] Operations Concept Document (OCD), TMT.OPS.MGT.07.002

# 6 Observatory Requirements

## 6.1 Observatory Requirements

### 6.1.1 Introduction

The top level engineering requirements for both the function and performance of the observatory are recorded in the Observatory Requirements Document (ORD)[1]. These requirements flow down from the TMT Science Requirements Document (SRD)[2], and the Operations Concept Document (OCD)[3]. This chapter gives an overview of the key observatory requirements contained in the ORD.

The observatory requirements are stated relative to the operating mode that the observatory is in. The defined modes for the observatory are: Observing Mode, which is sub-divided into Seeing Limited and Adaptive Optics modes, Servicing and Maintenance Mode for day time operations, and Stow Mode for when the observatory is shut down.

These observatory requirements are specific to the reference site of Armazones, Chile, which is the baseline site for the TMT observatory design. The environmental and atmospheric conditions used for the observatory requirements are based on our current understanding of the Armazones site. In the following discussion, the term system refers to the overall observatory as an integrated unit.

### 6.1.2 General Constraints

The observatory is required to operate and meet the requirements for 50 years with preventive maintenance. The observatory will comply with all local and national standards and regulations relevant to the construction and operation of the facility.

### 6.1.3 Site and Environmental Constraints

Environmental conditions for the observatory are documented in the ORD, including conditions under which it must meet the performance requirements, operate in an observational mode, operate in a maintenance and servicing mode, and survive earthquakes and adverse environmental and weather conditions with minimal damage.

The specified conditions include ambient temperature range, maximum temperature gradient, relative air humidity, air pressure range, external wind velocities, maximum ground vibration, as well as snow loads, earthquake events [4], and lightning strikes. The observing performance conditions under which the observatory must meet the performance requirements, and the observing operating conditions under which it must be able to make observations are listed in **Table 6-1**.

### 6.1.4 Observation Support

At early light, the system is required to support a classical observing mode operational model, and is also required to be upgradeable to support queue mode observations. The observatory is required to monitor the environmental and observational conditions to support the real time selection of observing programs, and will also monitor its own status to enable the assessment of whether a particular observation can be successfully completed.

**Table 6-1: Observatory Performance and Operating Conditions.**

| Description | Performance Conditions | Operating Conditions |
|---|---|---|
| Ambient Temperature Range | 276 K to 286 K (3ºC to +13ºC) (95% of the time, from the 2.5$^{th}$ to the 97.5$^{th}$ percentile) | 275 K to 288 K (2ºC to 15ºC) (98% of the time, from the 1$^{st}$ to the 99$^{th}$ percentile) |
| Ambient Relative Air Humidity | 0 to 90$^{th}$ percentile | All non-condensing conditions |
| External Mean Wind Speed Range (20 m above ground) | 2.8m/s to 8.6 m/s (55% of the time, from the 15$^{th}$ to 70$^{th}$ percentile site wind speed) | 0 m/s to 15.6 m/s (97% of the time, from the 0$^{th}$ to 97$^{th}$ percentile site wind speed) |

### 6.1.5 Observatory System Requirements

#### 6.1.5.1 Light Collection Geometry

The system will meet all requirements in the wavelength range from 0.34 to 28 microns, with a goal of 0.31 to 28 microns, unless otherwise stated for the individual configurations.

The telescope will have an entrance pupil with a circumscribed 30 m diameter circle. The optical surface will be comprised of tiled hexagonal segments. The system will have a maximum 4% obscuration due to the shadow of the secondary mirror and its support structure. The obscuration must be a simple shape, capable of being masked with a cold pupil in an instrument. The obscuration due to segment gaps shall be not be greater than 0.6%.

The telescope optical design will consist of three mirrors, with aspheric primary and secondary mirrors, and a flat tertiary mirror. The telescope will provide a 20 arcmin diameter unobstructed field of view, with the mirror clear apertures sized to provide a 15 arcmin field of view. The telescope foci will be located in a Nasmyth configuration at either side of the telescope, and will utilize a steerable tertiary mirror to feed several instrument locations. The Nasmyth platforms will be large enough to accommodate the first decade SAC instrument suite.

#### 6.1.5.2 Pointing on the Sky

The system will be able to point and observe anywhere from a 1º to 65º zenith angle, and from 0º to 360º azimuth angle. The system is required to provide sufficient azimuth range coverage to enable a continuous observation across any 180 degree range of azimuth angles, which results in a 540 degree overall azimuth range.

The system will point to a target in the whole accessible sky with an absolute RMS accuracy of 1 arcsec in each axis of altitude and elevation, with a goal to achieve 0.5 arcsec. It is required that the telescope and enclosure be able to move from any point in the sky to any other point within 3 minutes, and that it be able to repoint anywhere in the sky and begin observing with the same instrument configuration within 5 minutes.

#### 6.1.5.3 Guiding and Field De-Rotation

The system is required to track solar system targets, using fixed natural guide stars over the whole accessible sky, up to a rate of 1.1 times the sidereal rate. The system will also be able to de-rotate the science field as required by the instruments and AO systems. In seeing limited mode, the RMS image motion contribution of guiding and field de-rotation anywhere in the field of view of the given instrument will be less than 0.05 arcsec, and in adaptive optics mode the requirement is 0.002 arcsec. It is understood that in certain adaptive optics system configurations (AO plus instrument combinations) the allowable image jitter can be as small as $\lambda/10D$.

#### 6.1.5.4 Offsetting and Nodding

The system is required to support *acquisition offsetting*, which is the process of repointing of the telescope over small angles without any feedback, to an RMS accuracy of 0.05 arcsec for an offset of up to 1 arcmin. The system will support *guider offsetting*, which is the process of repointing of the telescope from one guiding location to another with the assistance of guider feedback, to the same accuracy as it is required to guide in seeing limited mode. The system will support *AO guider offsetting*, which is the process of repointing of the telescope from one guiding location to another with the assistance of guider feedback and adaptive optics image correction, to the same accuracy as is required to guide in adaptive optics mode.

The system will also be able to move repetitively between two (nod) or more (dither) given positions. For positions not farther apart than 1 arcsec, the system must be able to accomplish the operation at a rate of 5 seconds per position (including the starting point). For objects up to 10 arcsec apart, the system is required to accomplish the operation at a rate of 10 seconds per point. In either case the system must spend at least 80% of the allotted time at the end points.

#### 6.1.5.5 Image Quality

The seeing limited image quality budget [5] states that at 0.5 μm wavelength, the allowable 80% encircled energy diameter ($D_{80}$) of the zenith pointing telescope in seeing limited operating mode is 237 mas or less, including image jitter. At other wavelengths, the allowable seeing limited image size ($D_{80}$) at the Nasmyth focus is scaled relative to the specification at 0.5 μm as follows: $D_{80} \propto \lambda^{-1/5}$. At increasing zenith angles, the allowable seeing limited image size ($D_{80}$) at the Nasmyth focus is scaled in proportion to $(\sec z)^{3/5}$ relative to the requirement at zenith. The image quality delivered by the telescope optical system design at the Nasmyth focus is allowed to degrade quadratically with increasing telescope field angle to a maximum of 600 mas at the edge of the field, provided it is largely a low order mode (astigmatism for example) that is correctable with field correctors in instruments and AO systems.

The top level adaptive optics image quality specifications are intended to limit the high-spatial frequency errors for the entire observatory system. The residual on-axis wavefront error ($W_{RMS}$) of the zenith pointing telescope and enclosure system, including mirror and dome seeing but not atmospheric seeing, that are not correctable by an idealized 120 x 120 deformable mirror AO system with infinite temporal bandwidth is 25 nm. The residual on-axis wavefront error ($W_{RMS}$) of the zenith pointing telescope and enclosure system, including mirror and dome seeing but not atmospheric seeing, that are not correctable by an idealized 60 x 60 deformable mirror AO system with infinite temporal bandwidth is 45 nm. The residual on-axis wavefront error, ($W_{RMS}$), after correction by idealized 60 x 60 and 120 x 120 AO systems with infinite temporal bandwidth, of the zenith pointing telescope at the Nasmyth focus is allowed to degrade with increasing telescope zenith angle as follows: $W_{RMS} \propto \sqrt{\sec z}$ .

#### 6.1.5.6 Optical Throughput and Telescope Emissivity

The optical throughput of the telescope delivered to the Nasmyth foci is a function of the reflectance of M1, M2 and M3. The requirements on each mirror surface are listed in **Table 6-2**.

These reflectivity values are for fresh surfaces. The throughput of the 3 mirror system must not degrade faster than 0.81% per month due to dust accumulated on the optical surfaces and the ageing of the coating.

The thermal radiation collected at the focal surface, in the FOV of the system, from the primary, secondary, and tertiary mirror assemblies together must not exceed 7% of the radiation of a 273 K black body, assuming that a cold stop is used to mask out the telescope top end obstructions.

**Table 6-2: M1, M2 and M3 Mirror Coating Requirements.**

| | Range | Requirement | Goal |
|---|---|---|---|
| **Minimum Reflectivity** | 0.31 - 0.34 µm | | 0.8 |
| | 0.34 - 0.36 µm | 0.8 | 0.9 |
| | 0.36 - 0.40 µm | 0.8 → 0.9 | 0.9 → 0.95 |
| | 0.4 - 0.5 µm | 0.9 → 0.95 | 0.95 → 0.98 |
| | 0.5 - 0.7 µm | 0.95 → 0.97 | 0.98 |
| | 0.7 - 28 µm | 0.97 | 0.98 |
| **Maximum Emissivity** | 0.7 - 28 µm | 0.015 | 0.013 |
| **ΔR / wavelength** | 0.31 - 28 µm | < 0.003 / nm | |

#### 6.1.5.7 Other Optical Requirements

In seeing limited mode, after subtraction of the average image motion and the average field rotation, the position of each point in the field of view at the telescope Nasmyth foci will not shift relative to the center of the field of view by more than 0.06 arcsec, over any length of time. In addition, it is a goal to limit any such shift to no more than 0.02 arcsec.

The telescope system is required to keep the exit pupil centered within 0.3% of the pupil diameter.

Baffling must be provided by the instruments and AO systems to meet the instrument contrast and stray light requirements.

The observatory (telescope, AO system, or instrument as agreed), will provide atmospheric dispersion compensation to meet the instrument science requirements.

#### 6.1.5.8 Laser Guide Stars and Laser Guide Star Wavefront Sensing

The system must project sodium laser guide star asterisms to the sodium layer, which is at approximately 90 km altitude. As required by the science cases, the adaptive optics systems and instruments will incorporate laser guide star wavefront sensors to collect and analyze the returned 589 nm sodium light to provide active and adaptive optics corrections to the system.

### 6.1.6 General Instrumentation Requirements

#### 6.1.6.1 Instrument Reconfiguration and Availability

The system must be able to switch from one configuration to another one on stand-by, during night time, in less than 10 minutes from the end of one science observation to the start of the next. The system is required to be able to keep at least four instruments concurrently on standby, ready for observing.

#### 6.1.6.2 Nasmyth Platform Requirements

The Nasmyth platforms will provide support for large instruments, with masses up to 50,000 kg, and volumes of 500 $m^3$. The Nasmyth platforms will be reconfigurable, and are required to accommodate instruments that protrude up to 6 meters below and 4 meters above the optical axis. Instrument maintenance and servicing will be done on the Nasmyth Platforms. Sufficient space will be provided on the Nasmyth platforms to accommodate the instruments, their support electronics, services and regularly used servicing and maintenance equipment.

### 6.1.7 Early light Instrument Requirements

#### 6.1.7.1 Early light Instrument Suite

The early light instruments for TMT are the Narrow Field InfraRed Adaptive Optics System (NFIRAOS), the InfraRed Imaging Spectrograph (IRIS), InfraRed Multislit Spectrograph (IRMS) and the Wide Field Optical Spectrograph (WFOS). The key level 1 requirements for these instruments can be found below. Further discussion of TMT instrumentation can be found in Section 8.6, and further level 1 requirements can be found in the ORD.

#### 6.1.7.2 NFIRAOS Requirements

NFIRAOS is a multi-conjugate adaptive optics system utilizing laser guide stars. It is intended to feed near-diffraction limited images to TMT instruments that work in the near infrared, including IRIS and IRMS. NFIRAOS is required to provide a transmitted 2 arcmin diameter technical field with a focal ratio of f/15. The field can be switched between any one of three output instrument ports. At early light it will deliver images, with RMS wavefront errors of 187 nanometers (nm) on-axis and 191 nm over a 10 arcsec field of view, with 50% sky coverage at the galactic pole. NFIRAOS will be upgradeable to a higher order AO system in the future.

#### 6.1.7.3 IRIS Requirements

IRIS is intended to provide diffraction-limited moderate spectral resolution (R=4000) NIR spectra and images over a small field of view, using an integral field unit (IFU). **Table 6-3** lists key level 1 requirements for IRIS.

**Table 6-3: IRIS Requirements.**

| Description | Requirement |
|---|---|
| Wavelength Range | 0.8 – 2.5 μm |
| Field of View, Imaging | 10x10 arcsec for imaging mode |
| Spectral Resolution | R=4000 over J,H,K bands, one band at a time<br>R=2-50 for imaging mode |

#### 6.1.7.4 IRMS Requirements

IRMS is a near infrared multiple object spectrometer fed by an adaptive optics corrected beam. To the maximum extent possible, the IRMS instrument will be a clone of the Keck MOSFIRE instrument, which is currently in development. **Table 6-4** lists key level 1 requirements for IRMS.

**Table 6-4: IRMS Requirements.**

| Description | Requirement |
|---|---|
| Wavelength Range | The instrument shall operate over the Y,J, H, K bands. |
| Spectral Resolution | R = 5000 with a 160 mas slit |
| Imaging Mode | Shall provide imaging over the full 2' field of NFIRAOS |

#### 6.1.7.5 WFOS Requirements

WFOS is a wide field, seeing limited, multi-object optical spectrometer and imager. The system must be able to take images of the sky over the same field as it collects spectra, and must include atmospheric dispersion correction. Goals include the ability to image through narrow band filters, and to record the entire wavelength range in a single exposure. It is acceptable for the wavelength range to be split between multiple optimized arms covering suitable wavelength ranges. As a goal, WFOS will provide enhanced image quality using Ground Layer Adaptive Optics, when an adaptive secondary mirror is commissioned on the telescope. **Table 6-5** lists key level 1 requirements for WFOS.

**Table 6-5: WFOS Requirements.**

| Description | Requirement |
|---|---|
| Wavelength Range | 0.31 – 1.0µm |
| Image Quality | ≤ 0.2 arcsec FWHM |
| Field of View | 40.5 $arcmin^2$ |
| Total Slit Length | ≥ 500 arcsec |
| Spectral Resolution | R = 500-5000 for a 0.75 arcsec slit, 150-7500 (goal) |

### 6.1.8 First Decade Instrumentation Requirements

The TMT observatory will be designed and built in a manner that supports, in the first decade of operation, the implementation of the instrumentation defined in this section. Implementation and commissioning of any of the second or future generation instruments must not result in the loss of more than ten nights of productive science observing time.

The planned second and future generation instrumentation for TMT, along with some of the key requirements that drive the observatory design, includes:

- InfraRed Multi-Object Spectrograph (IRMOS), a near infrared spectrometer configuration with an AO system capable of correcting small areas of a large field, using Multiple Object Adaptive Optics (MOAO). The MOAO system will correct the system for several (>10) integral field units (IFUs) that are deployable over a 5 arcmin field of regard. Key requirements include:
    - Wavelength Range: 0.8 – 2.5 µm.
    - Field of View: 2" for each IFU over a 5 arcmin MOAO field of regard.
    - Spectral Resolution: R=2000 to 10000 (IFU) over entire J, H, K bands, one band at a time.
- Mid-InfraRed Echelle Spectrograph (MIRES), a small field of view mid-infrared high resolution spectrometer configuration including a dedicated AO system (MIRAO) operating at the diffraction limit. This

instrument shall be fed a mid-IR AO system (MIRAO) using both natural and laser guide stars to deliver diffraction limited images. Incorporation of a deformable mirror, as cold as practicable, into MIRES may be required if an adaptive secondary will not be available on an appropriate timescale. Key requirements include:

    - Wavelength Range: 8 - 18µm, goal 4.5-28µm.
    - Field of View: 10 arcsec.
    - Spectral Resolution: 5000≤R≤100,000 (with diffraction-limited slit).

- Planet Formation Imager (PFI), a high contrast imager configuration including an Extreme AO system with high accuracy and stability, and a coronagraph or similar instrument. The system should reach contrast ratios of $10^8$ in H band on stars with I < 8 mag before systematic errors dominate. Key requirements include:
    - Wavelength Range: 1-2.5µm, goal 1 - 5µm.
    - Field of view: 0.03-1 arcsec radius.

- Near Infrared Echelle Spectrograph (NIRES), a small field of view near infrared (1 – 2.5 micron) high spectral resolution spectrometer configuration utilizing diffraction limited images from NFIRAOS. Key requirements include:
    - Wavelength Range, 1µm- 2.5µm.
    - Spatial Sampling: Nyquist sampled ($\lambda$/2D) (0.004 arcsec).
    - Length of Slit: 2 arcsec and/or IFU.
    - Spectral Resolution: 20000≤R≤100,000.
- High Resolution Optical Spectrograph (HROS), a seeing limited optical spectrometer configuration with high spectral resolution with long term stability to achieve radial velocity measurement repeatability and accuracy of 1 m/s over time spans of ten years. Key requirements include:
    - Wavelength Range: 0.31 – 1.0µm (required) 0.3 – 1.3µm (goal).
    - Field of View: 10 arcsec.
    - Length of slit: 5 arcsec.
    - Spectral Resolution: (slit), R=50,000, (image slicer), R≥90,000.

- Wide Field InfraRed Camera (WIRC), a moderate field near infrared imager configuration fed by NFIRAOS to provide near diffraction limited images through a variety of filters with high photometric and astrometric accuracy. Key requirements include:
    - Wavelength Range, 0.8 – 2.5 µm, goal 0.6-5µm.
    - Field of View, 30 arcsec diameter.
    - Spatial Sampling, Nyquist sampled ($\lambda$/2D) (0.004 arcsec).
    - Spectral Resolution, R= 5-100 (narrow and broad band filters).

### 6.1.9 Summit Facility Requirements

#### 6.1.9.1 Enclosure, Fixed Enclosure Base and Telescope Pier

The TMT enclosure protects the telescope, instruments, and associated equipment from adverse environmental conditions during non-observing time. It will have an aperture opening and shutter of sufficient size to not vignette the optical path of the telescope during observations. The system will be capable of opening or closing the aperture shutter in two minutes. The enclosure aperture opening will be capable of a continuous and unlimited range of azimuth motion (no cable wraps) and zenith motion range from 0 to 65 degrees zenith angle, and must provide azimuth and zenith motion of the aperture opening in concert with the telescope to track the astronomical sky during observations. The enclosure will be capable of moving in azimuth and zenith position between observations within three minutes.

During observations, the enclosure will utilize a passive ventilation scheme to flush the enclosure volume at the start of observations, and to provide optimum observing aerodynamic and thermal conditions during observations. It must minimize dome seeing, mirror seeing, and wind buffeting during observations [4]. During the daytime, the enclosure will utilize an active cooling system to keep the internal temperature close to the expected night time ambient temperature. The enclosure will make design accommodations for a forced air ventilation system that will not be implemented at first light.

The enclosure design will incorporate vibration mitigation to minimize the generation and transmission of vibrations, from its drives and from wind on the enclosure, to the telescope, since it is better to prevent vibration rather than deal with its effects.

The enclosure will manage the daytime thermal load inside the enclosure from solar absorption, power dissipation, and air infiltration.

The enclosure design and maintenance plan must minimize the loss of observing time [6].

The enclosure fixed base will provide access doors to the adjacent summit facilities structure for mirror, instrument, and personnel movements.

The telescope pier design will incorporate vibration mitigation to minimize the generation and transmission of vibrations to the telescope, instruments, adaptive optics, alignment & phasing, and calibration subsystems.

The enclosure and summit buildings must be protected from lightning strikes by an external lightning conductor protection system.

#### 6.1.9.2 Mirror Maintenance

A mirror stripping and coating facility sufficient to process the M1 mirror segments, M2 and M3 mirrors will be located adjacent to the enclosure to minimize mirror transportation. A storage facility for the set of spare M1 mirror segments must be provided adjacent to the mirror stripping and coating facility.

The primary mirror system will be cleaned on a regular basis to maintain good reflectivity. It is anticipated that $CO_2$ snow will be used for this purpose. This equipment will require storage adjacent to the mirror maintenance areas.

#### 6.1.9.3 Operations Spaces

A control room will be provided adjacent to the enclosure with sufficient space for observing staff and associated computers and monitors. An air conditioned computer room will be provided adjacent to the control room.

#### 6.1.9.4 Lab and Shop Spaces

A mechanical workshop will be provided adjacent to the enclosure with sufficient machining, welding, and fabricating equipment, tools, consumables, and associated storage to support day to day maintenance activities at the summit.

An engineering workshop will be provided adjacent to the enclosure with sufficient optical, electronic, and software equipment, tools, consumables, and associated storage to support day to day maintenance activities at the summit.

#### 6.1.9.5 Personnel spaces

Personnel spaces, including entry lobby, conference room, offices, kitchenette/lounge, bathrooms, first aid, janitorial and associated storage will be provided adjacent to the enclosure to support the direct day time maintenance crew and night time observing crew.

#### 6.1.9.6 Shipping and Receiving

A shipping and receiving area will be provided adjacent to the enclosure for delivery/uncrating and removal/crating of components and equipment to/from the summit facilities. The shipping & receiving area will be equipped with an overhead gantry crane with sufficient headroom for associated component movements.

#### 6.1.9.7 Mechanical and Electrical Plant

A mechanical plant will be provided to supply the mechanical services required at the summit facilities, including chilled and circulated water/glycol, compressed/dry air, telescope and instrument hydraulic oil and power unit(s), cryogenic closed cycle coolers and/or facility helium circulation, enclosure pressurization, building air conditioning, fire suppression, water & waste storage, LN2 storage, etc.

An electrical plant will be provided to supply the electrical services required at the summit facilities, including power generation, transmission, and transform, power conditioning, uninterruptible power supply, telephone system, data interconnect, fire alarm, lighting control, etc.

#### 6.1.9.8 Roads and Parking

The roadway away from the summit facility will be paved or otherwise treated for a sufficient distance to minimize the generation of dust directed towards the summit facility. Parking and vehicle access will be provided to the summit facility.

### 6.1.10 Support Facility Requirements

The support facility will be located within a two hour drive of the summit, and below 3000 m elevation. The support facility will include the following components:

- Electrical and mechanical plant to supply services.
- Accommodation facilities, including sleeping, dining, sanitation, recreation, and communication capabilities will be provided at the support facility to support personnel who are required to remain close to the observatory.
- A maintenance yard, including technical workshops, vehicle and rolling stock storage, and offices will be provided at the support facility to support site services, roadway maintenance, vehicle and rolling stock maintenance, repairs and reconditioning of observatory components, and staging of new observatory components.
- Personnel spaces, including reception, conference room, offices, kitchenette/lounge, bathrooms, first aid, janitorial and associated storage will be provided at the support facility to support operations, administration, site services, engineering staff, and visitors.
- A computer room will be provided to house IT infrastructure including network hardware, servers, and a second location for backup data storage.
- A mechanical workshop will be provided at the support facility with sufficient machining, welding, and fabricating equipment, tools, consumables, and associated storage to support extended maintenance and staging of new component activities for the observatory.
- Storage and warehousing capacity will be provided at the support facility sufficient to house the recommended spare components and extended consumables for the observatory.
- A shipping and receiving area will be provided at the support facility for delivery/uncrating and removal/crating of components and equipment to/from the support facility.

### 6.1.11 Construction Camp

Accommodation facilities, including sleeping, dining, sanitation, recreation, and communication capabilities are required near the eventual support facility location to support construction personnel who are to remain close to the observatory (reference site preparation, erection, and AIV plans). It is desirable that the construction camp accommodations be reusable after the end of construction as additional overflow accommodations to the eventual support facility accommodations.

Staging areas for observatory construction components must be provided near the eventual support facility location (reference site preparation, erection, and AIV plans).

Temporary mechanical and electrical plants will be provided to supply the services required for the construction camp and staging areas.

Passenger vehicle parking shall be provided close to the construction camp building entries with sufficient spaces to support the construction personnel. Transport vehicle access and loading/unloading space must be provided close to the staging areas.

### 6.1.12 TMT Headquarters Offices, Science Center, and Data Archive

TMT headquarter offices will be established within or near a populated area located within the country and/or state as the TMT Observatory. These offices will host a variety of managerial, legal, business, and financial services necessary for observatory administration. In addition, office space will be provided for science, engineering, and technical staff pursuing off-site research or functional activities.

These offices are not a TMT construction project deliverable. They will be established in leased office space during Early Operations (see **Sections 5.1.2** and **10.1.1**). A purpose-built building or complex (like Keck or Gemini) is not envisioned at this time.

It may be desirable to establish one or more TMT Science Centers within the TMT partner countries to support science users with observation planning, scheduling and execution as well as data delivery and processing.

Each center would have a remote observing facility. The TMT instrumentation development office (see **Section 8.7.4**) could also be located at one of these centers.

Such centers are not a TMT construction project deliverable nor are they part of planned science operations baseline services (see **Section 5.2.1**). One or more such centers could be added later as part of the science operations enhanced service model (see **Section 5.2.2**).

It may be desirable to establish a TMT Data Archive within one of the TMT partner countries to store permanently all science and engineering data produced by the TMT Observatory. Data would be organized in such manner that data mining and archive research projects were possible. This archive would be connected to the Virtual Observatory and could be co-located with one of the TMT science centers discussed above.

Such an archive is not a TMT construction deliverable nor is it part of the envisioned science operations baseline services (see **Section 5.2.1**). Creation and operation of such an archive falls within the realm of science operations enhanced services (see **Section 5.2.2**).

### 6.1.13 Maintenance and Reliability

The OCD includes a section on Unscheduled Technical Downtime requirements. The key requirements from this section are repeated here.

In steady-state operations, the TMT Observatory is required to have no more than 3% unscheduled technical downtime between evening and morning nautical twilight during hours scheduled for science operations.

During the design and implementation phase, the following measures will be taken to minimize the number of failures as well as minimize the cost and time necessary to recover from such failures:

- Identify all potential single-point failures. Whenever technically and fiscally possible, build in redundancy to minimize the number of potential single-point failures.
- Enable subsystem condition monitoring through implementation of mechanical and/or electronic wear and performance indicators. As much as possible, such condition information will be captured and stored electronically for monitoring and analysis purposes.
- Identify all parts likely to become obsolete during the first TBD years of operation and procure enough spare parts (consistent with their expected Mean Time Between Failures) to cover all expected failures in that period.
- Use common mechanical and electronic parts and solutions for common tasks and requirements.
- Design assemblies so that components can be replaced quickly in the event of a failure.[1]

Reliability and time to repair budgets will be allocated at the system decomposition level, and must be consistent with the level 1 requirements for reliability and maintainability of the system. Definitions of the conditions that determine a subsystem failure will be defined at level 2 for all subsystems. In the design phase, before Critical Design Review, each subsystem design team must perform a subsystem reliability analysis, and component tests as appropriate, to show that it will meet the required level 1 reliability and maintainability budgets [6].

### 6.1.14 Environmental, Health and Safety Requirements

The safety priorities of the system are: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

A comprehensive safety plan will be established and implemented before construction starts at the observatory site. An operational safety plan will be established before Early Operations starts. All equipment with functions or malfunctions potentially capable of harming people or causing significant financial loss are required to have a hard wired interlock system able to prevent access to hazardous areas or operations.

The observatory will comply with all applicable national and local environmental and occupational health regulations and standards. The observatory will comply with all local environmental regulation and international environmental standards applicable to the observatory site, appearance, and operations.

[1] In industry, an assembly or component that can be replaced quickly to restore the entire system to service is often called a Line Replaceable Unit (LRU).

## 6.2 Requirements Flow Down and Traceability

### 6.2.1 Flow Down Strategy

#### 6.2.1.1 Documentation Tree

Configuration management encompasses (i) establishing a consistent system configuration, (ii) maintaining and stabilizing it, and (iii) documenting both the configuration and the design process.

During the development phase, the system specifications become more and more detailed before reaching the point where the actual manufacturing or purchasing can start. This process of "digging deeper" into the design is captured by various documents from the high level requirements to system architecture, to subsystem requirements, to conceptual, preliminary, and eventually to final design.

The integration and test phase can be perceived as "climbing out" from the detailed design and fabrication phase and implementing and verifying the system with a progressively wider perspective and scope. The integration and test phase has its own required documentation essential both for the success of the project and later for efficient maintenance.

**Figure 6-1** shows the TMT realization of the traditional V-diagram. It is worth noting that the project V-diagram does not go beyond subsystems, as in general the assembly and component requirements and design documents are the responsibilities of the subsystem teams.

To maintain a stable configuration and guard the integrity of the design process, the documents will be formally controlled. Any change to these documents will be disseminated within the project and checked against the current design directions of the entire system and its subsystems before it is implemented. This process is embodied by the Change Control Board, an advisory group to the project manager that includes the project and observatory scientists, the systems engineer, the department heads, and the group leaders.

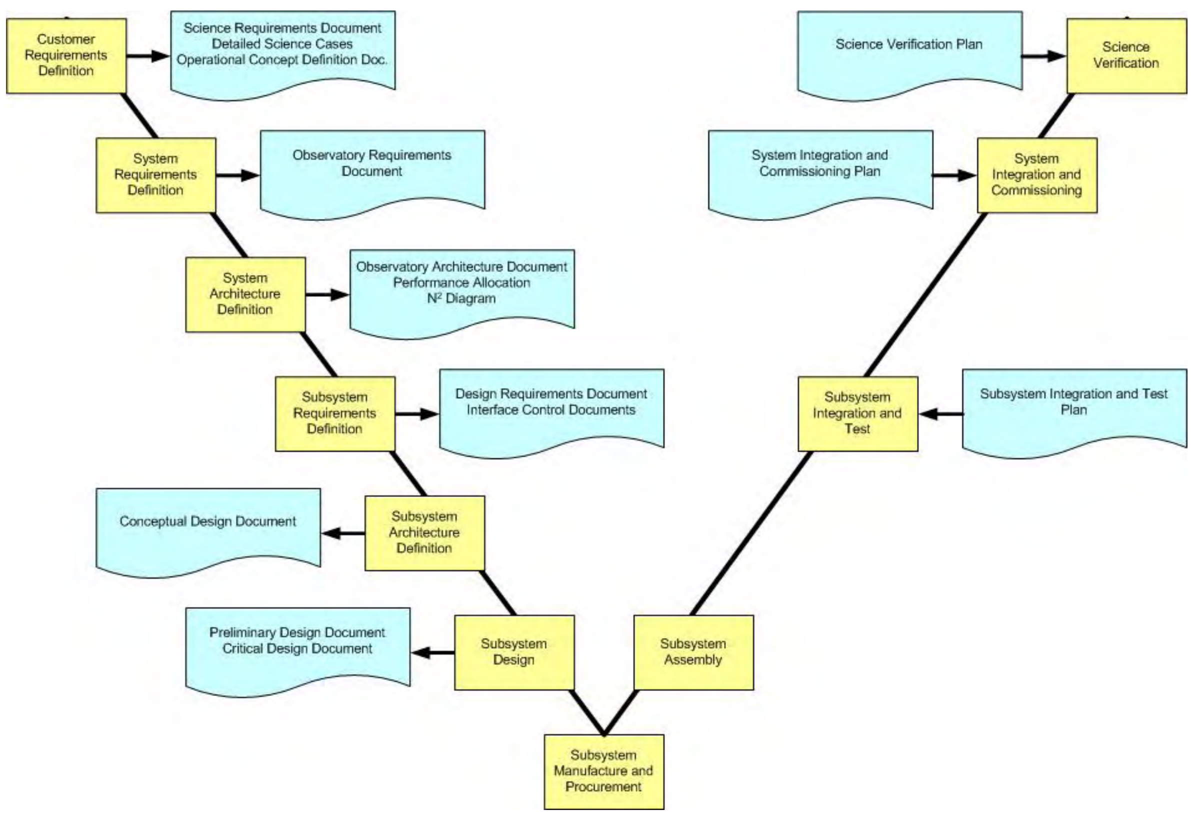


**Fig 6-1: Structure of requirements documentation.**

#### 6.2.1.2 Traceability

The requirements developed for TMT will be traceable, in terms of how a requirement flows down to subsystems and how it is implemented in the design, and upwards from the subsystem to show why a system has to meet a certain requirement.

The metadata related to the requirement traceability matrix will include:

- The source of the requirement
- Why the requirement exists (rationale)
- What requirements are related to it
- How the requirement is met in the system design, implementation and user documentation.
- How the requirement is checked in the test plan.

### 6.2.2 Status of TMT Requirements

At this time the Level 0 Science, and Level 1 System requirements are fully documented, released, and under change control. Level 2 Subsystem and lower requirements are at various levels of development. The project plans to complete the Level 2 requirements and place them under change control by November 2007.

## *6.3 Observatory Requirements Documentation*

### 6.3.1 Introduction

TMT requirements are organized into three levels, Science, System and Subsystem, as shown in **Figure 6-2**. The Level 0 Science requirements are set by the Project Scientist with input from the scientific user community through the TMT Science Advisory Committee, and are approved by the TMT Board. They dictate what is required to enable the science envisioned for the Observatory. A Science Verification Plan is provided at the top level to check that these requirements are met. The Level 1 System requirements are the top level engineering requirements for the observatory, and they are traceable to the Science requirements. They include the top level operational concepts, the system level requirements including performance budgets and functionality that the observatory must provide, and the top level engineering architecture for the entire facility, including the subsystem decomposition. There is an Integration and Commissioning plan at the system level that documents how the observatory will be assembled and tested. The Subsystem requirements are traceable to the system requirements and ensure that each component of the observatory delivers the performance and functionality required to meet the system level performance needs. The subsystem documentation includes interfaces between subsystems and design documents that show that design implementation will meet the requirements. Each Subsystem must also provide an integration and test plan, to ensure that the system can be successfully integrated with the observatory and that its performance and functionality can be verified.

### 6.3.2 Level 1 Requirements Documents and Structure

The Observatory Level 1 requirements documents consist of the Operations Concept Document (OCD), the Observatory Requirements Document (ORD), and the Observatory Architecture Document (OAD). Within the Level 1 requirements there is a hierarchy in that the OCD flows down into the ORD, and both the OCD and the ORD flow down into the OAD. Level 2 requirements can be traced to any of these Level 1 documents.

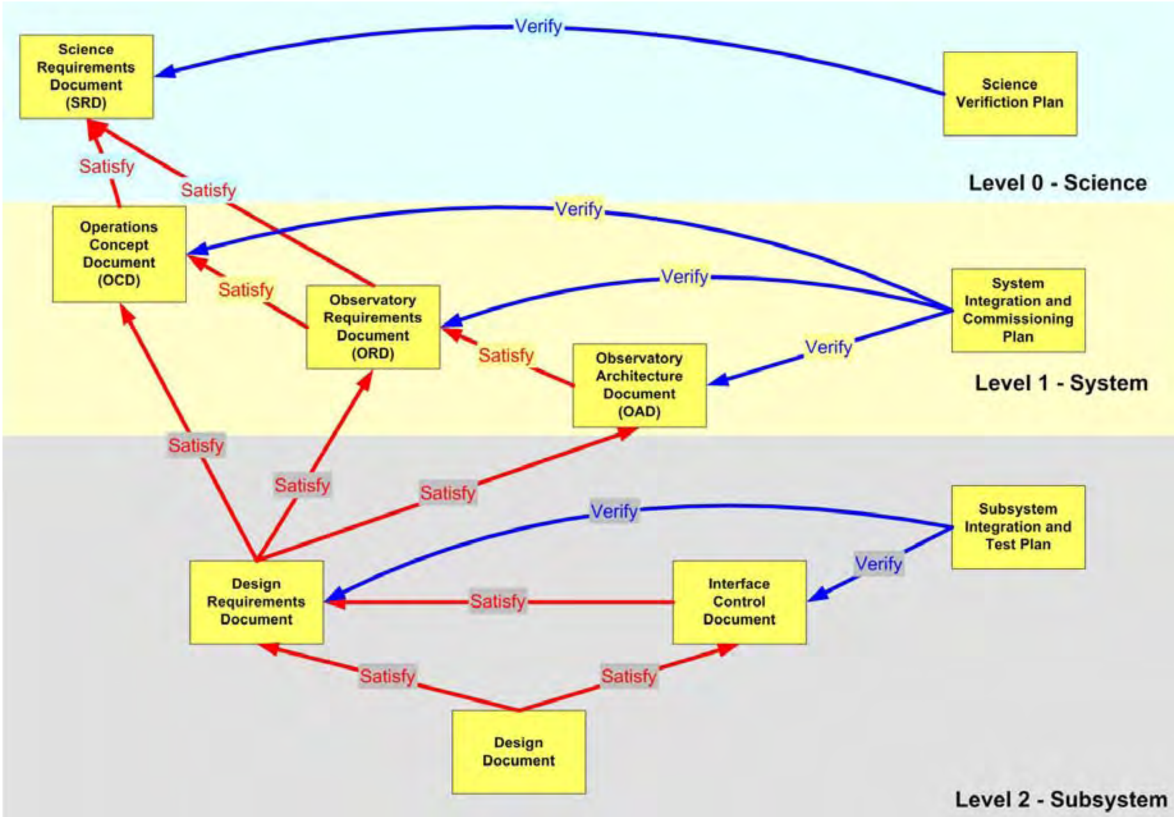


**Fig 6-2: Structure of requirements documentation.**

## *References*


[1] Observatory Requirements Document (ORD), TMT.SEN.DRD.05.001

[2] Science Requirements Document (SRD), TMT.PSC.DRD.05.001

[3] Operations Concept Document (OCD), TMT.OPS.MGT.07.002

[4] Seismic Analysis Two Telescope Sites, Mauna Kea Hawaii, and Cerro Pachon, Chile for Gemini 8-M Telescopes Project. Prepared by DAMES & MOORE, INC, February 1994. GSM.FAC.TEC.94.001

[5] T. Mast and J. Nelson, TMT Image Size and Wavefront Error Budget, TMT.OPT.TEC.07.001, TMT.OPT.TEC.07.002, TMT.OPT.TEC.07.003

[6] Glen Herriot, TMT Observatory Reliability and Availability Budget, TMT.SEN.TEC.07.005

# 7 System Design and Performance

This section summarizes the system architecture of the Observatory. The high level design described satisfies the requirements established in the Observatory Operation Concept Definition and Observatory Requirements Documents. On the other hand, this architectural design creates further requirements for the subsystems of the observatory.

The section also describes system performance allocations, as well as provides an estimate for the expected system performance.

## *7.1 System Design Philosophy*

### 7.1.1 Design philosophy

Our design philosophy is based on the conviction that the development and implementation of a 30 meter, near diffraction limited telescope is above all a system challenge. It requires the seamless integration of the telescope, the adaptive optics systems and the instruments, which in turn precipitates the need for an integrated design approach. Our approach takes into account simultaneously a whole range of issues: various site characteristics, enclosure configuration, telescope structural layout; orchestrating a complex control system driving active and adaptive optical elements; fabricating, polishing, controlling, and maintaining the primary, secondary, and tertiary mirror surfaces; and distributing these functionalities among the various subsystems.

The single most important technological achievement of the last decades has been the explosion of computing power and matching evolution of computing algorithms. The most visible example of reducing physical robustness by improved computations was the emergence of altitude-azimuth mounts enabled by the fast and precise conversion of sky coordinates to telescope elevation and azimuth angles. While all of the early 4 meter class telescopes had inherently massive equatorial mounts, all of the 8-10 meter class observatories utilized the altitude-azimuth mount, which provided a more direct load path and consequently a significantly lighter telescope structure.

Active optics, the real time adjustment of optical surface shapes, and adaptive optics, the real time correction for the optical effects of atmospheric turbulence are other well known examples of the same trend. Active optics allowed the use of thin glass shells instead of enormous blocks of glass for mirror substrates, while it also facilitated faster mirrors resulting in shorter telescope structures and smaller domes. Adaptive optics enables astronomy formerly unimaginable from the ground and so provides strong incentives for extremely large ground based astronomical telescopes.

The emergence of new modeling capabilities can also be linked to improved computers. For the last generation of telescopes, the most consequential new method was finite element analysis (FEA). This technique revolutionized both structure and mirror designs and facilitated active optics algorithms.

TMT is determined to push forward on the same trends in order to resolve our major technical challenges and reduce the cost of developing and constructing the observatory.

- The *phasing of the highly segmented primary mirror* and the shape and alignment maintenance of all the optical surfaces requires a complexity of optical, mechanical, and temperature measurements and controls of telescope structure and optical surfaces that is unique in astronomical telescopes.
- *Reducing wind buffeting, dome and mirror seeing* to the level permitting us to achieve our science goals requires a design informed by the combination of the most advanced computer modeling techniques in the fields of optics, dynamic controls, and computational fluid dynamics (CFD).
- *Scaling the current adaptive optics* concepts up to a 30 meter aperture and providing the image quality demanded by our science goals requires challenging computing power, algorithms, and unique components, like polar coordinate wavefront sensor detectors and high resolution deformable mirrors.

### 7.1.2 Major design choices

The current design architecture for TMT has evolved through numerous design trades.

**Optical design**
The Ritchey-Chretien optical design chosen for TMT reduces the cost of the observatory, as it permits a shorter telescope and smaller secondary and tertiary mirrors. A Gregorian layout would provide an accessible prime

focus for an optical test instrument or test source, as well as a concave secondary mirror. However, the Alignment and Phasing System, aided by the Global Metrology System offers a superior alternative to prime focus optical tests. Furthermore, recent advances in interferometric techniques, in particular stitching sub-apertures into continuous interferograms all but eliminated the cost advantage of concave surfaces in testing large optics.

Early on, the project settled on Nasmyth foci [1], as the Nasmyth platforms are more versatile in supporting the entire instrument suite envisioned for the TMT. The Nasmyth platforms can hold several stand-by instruments ready for observation, which is essential for meeting science efficiency objectives like the 10 minutes system configuration (instrument – AO system) change requirement. The price to be paid for this versatility is the additional warm optical surface of the tertiary mirror, increasing slightly the system emissivity in the infrared bands.

Instead of further increasing the number of optical surfaces by introducing a quaternary mirror distributing the light on the Nasmyth platform, the TMT design architecture includes an articulated tertiary mirror capable of directing the science beam to various Nasmyth platform locations. On the other hand, for instrument positions not on the elevation axis, the continuous motion of the tertiary mirror leads to slightly increased image jitter due to the imperfect bearings and drives of the mirror support system.

A fast primary mirror precipitates tighter optical tolerances and higher asphericity. However, these difficulties are balanced against a shorter telescope and consequently smaller dome, which in turn results in reduced construction cost of the observatory [1]. Consequently, the reference design calls for an ambitious f/1 primary focal ratio.

The f/15 final focal ratio was chosen for the telescope [2]. A slower telescope would decrease the diameter of the secondary mirror at the expense of increasing the diameter of the focal plane, i.e. the size of the AO systems and instruments. The project decision gave preference to mitigating the long term risk of future instruments being unable to take advantage of the continuous field of view of the telescope, above the mid term risk associated with a slightly larger telescope.

**Adaptive Optics**

A very wide variety of AO system concepts have been discussed and considered for TMT, including Ground Layer AO (GLAO), Laser Tomography AO (LTAO), Multi-Conjugate AO (MCAO), Multi-Object AO (MOAO), and Extreme AO (ExAO). A Laser Guide Star (LGS) MCAO system has been selected for our early light AO facility, since it provides the best match to the SRD sky coverage and image quality requirements for narrow-field, near-IR instrumentation while making maximum use of existing and near-term AO component technologies. NGS MCAO has already been successfully demonstrated on-sky, with further on-sky experiments and systems planned for 2007-8. As described in **Section 8.5** below, the component requirements for DMs, lasers, beam projection systems, LGS WFS detectors, and IR Natural Guide Star (NGS) WFS detectors correspond to either existing hardware, prototypes currently in fabrication, or (in the case of IR detectors) the next generation of devices envisioned for 8-10 meter class AO systems. The first-light AO architecture avoids longer-term and riskier elements, such as Micro Electro- Mechanical Systems (MEMS), an adaptive M2, and open-loop DM control.

**Mechanical layout**

Although there are fairly strong arguments favoring a radio-telescope like telescope structure, among them the potential for a lighter secondary mirror support structure, more direct load path, significantly smaller elevation journals (C-rings), and shorter back focal length due to the accommodation of the Nasmyth platforms underneath the primary mirror, the project settled on a layout in which the elevation axis is above the primary mirror [1]. The trade studies leading to the reference design found no evidence of noteworthy performance difference between the two layouts, while the chosen layout promised lower cost due to reduced secondary mirror diameter, telescope structural length, and enclosure size. Furthermore, the "M1+" design, having the elevation axis above the primary mirror, allows more versatile utilization of the Nasmyth platforms, as beam obscuration by the structure is more controlled.

The project adopted Nasmyth platforms that are 7 meters below the elevation axis [3]. In this concept, each instrument has a dedicated support structure that enables suitable access to the instrument for installation and maintenance. Building the platforms at this elevation accommodates even the largest seeing limited instruments without the need for breaking the continuous platform and provides the most versatile instrument support. It also enables packaging the electronics cabinets and routing and maintenance of services below the instruments in a readily accessible area. Above all, this layout provides the least blockage to air flow around the primary mirror.

### Segment size

Extensive trade studies led to the conclusion that the (i) primary mirror should be segmented, (ii) the segments should be hexagonal, as opposed to sector shaped, and (iii) the optimal segment circumscribed diameter is somewhere between 1 and 2 meters. The project settled on 1.44 meter nominal segment size after comprehensive studies and deliberations [4]. The optical performance of the telescope is practically independent of the segment size in the 1.2-1.5 meter range. Simulations showed that even the Planet Formation Instrument, the instrument assumed to be the most sensitive to segmentation parameters, can achieve practically the same performance.

The 1.44 meter size is about the upper limit that places no restriction on our choice of mirror blank supplier. However, this size results in segments at the outer edge of the primary mirror with higher asphericity than that of the Keck segments, which leads to increased polishing risk.

The larger segment size results in a lower number of segments. That in turn shortens installation time, reduces the number of support components and control electronics, consequently improves the reliability of the system, and also reduces maintenance time (segment exchange and re-alignment).

By choosing a larger segment size and lower segment number, the project again gave preference to mitigating the long term risks of higher segment and associated part counts above the mid term construction risk related to the more aspheric segments.

### Enclosure

TMT has carried out a thorough comparative study of four enclosure types intended to provide the basis for selection of single enclosure architecture [5]. The process included structural studies of candidate dome-shutter, co-rotating, carousel and calotte configurations, mechanical studies of these varieties, comparative cost-risk studies and aerodynamic and thermal modeling. Based on these studies the project adopted the most cost-effective calotte type, which also provides the best wind protection.

The size of the enclosure is determined by the adequate accommodation of instruments on the Nasmyth platform and more consequentially, by the adequate aero-thermal performance of the enclosure. By balancing the potential cost savings and technical performance [6], the project decided on a 33 meter outer enclosure radius.

## *7.2 Observatory Layout*

A more detailed description of the observatory layout can be found in the Observatory Architecture Document (OAD) [7].

### 7.2.1 Optical design

The TMT baseline design is a filled aperture, segmented mirror telescope with circumscribed primary mirror diameter of 30 meters. It is worth noting that segmentation is the only feasible technology available today for filled apertures of this size. The primary mirror has 492 hexagonal segments with a nominal circumscribed diameter of 1.44 meters.

The optical layout of the telescope is shown in **Fig. 7-1**. The tertiary mirror is able to rotate in two orthogonal directions. This allows it to direct the beam to instruments on the Nasmyth platforms with the beam either oriented along the elevation axis, or at an angle to the elevation axis, as illustrated in **Fig. 7-3**.

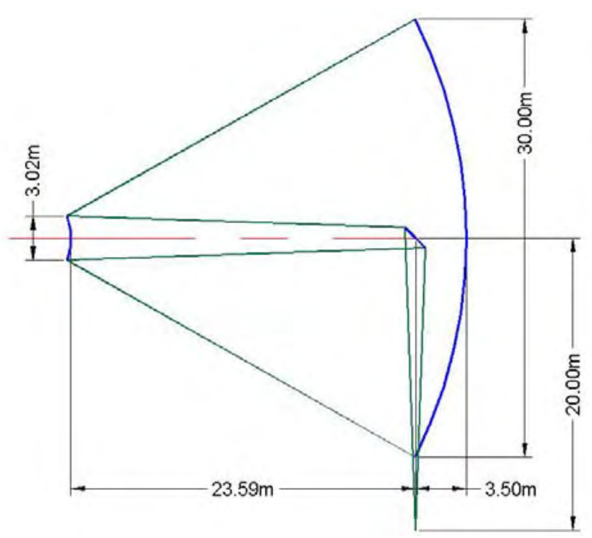


**Fig 7-1: Optical layout of the telescope.**

The optical design of the TMT is an aplanatic Cassegrain (Ritchey-Chrétien), where both spherical aberration and coma are corrected by design. The aperture stop is at the primary mirror; hence the exit pupil is a virtual image of the primary mirror located 2.7929 meters behind the secondary mirror. The exit pupil diameter is 3.0924 meters. The telescope elevation axis is 3.5 meters above the primary mirror vertex. The back focal distance is 16.5m; the focal surface is located 20 meters from the center of the telescope (vertex of the tertiary mirror).

The system does not provide stray light baffles in the light train up to and including the Nasmyth focus. Stray light control is provided in downstream optical and instrument designs.

The telescope does not have a facility atmospheric dispersion compensator. All atmospheric dispersion compensation for the instruments and adaptive optics systems is incorporated into those systems. The optical prescription for TMT is shown in **Table 7-1** [8].

**Table 7-1: Optical prescription of the Thirty Meter Telescope.**

| **Parameter** | **Value** |
|---|---|
| Final focal length and plate scale | 450 m; 0.45837 arcsec/mm |
| Unvignetted field of view (FOV) | 15 arcmin |
| Unobstructed field of view | 20 arcmin |
| Primary mirror focal length | 30 m |
| Primary mirror conic constant | - 1.0009535 |
| Primary mirror nominal and actual circumscribed diameter | 30 m |
| Primary to secondary mirror separation | 27.093750 m |
| Secondary mirror focal length | 3.1138393 m |
| Secondary mirror conic constant | - 1.31822813 |
| Secondary mirror nominal diameter (beam footprints for FOV) | 3.0245 m |
| Tertiary mirror focal length | Infinity (flat) |
| Tertiary mirror nominal diameter (beam footprints for FOV) | Ellipsoid: 2.4502 – 3.5079 m |
| Field curvature (concave towards the sky) | - 3.0092 m |
| Focal surface diameter | 1.9635 m |

### 7.2.2 Telescope layout

TMT is a conventional altitude-azimuth telescope (see **Fig. 7-2**). The telescope pointing is primarily defined by its rotation around the local vertical (azimuth) and its angle relative to the local vertical (elevation).

The observatory floor is at ground level. A concrete pier supports the azimuth journal at 3.5 meters above ground. The height of elevation axis above the azimuth journal is 19.5 meters.

No point of the telescope structure, including equipment on the Nasmyth platform and behind the secondary mirror, may be more than 28.5 meters from the intersection of the optical and elevation axes. This “stay-in” radius provides a 0.5 meter safety gap between the telescope and enclosure.

The telescope elevation structure will operate from -1º to 90º zenith angle, while the azimuth structure will rotate from -270º to 270º azimuth angle continuously, without unwrapping the cables.

The foundation of the telescope is separated from the foundations of the enclosure and summit facilities. Vibration isolation is expected to be installed between the foundations of the telescope and enclosure or summit facilities to limit the transmission of vibration due to enclosure rotation and wind buffeting, as well limiting transmission from machinery in the summit facility to the telescope foundation.

The telescope structure supports the Nasmyth platforms and the Laser Guide Star Facility (LGSF). The laser room is mounted on the elevation journal, while the laser launch telescope is behind the secondary mirror.

The telescope is expected to be stowed in the horizon pointing orientation.

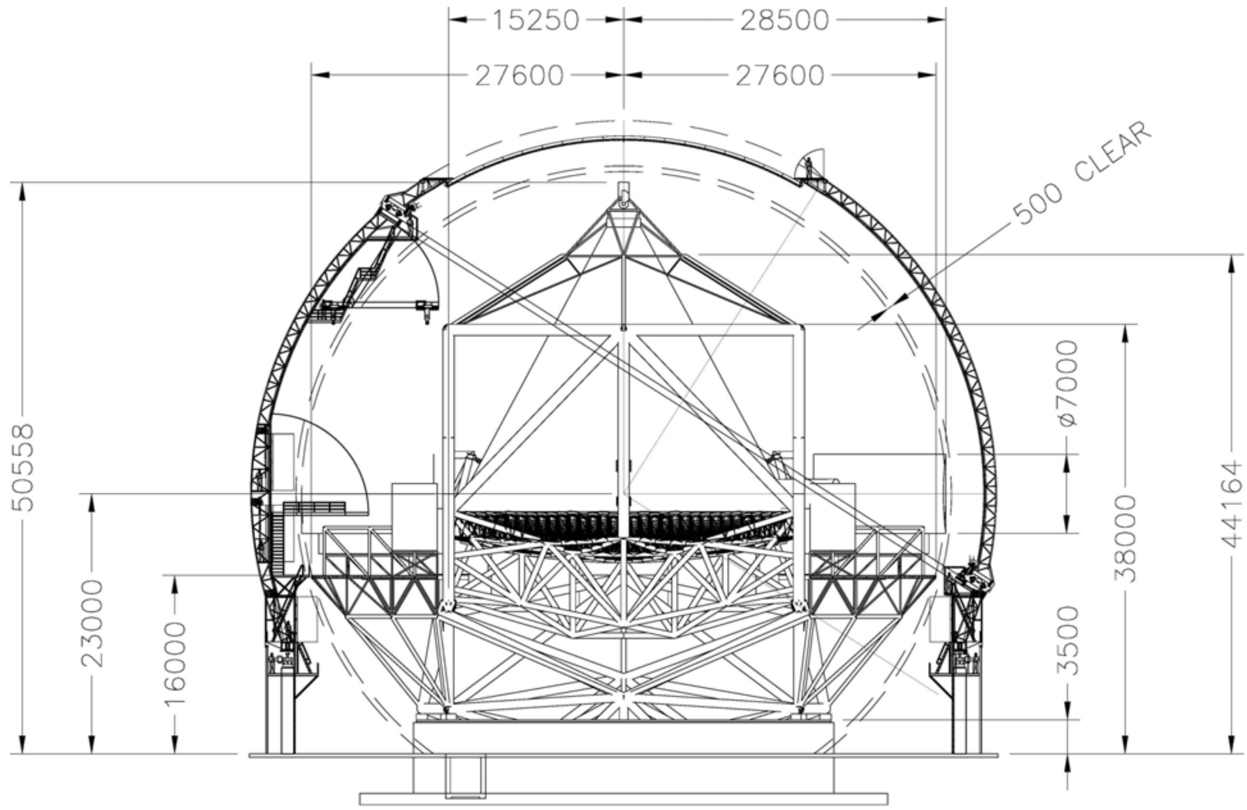


Fig 7-2: Telescope layout.

### 7.2.3 Nasmyth platform

The observatory has two horizontal Nasmyth platforms 7 meters below the elevations axis, as seen in **Fig. 7-3**. The right platform (in the figure) is dedicated to the seeing limited instruments (WFOS on the elevation axis and HROS) and IRMOS. On the other platform there is room for the facility AO system (NFIRAOS) with potentially three instruments attached (IRIS, IRMS, and later NIRES), the Alignment and Phasing System, PFI, and MIRES. At the corner of this platform there is space for a temporary clean room that could serve as an instrument laboratory during commissioning.

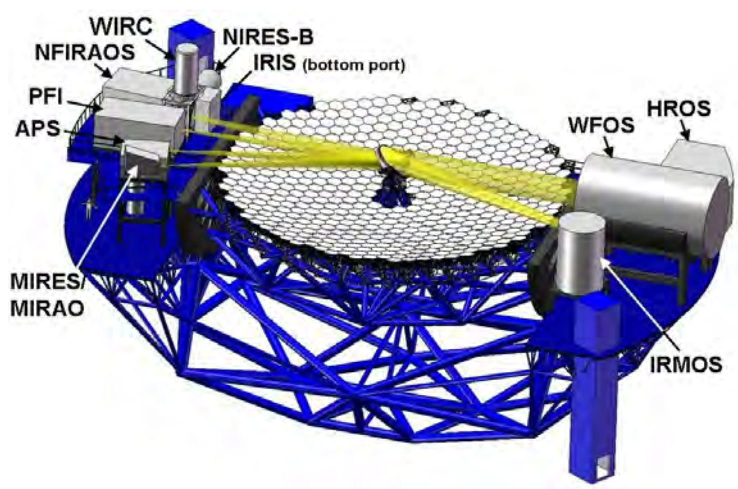


**Fig 7-3: The Nasmyth platforms with entire envisioned instrument suite supporting the science cases; the early light instrument suite includes WFOS, NFIRAOS, IRIS and IRMS, as well as the APS.**

The early light Nasmyth platform layout includes APS, NFIRAOS, IRIS, IRMS, and WFOS only, as well as the clean room.

WFOS and, in early light operation, APS, are on the elevation axis positions on the opposing platforms. The slight jitter increase due to the required continuous tracking with M3 in off elevation axis positions results in less image degradation in AO equipped instruments than in seeing limited ones.

A significant portion of the platforms are not addressable by the tertiary mirror due to geometrical restrictions. The addressable directions for small field of view instruments are in between -28° to 6° and 174° to 208°, expressed in the Elevation Coordinate System with origin at the intersection of the optical and elevation axes (see **Fig. 8-15**).

The encircled radius of the platforms is 27.6 meters, while their inner edge is 16 meters from the M3 vertex. The length of the platforms is 27.5 meters.

The Nasmyth platforms are accessible from the observatory floor by stairs and elevators.

### 7.2.4 Enclosure

The enclosure is a Calotte type with an external radius of 33 meters. The enclosure has two distinct components: the spherical, rotating dome and the cylindrical, fixed enclosure supporting the dome (see **Fig. 8-4**). The fixed azimuth track top bearing surface, which is the interface between the enclosure fixed base and rotating base, is at an elevation of 7.6 m above the ground.

To allow for pointing the telescope to the horizon for maintenance and stow, the telescope elevation axis goes through the center of the spherical dome.

No point of the enclosure may be closer to the intersection of the optical and elevation axes than 29 meters.

The Calotte enclosure provides superior wind protection due to its inherently small, circular opening. Deployable “lashes” forming a cylindrical extension to the opening further improve the wind protection of the secondary mirror at high external wind speeds by moving the shear layer at the opening farther from the mirror.

Three rows of vents, right above and below the primary mirror elevation provide adequate flushing of the mirror to minimize the thermal boundary layer at the optical surface that results in mirror seeing. The projected cross sectional area of the vents is comparable to the area of the observing opening. Furthermore, the vents are optimized to provide several air volume exchanges per hour under low to moderate external wind speeds, in order to minimize dome seeing, i.e. image degradation due to non-isothermal air turbulence inside the enclosure.

The enclosure will be air conditioned during daytime to ensure optimal initial mirror structure temperatures for the observations during the night.

Entrainment of high ground temperature gradients into the enclosure was avoided by raising the lowest vent row above the expected ground boundary layer.

### 7.2.5 Cranes and personnel access

Cranes, walkways, elevators and stairs facilitate safe and efficient access to servicing points inside the enclosure and on the telescope structure for maintenance and repair during operation. They are also necessary for removal and installation of components from the enclosure, telescope structure and telescope-mounted systems: M1 segments and segment supports, M2 assembly, M3 assembly, optical test instruments, instruments and AO systems including LGSF, and miscellaneous items such as cabinets for electronics, light fixtures and engineering sensors.

**Fig 7-4: Stairs and walkways on the enclosure.**

Servicing points on the enclosure are on the interior surface, particularly at the interface planes between the enclosure fixed base and rotating dome, enclosure cap and rotating base, shutter and enclosure cap, and vent openings. Service points on the telescope structure are inside the telescope pier where the azimuth mount control hardware and cable wrap are located, azimuth track, base and top of the azimuth structure where hydrostatic bearings are mounted, elevation journals where the elevation mount control hardware is attached, mirror cell for M1 segments and M3 assembly, Nasmyth platforms for the instrumentation, along the vertical column and top end of the telescope for M2 assembly and LGSF subsystems.

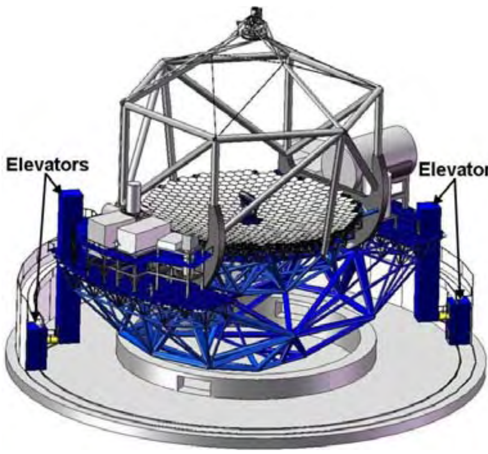


Fig 7-5: Elevators providing access to the Nasmyth platforms and the telescope structure.

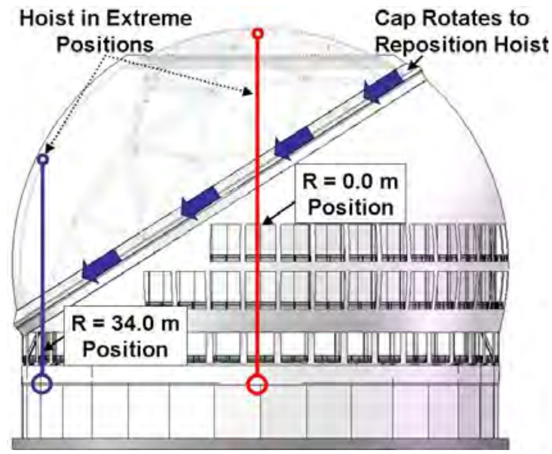


Fig 7-6: Radial travel of the cap mounted hoist. The range of motion is a circular path about the cap axis.

The enclosure and telescope structure are designed with stairs, walkways and elevators to allow access to the aforementioned servicing points. **Fig. 7-4** shows the ship ladders and walkways for accessing the vent openings and the interface between the cap and rotating base. Additional walkways also lead to the interface between the shutter and cap where outside access is provided by hatchways through the enclosure wall. **Fig. 7-5** shows access to the Nasmyth platform from the observatory floor via the fixed base and Nasmyth platform elevators. Not shown in the figure are the walkways and stairways that allow access from the Nasmyth platforms to the various servicing points on the elevation structure. Access into the telescope pier is via an opening through the pier wall.

Two cranes are provided for lifting operations; both are mounted on the enclosure. A 20 tonne capacity enclosure mounted crane is attached on the rotation base with its boom aligned radially towards the center of the dome (see **Fig. 7-7**). The swept-volume of the Nasmyth platform is reachable by combined boom travel and rotating base's angular motion. A 10 tonne capacity cap mounted hoist is attached to the center of shutter. **Fig. 7-6** shows schematically the radial travel between the center and edge of the dome that is achieved by the cap's angular rotation. The interior volume of the dome is reachable by combined base and cap angular motions. However, the cranes are limited to vertical and overhead lifts.

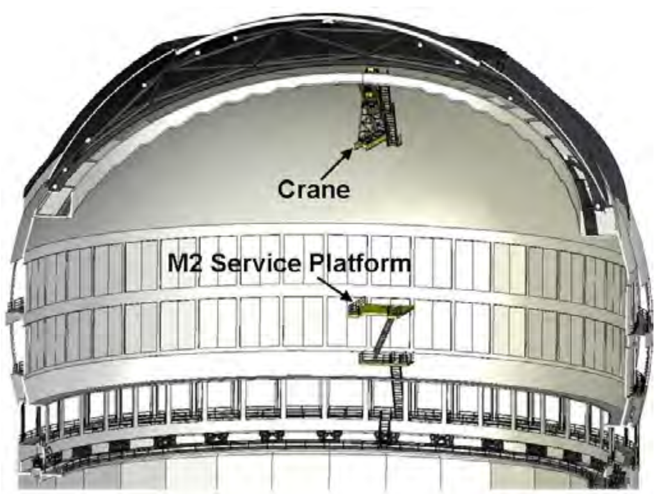


Fig 7-7: The cap mounted 20 tonne crane and the M2 service platform. Both are folded up during normal operations in order to move them out of the way of the telescope.

Instruments are accessed by portable walkways attached to the instrument support structures or by a motorized scissor-lift with personnel platform driven on the Nasmyth platform. Whole instruments or their components can be lifted onto the Nasmyth platform by the crane systems. For non-vertical lifts such as handling of small components or removal of small subassemblies from inside an instrument that does not warrant extensive disassembly in order to accommodate vertical lift, manually operated articulated lifting arm similar to those used in assembly plants is envisioned. The articulated lifting arm is designed to carry and balance its payload, usually in the range of 100 kg to 200 kg, such that the operator can maneuver and position the load without physical strain. Customized end effectors can be attached for delicate components and for long reach, depending on the operation.

Access to the LGFS system varies depending on the locations of the components. The LSEs are accessed from each Nasmyth platform. The

BTO duct along each vertical column is accessed either from the platform via a column mounted ladder with fall-guard or from the observatory floor with a personnel platform mounted on a mobile articulated boom ("cherry picker"). The components mounted behind M2 can be accessed by the same personnel platform or via the enclosure mounted platform used for servicing the M2 assembly with the telescope at horizon pointing (see **Section 8.3.7** and **Fig. 7-7**).

The interior surface of the enclosure is accessed by the same mobile articulated booms mounted personnel platform, which has 43 m vertical and 20 m horizontal reach. Interior surface higher than 43 m on the cap can be brought lower by cap rotation. In addition, a mobile articulated boom crane with a capacity of 4.5 tonnes augments lifting operations up to the Nasmyth platform level from the observatory floor.

Crane and personnel access concepts for installing, maintaining and servicing the observatory are works in progress. The plan is to involve instrument builders in finalizing handling equipment and the corresponding mechanical interfaces.

### 7.2.6 Facilities

The telescope, enclosure, and summit facility constitute the core of the observatory located on an appropriate mountain top. The site layout on our current reference site, Armazones is shown in **Fig. 7-8**.

The summit facility will house the control and computer rooms, the mirror stripping, coating, and storage facilities, electronics and mechanical shops, shipping and receiving, limited office space, a conference room, and utilities. Some of the utilities are located in a separate building on the summit to minimize vibration transfer.

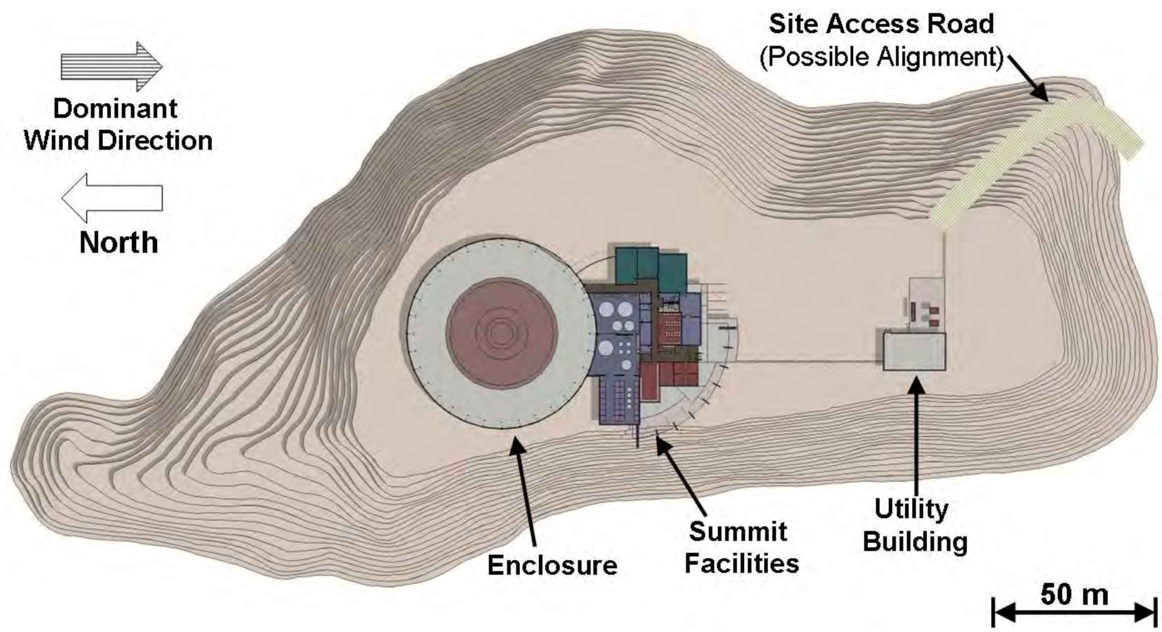


**Fig 7-8: Current enclosure and summit facility layout on Armazones.**

Besides the mountain top establishment, TMT will include a support facility in the vicinity of the summit. The support facility consists of administration, shop, office, and laboratory space, the maintenance and utility yard, as well as the accommodation and dinning facilities. Office space for the headquarters will be rented in Santiago.

## *7.3 Observatory Behavior*

A more detailed description of the observatory behavior can be found in the Observatory Architecture Document (OAD) [7]

### 7.3.1 Control architecture

**Pointing, tracking, and guiding**

The system establishes the alignment of the telescope relative to the sky, i.e. the optical axis of the primary mirror, primarily by means of mount drives setting the telescope azimuth and elevation angles.

Pointing is not supported by optical feedback (e.g. acquisition camera or guide WFS) as its very objective is to establish the appropriate conditions for closing any optical loop. Pointing is aided by the pointing model to achieve the required accuracy. The pointing model is a Look-Up-Table (LUT) based or best fit estimated correction to the theoretical mount drive commands. The pointing model comprises the relevant imperfections of the telescope and its control systems for various environmental and operating conditions, most prominently temperature and elevation angle. It also contains astrometry corrections.

Tracking, i.e. following the virtual sky motion without the aid of any sky reference, is a special sequence of pointing, possibly with pre-calculated trajectory. Tracking relies on calculating mount coordinates from the sky coordinates of the target, and correcting them with the pointing model.

The system improves the alignment of the telescope relative to the sky by means of guiding. Guiding corrects residual image motions with closed optical feedback loops reconstructing image motion of a natural guide star into mount elevation and azimuth angles. In seeing limited operation, motion is directly calculated by a mini real time computer (RTC) from the slope measurements of the guiding WFS located in the instrument. In adaptive optics operation it is computed by averaging the AO fast tip/tilt mirror commands and then scaling and rotating them into telescope modes (degrees of freedom) that are transferred to the Telescope Control System. The bandwidth of the guiding loop is expected to be 0.3 Hz.

Achieving the exceptionally high guiding precision required in some near diffraction limited observing configurations requires the utilization of the adaptive optics fast tip/tilt mirror to aid guiding, i.e. reduce image jitter.

**Field rotation**

Field de-rotation is the responsibility of the instruments. Instruments and AO systems that need higher field rotation accuracy than the seeing limited requirements will provide the means to calibrate their de-rotator, and/or correct rotation errors by real time optical feedback. Detecting rotation errors requires an extension to the guiding/aO sensors to allow off-axis measurements.

**Enclosure configuration control**

In order to maintain optimal air flow field inside the enclosure and in particular above the primary mirror, i.e. limit mirror and dome seeing and wind buffeting, the enclosure vents and the flaps around its opening need to be adjusted for each observation run. The adjustment is guided by wind speed measurements around the primary and secondary mirrors.

**Active Optics (aO)**

The system maintains the shape of the optical surfaces and their alignment relative to each other, i.e. the collimation of the telescope, by means of active optics compensation of thermal, gravitational, and vibration disturbances.

The active optics system adjusts the following degrees of freedom of the telescope:

- M1 rigid body 3 degrees of freedom (DoF (tip, tilt, piston) by means of the segment actuators;
- M1 segment position in 3 DoF (tip, tilt, piston) by means of 3 axial position actuators per segment;
- M1 segment shapes in 18 DoF by means of the warping harnesses;
- M2 position in 5 DoF (tip, tilt, piston, x and y decenters) by means of a hexapod;
- M2 shape in 132 DoF by means of axial and lateral actuators;
- M3 position in 2 DoF (tip and rotation about the telescope optical axis) ;
- M3 shape in 180 DoF by means of tri-axial actuators.

**Alignment and Phasing System (APS)**

The active optics system relies on APS to establish default commands for each actuator at different elevation angles and temperatures. The APS makes wavefront and interference measurements to estimate the shape and position of the optical surfaces. Based on these measurements, the Telescope Control System establishes a flexure model in the form of LUTs for all active optics actuators. The flexure model can be perceived as an “off-line” optical feedback loop with extremely low update rate, expected to be between a week and a month.

The APS will measure M1 segment tip/tilts, edge steps between adjacent segments, and the shape of the segments. Furthermore, APS can estimate the 5 rigid body degrees of freedom of M2 and M3, as well as the shape of both mirrors up to 8th radial order Zernike terms by means of off-axis wavefront measurements facilitated by moving M3 and the telescope to consecutively acquire off-axis field points on the APS wavefront sensors.

**Active Optics compensation strategy**

To limit drifts in the active optics system and correct small errors not completely accounted for by the pointing and flexure models, the adaptive optics system, or in absence of it an "on-instrument" NGS WFS and associated miniRTC will provide time averaged on-axis wavefront errors to the active optics system. The information supplied is the same in both seeing limited and near diffraction limited observations:

- OPD focus is reconstructed into M2 piston with ~0.1 Hz control bandwidth.
- OPD coma is reconstructed into M2 decenter, with ~0.01 Hz control loop bandwidth. The OPD tilt resulting from M2 decenter is compensated by the much faster guiding system through the mount actuators.
- Time averages of higher order OPD Zernike modes, up to the 6th radial order are reconstructed into M1 mirror modes with ~0.001 Hz control loop bandwidth.

The "on-instrument" WFS is either adjacent to the entrance window of the instrument, or preferably located inside the instrument. It is locked on a natural guide star and expected to have 6 by 6 sub-apertures.

The sky coverage limitations in seeing limited operations are not expected to be significant, as the allowable anisoplanatic error is large and the required sampling rate is not greater than 5 Hz. Preliminary estimates show that with guide stars of magnitude V=20 to V=22 the required signal to noise ratio (SNR) can be achieved. Such guide stars are expected to be found most often not farther than 75 to 150 arcsec from the target.

Fig. 7-9 illustrates how the wavefront information flows from the instrument to the telescope actuators in seeing limited and near diffraction limited observations. It does not detail the local, feedback loops around mechanical (position, force etc.) sensors. One major such a control loop is the primary mirror control system (M1CS) using edge sensor measurements to keep the mirror phased with 0.5 Hz bandwidth.

There is no compensation, i.e. closed optical loop correction, for pupil position, distortion, and plate scale variations. These characteristics of the system are controlled by the pointing and flexure models only.

**Adaptive Optics (AO)**

In adaptive optics operating mode the system delivers the image of the science object to the instrument with aberrations significantly reduced by means of adaptive optics compensation of atmospheric turbulence effects and residual telescope aberrations.

The AO performance requirements are qualitatively very different for each class of TMT configuration, and different AO system concepts (or "modes") are most suitable for each case. Although only MCAO is planned for first light of the observatory, the system architecture clearly anticipates future upgrades realizing a wide range of AO modes:

- The needs of near infra-red spectroscopy and imaging instruments (IRIS, IRMS, and later NIRES and WIRC) are well met by a multi-conjugate AO (***MCAO***) system that utilizes multiple laser guide stars (LGSs) and deformable mirrors (DMs) to measure and correct atmospheric turbulence in three dimensions, thereby providing near diffraction limited image quality over a field-of-view significantly larger than the conventional isoplanatic angle.
- The degree of atmospheric turbulence compensation required for observations in the mid-IR is comparatively modest, but system emissivity must be reduced by minimizing the number of warm surfaces in the optical path. This mandates a separate mid-IR AO (***MIRAO***) system in support of MIRES system configuration. The initial version of MIRAO would utilize a conventional 31 by 31 piezostack DM (on a tip/tilt stage) in a 3-mirror optical relay very similar to existing AO system designs. The MIRES configuration is not planned for first light.
- Ground-layer adaptive optics (***GLAO***), which estimates and corrects low-altitude atmospheric turbulence by averaging wavefront sensor measurement from multiple widely-spaced guide stars, is the preferred approach to enhancing atmospheric seeing (and thereby improving observational efficiency) for wide-field optical (and near-IR) spectroscopy, like WFOS. GLAO is not expected at first light.
- Because the 5 arcminute field specified for multi-object spectroscopy is too large to be corrected by a practical MCAO system, multi-object AO (***MOAO***) is proposed as a means of providing separate

wavefront corrections for multiple small scientific fields based upon a three-dimensional atmospheric turbulence estimate obtained using multiple laser guide stars. In principal, MOAO can be coupled to integral field unit (IFU) multi-object spectrographs like IRMOS, but the concept requires open-loop control of high-order MEMS wavefront correctors. Both IRMOS and the MOAO concept is considered too challenging for TMT first light.

- Finally, the AO requirements for very-high-contrast imaging and IFU spectroscopy will be addressed by an Extreme AO (***ExAO***) system combining very high-order atmospheric compensation, a nulling interferometer or similar diffraction suppression system, and an additional second-stage wavefront sensor used for detecting and correcting the systematic errors in the AO system that would otherwise introduce "superspeckles" and degrade the achievable contrast. The ExAO design concept is developed for the Planet Formation Instrument (PFI) that is not planned for TMT first light.

**Facility AO system**

The facility AO system is an MCAO system with two deformable mirrors conjugate to 0 km and 12 km, with 6 Na laser and up to three near-infrared natural guide stars used in closed loop. The early light realization of this facility AO system is the Narrow Field Infrared AO System (NFIRAOS). The MCAO capability provided for NFIRAOS enables its application in up to 2 arcminute field imaging (IRIS), and also improves sky coverage by compensating (or "sharpening") natural guide star images over a 2 arcminute technical field of view.

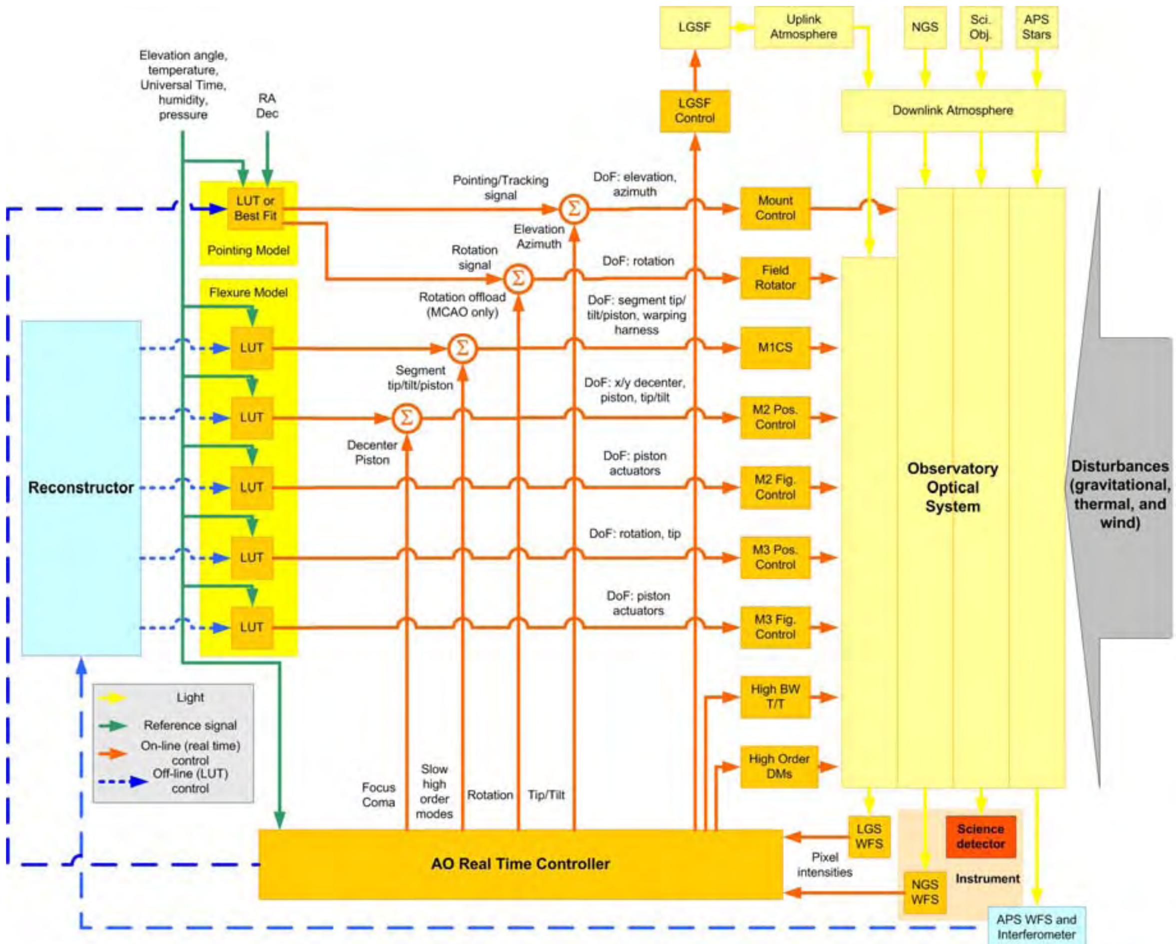


**Fig 7-9: Control architecture for adaptive optics observations. In seeing limited observations, the Laser Guide Star beam path, the high order deformable mirrors, and the high bandwidth tip/tilt stage are not operational; the AO RTC is replaced with a miniRTC.**

The early light implementation of NFIRAOS will provide an on-axis wavefront error of 187 nm RMS, and 191 nm RMS over a 10 arcsec FOV. The on-axis performance of a future NFIRAOS upgrade is estimated to be about 130-135 nm RMS, assuming that (i) the ground-layer, order 61 by 61 DM is replaced by a 121 by 121 mirror with a 2.5mm inter-actuator pitch, and (ii) advanced, pulsed laser systems are available to eliminate wavefront sensing errors associated with the nonzero thickness of the sodium layer. An adaptive secondary mirror (AM2) is also the preferred option for providing low-order, large amplitude wavefront corrections, since piezostack DMs have not yet demonstrated the required stroke with 2.5mm actuator spacing.

The facility AO system provides a high spatial resolution, slow "truth" NGS WFS to prevent long term drifts in the corrected wavefront due to variations in the sodium layer profile, WFS background noise due to Rayleigh backscatter, or other system calibration errors.

The adaptive optics system architecture is further detailed in **Section 8.5**.

### 7.3.2 Software architecture

The most important task for the TMT software system is the efficient execution of scientific observations. This is accomplished using the Observation Execution System (OES) that is in turn embedded in the higher level Program Execution System (PES) described in **Section 8.4**.

The major objectives for the OES architecture are: (i) support the control architecture outlined in **Section 7.3.1**; (ii) allow efficient observatory system configuration for scientific observations; and (iii) implement the capture, transport, and storage of all science and engineering data streams.

The distributed TMT control architecture leads to a similarly distributed software architecture, where individual software subsystems (components) are interconnected via a software communications backbone (connector). These software subsystems can be standalone software applications (e.g. AO Sequencer) or they can be the software component of an integrated software/hardware Level-2 subsystem (e.g. IRIS).

The software backbone is an aggregate of various communication channels corresponding to different command, configuration, or data transfer services as described in more detail in **Section 8.4**. The connections shown in **Fig. 7-10** correspond to one or more such channels.

For most night-time operations, the OES command-and-control architecture is hierarchical (see **Fig. 7-10**). The transition from one system configuration ("observational setup") to another results from a sequence of activities initiated and coordinated by the Observatory Control System (master sequencer) component of the Executive Software. This coordination is accomplished in concert with a set of lower tier sequencers. For a detailed example of one such lower tier sequencer, see the AO Sequencer discussion in **Section 8.5.2.3**. In a limited sense, the OES command-and-control architecture is dynamic – different hierarchical relationships are established logically for different observational setups. For example, **Fig. 7-10** shows the hierarchical relationship established to execute an IRIS observation using laser guide stars. The communication architecture that enables this dynamic control sequence is shown in **Fig. 8-46**.

For more details, see the Observatory Architecture Document (OAD) [7].

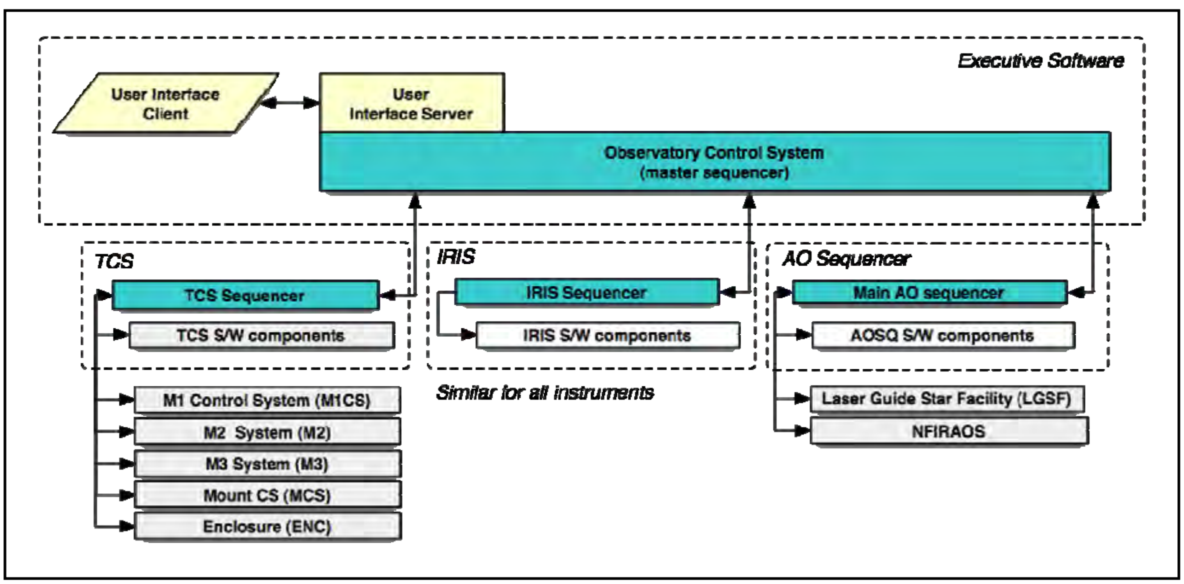


**Fig 7-10: OES command hierarchy (configured for IRIS with laser guide stars observation).**

### 7.3.3 Acquisition

Acquisition is the process of (i) locking the telescope to the sky (guide star acquisition), and (ii) establishing proper alignment of the science target with the instrument (science target acquisition).

Both guide star and science target acquisition is coordinated by the Observation Execution System, while the necessary sensors are the responsibility of the AO system, or for seeing limited observations, the instrument. There is no facility acquisition and guiding system. Nevertheless, there are standard procedures detailed below that all AO systems and instruments support.

Each system configuration (instrument-AO combination) provides reliable means for both guide star and science target acquisition by implementing one of the following two general procedures.

- For configurations with a guide WFS that has large enough field of view to accommodate telescope pointing repeatability (1 arcsec), the acquisition can be made in a single pointing step. Yet even in this case, it may be necessary to re-align the wavefront sensors relative to the instrument after the initial acquisition.

  Early light instruments choosing this option will provide provisions for dependable acquisition in the commissioning phase when the pointing precision of the telescope may not meet the requirement.

- For configurations where technically or financially it is not feasible to use a guide WFS with a sufficiently large FOV, the instrument provides an at least 20 arcsec acquisition camera. After acquiring the guide star on the camera, telescope blind offset places the guide star on the WFS.

  The acquisition camera has the same spectral sensitivity as the WFS to prevent long integration time and consequently a time consuming acquisition process.

To accommodate the second acquisition option, the telescope will be able to offset without optical feedback up to 1 arcmin with 50 mas repeatability (1 sigma). It is understood that this high precision offset is meaningful only with high order (laser guide star) adaptive optics corrections reducing image blur to the level commensurate to the FOV of the WFS. It is also understood that this offset requirement includes a blind tracking component due to the finite time of the offset operation.

Although the WFS pick-off positions are intended to be set to ensure appropriate target positioning on the science detector or slit, it may be necessary to test and correct this condition with collecting and analyzing actual science data.

## *7.4 Optical Error Budgets*

### 7.4.1 Overview

The ultimate image performance metric TMT adopted is the long exposure Point Spread Function (PSF). However, it is a two dimensional function that is hard to visualize and compare. Although the actual spatial distribution of energy described by the PSF is important for some applications, like adaptive optics or high contrast imaging, for most applications a single-number metric, the diameter encircling a given portion of the total light energy is adequate. The usual encircled energy metric is the diameter encircling 80% of the energy ($D_{80}$, $\theta(80)$, 80% encircled energy, EE80).

Besides the encircled energy diameter, another single number measure of image quality with widespread use is the RMS exit pupil wavefront aberration (optical path difference). TMT is using this measure to characterize optical performance in the context of adaptive optics, as it is more appropriate for wavefront errors considerably smaller than the observing wavelength.

The observatory performance is the function of various disturbance effects and processes:

- Deterministic, constant effects, like
    - Residual errors of the optical design
    - Aperture diffraction
    - Pupil obscuration diffraction
- Deterministic effects randomized by environmental and operational parameters, like
    - Gravitational print through of the axial and lateral mirror support structure
    - In-plane segment displacement due to gravity
    - Thermal deformation of optical surfaces and support structures
- Random processes, like

- o Wind buffeting
- o Local (dome and mirror) seeing
- o Actuator and sensor noise and drift, including atmospheric background on guide and aO WFSs
- o Random component and material imperfections, like polishing errors, coefficient of thermal expansion (CTE) variations, etc.

It is reasonable to assume that disturbances in the first three and last two groups (constant effects, noise, and imperfections) are statistically independent of each other and the rest of the disturbances. On the other hand, there are strong couplings that exist among the other effects:

- Gravitational print through and in-plane segment displacement are strong functions of elevation angle, as are wind buffeting and local seeing;
- Thermal deformation is a strong function of optical surface and support structure temperatures, as is local seeing;
- Wind buffeting is a strong function of external wind velocity, as is local seeing; actually these effects can be traded against each other, as at high wind speeds wind buffeting dominates, while at low wind the non-isothermal turbulence above the primary mirror is the principal seeing contributor.

For top-down error budgeting purposes these couplings are neglected in the rest of this section. However, the joint performance degradation effects are estimated from bottom up in the next section (**7.5 )**.

### 7.4.2 Image size budget for seeing limited observations

**On-axis budget**
The following error budget provides image jitter and image blur allocations for on-axis images of the zenith pointing telescope, not including the instrument. It also does not include image rotators and atmospheric dispersion compensators, as these functions are allocated to the instrument.

The image size error budget is detailed in [11].

**Off-axis budget**
The image blur of a Ritchey-Chretien optical design increases with field angle due to field dependent astigmatism inherent to the design. The corresponding 80% encircled energy diameter is a quadratic function of the field angle, resulting in 0.507 arcsec blur at 10 arcmin.

When the optical design error is added in quadrature to the on-axis error allocation, the resultant error is 0.560 arcsec at the edge of the FOV. An additional 7% increase is budgeted in the form of field dependent errors. This additional allowance is 0.220 arcsec at the edge of the field, leading to a total 80% encircled energy diameter of 0.6 arcsec at 10 arcmin.

**Elevation angle dependence of the budget**
The overall error budget is allowed to degrade the same way as the atmospheric seeing does, i.e. $D_{80} \propto (\sec z)^{3/5}$. From 0 to 65 degrees zenith angle the 80% encircled energy diameter increases with a factor of 1.68, resulting in 0.398 arcsec on-axis and 0.720 arcsec at the edge of the FOV.

### 7.4.3 Facility AO system (NFIRAOS) wavefront error budget

The RMS wavefront error budget in **Table 7-3** defines the error allocation at the center of the AO corrected field. At 10 arcsec field the performance is slightly worse, 191 nm RMS. The achieved Strehl ratio is shown in **Fig. 7-11**, as a function of wavelength.

**Table 7-2: $D_{80}$ on-axis image jitter and blur budget in mas for zenith pointing telescope, at 0.5 µm wavelength.**

| | | | | | |
|---|---|---|---|---|---|
| System (up to the Nasmyth focus) | | | | | 237 |
| Dome seeing | | | | 50 | |
| Mirror Seeing | | | | 50 | |
| Telescope | | | | 227 | |
| Optical design | | | 6 | | |
| Optical surface shapes | | | 216 | | |
| M1 shape | | 202 | | | |
| Segment figuring | 174 | | | | |
| Segment thermal distortion | 65 | | | | |
| Segment support print-through | 41 | | | | |
| Segment alignment – in-plane | 27 | | | | |
| Segment alignment – out-of-plane | 60 | | | | |
| Segment alignment – dynamic | 22 | | | | |
| M2 shape | | 66 | | | |
| Figuring | 53 | | | | |
| Thermal distortion | 1 | | | | |
| Support print-through | 38 | | | | |
| Shape alignment | 10 | | | | |
| Shape alignment – dynamic | 0 | | | | |
| M3 shape | | 37 | | | |
| Figuring | 20 | | | | |
| Thermal distortion | 0 | | | | |
| Support print-through | 29 | | | | |
| Shape alignment | 10 | | | | |
| Shape alignment – dynamic | 0 | | | | |
| Optical alignment – image jitter | | | 61 | | |
| M1 (relative to the sky) | | 43 | | | |
| M2 (relative to M1) | | 37 | | | |
| M3 (relative to M1) | | 5 | | | |
| Instrument (relative to M1) | | 23 | | | |
| Optical alignment – image blur | | | 34 | | |
| M2 (relative to M1) | | 27 | | | |
| M3 (relative to M1) | | 16 | | | |
| Instrument (relative to M1) | | 10 | | | |

**Table 7-3: NFIRAOS on axis RMS wavefront error budget in nm (60 x 60 actuators).**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delivered wavefront | | | | | | | 187 |
| | Higher order | | | | | 167 | |
| | | Fundamental AO | | | 130 | | |
| | | Implementation | | | 89 | | |
| | | Residual telescope | | | 45 | | |
| | | | M1 shape | 40 | | | |
| | | | M2 shape | 19 | | | |
| | | | M3 shape | 10 | | | |
| | | Residual instrument | | | 30 | | |
| | | Residual dome seeing | | | 13 | | |
| | | Residual mirror seeing | | | 13 | | |
| | Tip/tilt | | | | | 85 | |
| | | Residual telescope vibration | | | 34 | | |
| | | Servo lag | | | 20 | | |
| | | Tilt anisoplanatism | | | 52 | | |
| | | NGS WFS noise | | | 60 | | |

### 7.4.4 Pointing error budget

The pointing error budget allocates repeatability errors to the alignment tolerances of the various optical elements. Although the pointing accuracy of the telescope is an absolute measure, it is achieved by intermittent calibration of the pointing system, i.e. building a pointing model. Consequently, the pointing accuracy depends only on the repeatability of the calibration settings and measurements.

For this error budget, repeatability is measured as the standard deviation (1 $\sigma$) of the pointing on the sky, in arcsec. The pointing error is defined in two dimensions, i.e. we assume statistically independent azimuth and elevation errors.

Pointing error is measured on the APS. Instruments and AO systems in different positions on the Nasmyth platform may experience slightly different pointing errors, depending on the stability and accuracy of the relative positioning of the instrument and calibration camera.

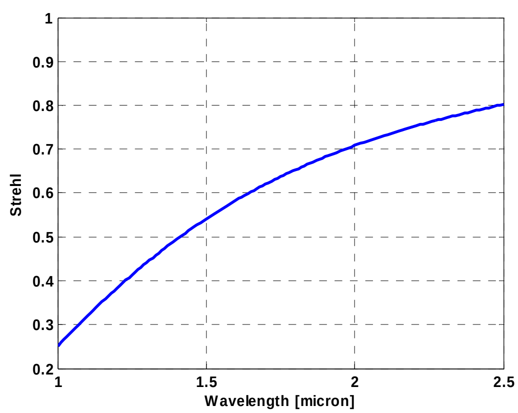


**Fig 7-11: NFIRAOS Strehl ratio as a function of wavelength.**

### 7.4.5 Pupil alignment budget

The system pupil misalignment is defined as the misalignment of the primary mirror (entrance pupil) image delivered to an instrument. Further possible pupil shifts introduced by the misalignment of the instrument are not considered here.

**Table 7-4: Telescope pointing error budget in arcsec.**

| | | | |
|---|---|---|---|
| Telescope | | | 1.00 |
| | Residual astrometry | 0.2 | |
| | Mount (encoder) | 0.5 | |
| | Mount/M1 (alignment of elevation/azimuth axes, M1 tip/tilt) | 0.5 | |
| | M2 alignment (relative to M1) | 0.6 | |
| | M3 alignment (relative to M1) | 0.4 | |
| | Pointing camera location (relative to M1) | 0.2 | |

**Table 7-5: RMS Pupil alignment error budget in % of pupil diameter.**

| | | | | | |
|---|---|---|---|---|---|
| Observatory | | | | | 0.1 |
| | Telescope | | | 0.065 | |
| | | Mount | 0.000 | | |
| | | M1 alignment (relative to mount) | 0.001 | | |
| | | M2 alignment (relative to M1) | 0.026 | | |
| | | M3 alignment (relative to M1) | 0.0060 | | |
| | Instrument alignment (relative to M1) | | | 0.074 | |

## *7.5 Performance Estimates*

This section focuses on performance estimates for seeing limited observations. The results of extensive adaptive optics simulations are summarized in **Section 8.5.2.1**.

Performance estimation, i.e. modeling, provides validation of the top-down error budget. It can verify the sensitivities assumed in the top-down budget for the statistically independent disturbances and imperfections. It can also validate the budget by proving, with joint simulations of potentially coupled processes, that if individual subsystems meet their error allocations then the entire system will meet its overall requirement.

System performance is a function of the operating point, i.e. the set of default system design parameters. In most cases it is hard to partition the system performance into various “buckets” corresponding to the different parameters, because of the statistical and spatial interdependence of the related aberrations. Nevertheless, it is still possible to trade parameter values against each other by calculating the sensitivities of the performance to these parameter changes around the operating point.

The performance of the system is best characterized by probability distributions of the encircled energy diameter, instead of its mean and variance only. Besides establishing the percentage of time the system meets the requirements, the probability distribution provides a measure of how “gracefully” the performance degrades beyond the optimal region. Better understanding of the performance distribution can tailor science expectations about the observatory and support the validation of the fundamental science cases.

For steady state, the probability distributions could be generated by Monte-Carlo simulation or occasionally even by analytically combining the various processes. Unfortunately, some major factors of local seeing, like mirror glass temperatures are changing rather slowly compared to the speed of parameter changes. Consequently the system is always in transient state. It means the system has memory, i.e. both its instantaneous and time averaged performance depends on its history.

Instead of the regular Monte-Carlo method, we use long term time histories of the system and its environment to estimate local seeing probability distributions [12]. A “standard year” was developed that includes 2 minute temporal resolution time histories of

- external mean wind speed and direction
- external air temperature
- telescope pointing (elevation and azimuth angles) during observations

It is obvious that the combination of these parameters can be optimized in various ways, i.e. various observing models can be emulated. While a relatively simple optimization, like picking the optimal mirror temperature for beginning of the night, needs to be implemented to carry out the calculations and reach preliminary results, the framework allows future exploration of more sophisticated methods potentially involving even atmospheric seeing.

Using probability distributions for performance estimates requires an error budget expressed also as probability distributions, instead of just in RMS values. By creating an error budget time record using the zenith angle record in the "standard year", the various budget terms can be extended into the required distributions. In the following sections, the performance of the system is compared to these distributions.

The probability distributions were calculated by adding in quadrature the various error components for every 2 minute interval and then extracting stochastic characteristics of the error time histories. Conditional distributions can also be computed, where parameters are kept constant as a condition. These distributions are useful to understand the dependence of performance on these parameters, like zenith angle or external wind velocity.

The following sections assess the largest correlated effects: primary mirror print through, wind buffeting, and local (dome and mirror) seeing. The plan is to extend modeling in the future to include: solid thermal effects, polishing errors, M2 and M3 print through, and the active optics shape control loops.

### 7.5.1 Gravitational effects

Zenith angle dependent gravitational effects have significant impact on the shape of the optical surfaces and consequently on the image quality of the telescope. The most pronounced effect is expected to be the print through of the segment whiffletree and lateral support system. The high spatial frequency nature of these wavefront errors makes it practically impossible to correct them either with the active or the adaptive optics systems.

The error budget allocation for M1 segment print through is 25 mas for the zenith pointing telescope. However, the error is expected to increase significantly as the telescope moves towards the horizon, resulting in 125 mas $D_{80}$ at 65 degree zenith angle**.**

To assess segment print through effects, rigid body and surface perturbations were combined with a full optical simulation of the M1-M2-M3 system using the Modeling and Analysis for Controlled Optical Systems (MACOS) software, JPL's in-house optical modeling tool [13]. This tool provides the capability to model the TMT primary mirror as a segmented surface and to quantify structural, gravitational, and thermal effects. The OPD over the exit pupil is calculated using sequential ray-tracing in order to develop the metrics of RMS and Peak-Valley wavefront statistics, the PSF, and enclosed energy curves

A model of the segment whiffletree print through was applied to each segment. This print through data was computed in a finite element model under different gravity conditions [14]. While correcting gravity sag, the whiffletrees introduce higher-order aberrations in the segments, which increase in magnitude as the telescope moves from zenith to horizon

Several assumptions were made in this initial simulation [15]. It is assumed that the segments are perfectly polished when the telescope is at zenith. All segments were modeled to be of identical size. The actual M1 segments will be of slightly different shape because of the varying asphericity of the mirror. These differences are on the order of 1-10 mm, however; since the smallest resolution element in the current simulation is ~1.5 cm it would not be possible to properly resolve these differences. Therefore the current model uses a uniform segment size of 1.432 m (corner to corner). In addition, the M1 is currently modeled to be flat for the purposes of gravity-induced print through. This does not affect the radius of curvature of the mirror in the optical model, but does allow for a simplified calculation of a particular segment's gravity vector orientation. Thus when the telescope points at zenith the gravity vector is straight down and normal to all of the segment surfaces. These results used a non-obscured aperture except for the deletion of the 7 inner segments

The pertinent metrics (RMS and P-V wavefront error, and 80% enclosed energy diameter) were calculated for the surface print-through over a range of telescope angles. At zenith the wavefront error is zero and the resulting 80% enclosed energy diameter because of diffraction effects is 8 mas at 500 nm. At a 65° zenith angle, this error grows to 26 mas. **Fig. 7-12** indicates the performance of the current design compared to the error budget and shows the enclosed energy values as a function of zenith angle. Both the error budget and telescope performance were calculated using the same standard year

The tool developed for this task will be used for further performance validation of errors due to segment polishing, thermal expansion, misalignments, and phasing measurement errors.

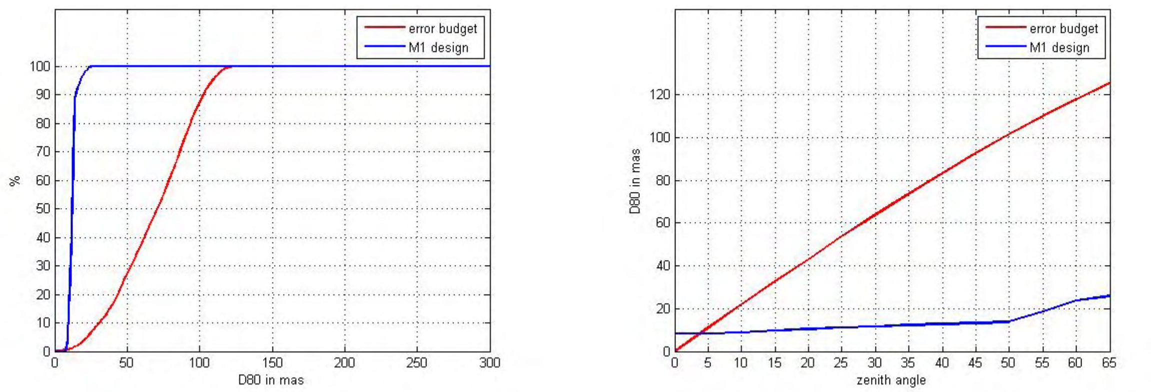


**Fig 7-12: Cumulative probability distribution of gravity induced segment shape aberrations (left) and the zenith angle dependence of these aberrations (right).**

### 7.5.2 Wind buffeting

Wind loads on the telescope structure are the largest dynamic forces that must be mitigated. The enclosure is designed to shield the telescope from external winds and will reduce the wind speed at M2 to 25% of the external wind speed for upwind orientations. Wind loads are further reduced by minimizing the cross-sectional area of M2 and the upper telescope structure (in contrast to a spider-supported secondary). However, some air flow through the dome is essential to minimize dome and mirror seeing caused by thermal variations. This flow is achieved through venting, with the vent area controlled as a function of external wind speed and orientation to maintain a target wind speed of 1.5 m/s on M1. For low to moderate external wind speeds, the resulting wind loads on M1 are expected to dominate the telescope response to wind.

Residual wind buffeting after guiding and aO corrections is captured in various error budget entries. Altogether 38 mas $D_{80}$ error is allocated to wind induced image degradation for zenith pointing telescope. However, it may increase with increasing zenith angle, z, as the overall error budget, i.e with the factor of $\left[\cos(z)\right]^{-3/5}$.

Dynamic integrated modeling [16] provides the probability distribution of wind induced optical aberrations as shown in **Fig. 7-13**. While the observatory meets the error budget allocation to wind induced image degradation 62% of the time, the median image size due to wind buffeting is below the error budget for all elevation angles.

The model includes predicted wind loads as specified in [17], the structural model (including soil and pier), linear optical model, and all relevant feedback control loops including guiding. Most of the response at all external wind speeds is image motion caused by the finite bandwidth of the elevation control system, and the performance is thus most sensitive to the elevation control bandwidth. The achievable control bandwidth is limited by the telescope structural dynamics. The first structural resonance (with drive loops open, not locked) at 2.2 Hz is phase-stabilized, and the elevation control bandwidth of 1.3 Hz (loop crossover) is limited by a second dominant structural mode at 5.5 Hz. The azimuth bandwidth is less important for performance and is limited by a structural mode at 4.9 Hz.

For median wind conditions, the wind loads on M1 are the most significant contributor to the response and the response is thus weakly dependent on orientation or external wind speed. At high external wind speeds (above the 75$^{th}$ percentile), the forces on M2 result in much higher image degradation. At low external wind speeds (below the 30$^{th}$ percentile), the desired venting of M1 is not achievable and the response to wind loads is small (although the resulting dome/mirror seeing will be worse).

The image degradation at high wind speeds can be mitigated through observing strategy (pointing downwind during extreme high winds).

Changing the enclosure size (M2 shielding) will affect the wind response at high external wind speeds. Changing the desired wind speed on M1 will affect the median wind response. Changing the elevation axis control bandwidth in particular will affect the entire response curve; changes in structural damping or structural design that affect the achievable bandwidth are thus significant.

Most of the image motion and image blur due to wind loads can be compensated by the adaptive optics system with the exception of high wavenumber segment edge discontinuities on the primary mirror. The rms edge discontinuity depends on high wavenumber details of the flow field that are difficult to predict but can be bounded. Maintaining an M1 control bandwidth of 0.5 Hz or greater is expected to be sufficient to provide adequate telescope performance for AO operations.

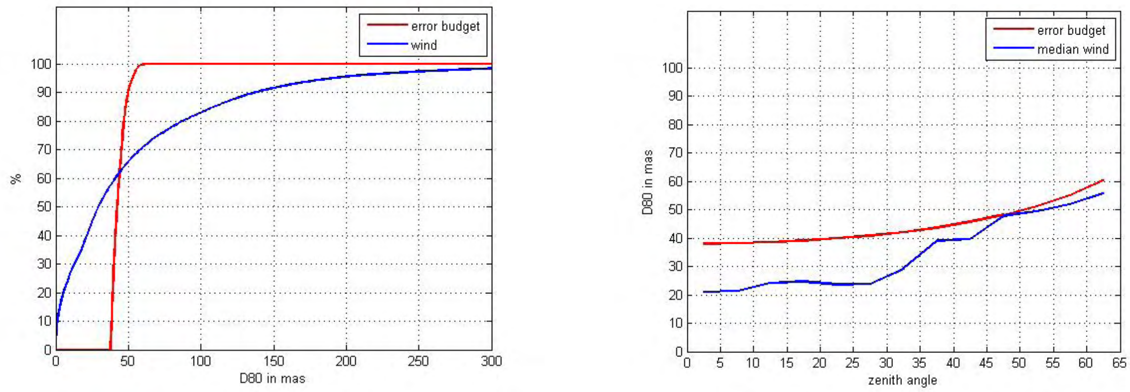


**Fig 7-13: Cumulative probability distribution of wind induced dynamic aberrations (left) and median wind induced image degradation as a function of zenith angle (right).**

### 7.5.3 Local seeing

The image degradation caused by the temperature difference between the optical surface and the ambient air is called mirror seeing, while image degradation due to non-isothermal air turbulence inside the enclosure and in front of the observing opening is known as dome seeing. Due to the geometry, mirror seeing is dominated by the primary mirror, where the segment thermal inertia results in a mirror time constant large enough not to allow the optical surface to follow the ambient air temperature changes.

Most of the heat generated in the back of the primary mirror (actuators, electronics boxes) is dissipated into the segments increasing their temperature. Although the design of the support assembly should control the magnitude and direction of the heat flux, and thin primary mirror segments with high conductivity further reduce the time constant minimizing the thermal gradient, the most effective way of mitigating mirror seeing is heat convection to the ambient air flowing above the optical surface through vents on the enclosure.

The enclosure creates a rather quiescent environment for the telescope, where the air may be trapped and can develop thermal gradients due to heat sources such as instruments and drives, as well as the telescope structure and enclosure walls, which do not follow the ambient air temperature. Moreover, turbulence in the optical path, caused by flow over the exterior of the enclosure and the aperture, may further degrade the image quality. The TMT enclosure and facilities building are designed to minimize this exterior turbulence

Dome and mirror seeing together account for 71 mas $D_{80}$ diameter in the error budget (50 mas for each term) at zenith. The zenith angle (z) dependence factor is $\left[\cos(z)\right]^{-3/5}$

The methodology behind the thermal seeing models is presented in [17]. For the mirror seeing model a target wind velocity on the primary mirror of 1.5 m/s was chosen, consistent with the wind buffeting model and operating venting strategy described in the previous section. This happens to be the velocity required to maintain forced convection above a 30m surface. The increase of image jitter above 1.5 m/s target velocity overshadows the decrease in mirror seeing, which is why we cannot select 2 m/s. The mirror temperature at sunset is chosen so that the average seeing throughout the night is optimized. This assumes that the long-time-scale ambient temperature behavior for a given night can be known well before sunset in order to precondition the mirror. If a fixed temperature not based on weather forecast is chosen (for instance that of the previous midnight), the median expected mirror seeing will increase by several tens of mas. The net heat flux into the back of the mirror was chosen to be 2 W/m$^2$, based on the expected convective heat transfer rates and radiation control. For the dome seeing simulations a net heat transfer rate of 5 W/m$^2$ was chosen for the enclosure surfaces, since they will radiate to the cold night sky. For both models the wind velocities inside the enclosure were provided by the same Computational Fluid Dynamics simulations used in the wind buffeting model.

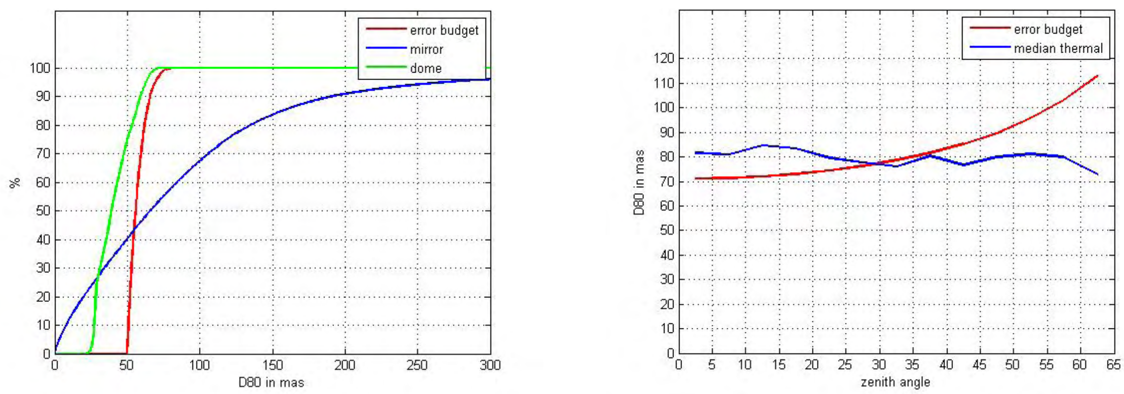


**Fig 7-14: Cumulative probability distributions for mirror and dome seeing (left) and combined median thermal seeing as a function of zenith angle (right).**

The resulting probability distributions for mirror and dome seeing are shown in **Fig. 7-14**. Dome seeing exhibits a minimum around 30$^o$ – 35$^o$ zenith angle [18]. It also exhibits a maximum at 0$^o$ azimuth relative to wind, due to the higher turbulence and temperature gradients in the vicinity of the aperture. It is expected to meet the error budget 100% of the time, as long as air exchange is provided. Mirror seeing is greatly influenced by the temporal temperature gradients during the night. It is inversely proportional to velocity at low wind speeds and thus deviates significantly from the $\left[\cos(z)\right]^{-3/5}$ rule. But even at higher speeds, it increases when telescope azimuth angles relative to wind direction are higher than 90$^o$, since most of the time the front side of the mirror is in the mirror cell wake, thus negating the good dome seeing behavior. This results in a rather flat behavior of the overall thermal seeing with zenith angle, as shown in **Fig. 7-14**. The somewhat higher values at low zenith angles are biased by the low end of wind speeds, since natural mirror seeing is worse when the mirror is facing up. The mirror seeing is currently expected to meet its error budget 43% of the time.

### 7.5.4 Overall performance evaluation

In order to assess the performance of the entire system, the effects of different disturbances need to be combined [19]. For effects not simulated yet, the combined model uses their error budget values and expected zenith dependencies.

The cumulative probability distribution of the overall image size is shown in **Fig. 7-15**. The observatory meets the image size error budget 83% of the observing time, which is better than the required 50%. The graph on the right of the same figure indicates the zenith angle dependence of the overall image size. For zenith angles larger than 18 degrees, the error budget is met more than 50% of the time, while below that angle the probability of achieving the required performance is slightly less.

The dominant part of the error budget, approximately 217 mas is expected to be independent of telescope zenith angle, including thermal effects, alignment errors, material and fabrication imperfections, actuator and sensor noise, as well as equipment vibrations. The RSS of the zenith angle dependent terms is only 96 mas. To some extent the zenith independent terms act as a “buffer” in compensating for irregular dependencies and slight, localized budget overruns.

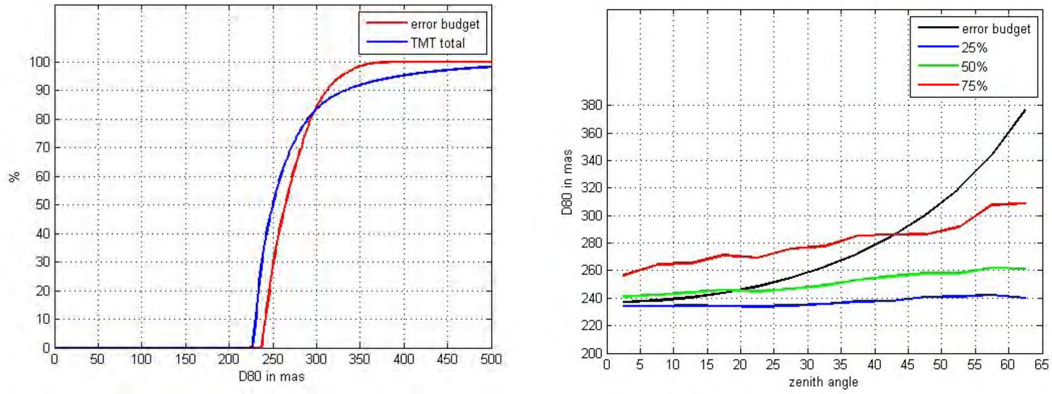


**Fig 7-15: Cumulative probability distribution for overall image size (left) and zenith angle dependence of the 25, 50, and 75 percentile image size (right).**

[Fig. 7-16](#) visualizes the trade between local seeing and wind buffeting. In a substantial range of external mean wind velocity, from 2.8 m/s to 7 m/s, the median wind and thermal seeing errors meet their combined allocation. At low wind speeds local thermal seeing dominates, while at high wind speeds wind buffeting increases the image size, mostly through image jitter. All the simulations reported assume at least ~7.5% venting even at high wind speeds to limit dome seeing and eliminate shear layer acoustic resonances in the enclosure.

[Fig. 7-17](#) shows the conditional probability density of the image size as a function of the zenith angle. The integral below the error budget curve accounts for 83% of the total integral of the density function, indicating the fraction of time the system meets the error budget requirement. The contour plot also reflects the probability density distribution of observing zenith angles, which are 60% of the time between 20 and 45 degrees.

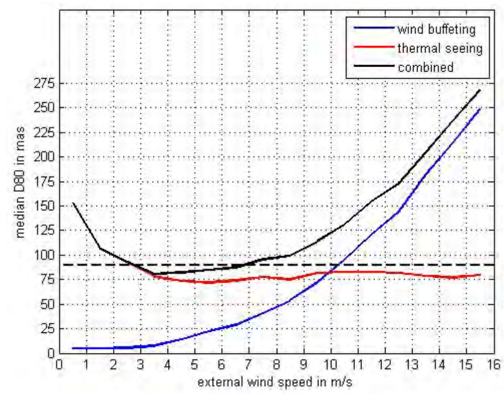


**Fig 7-16: Median wind induced image degradation and local thermal seeing as functions of the external mean wind velocity estimate.**

## 7.6 Reliability and Availability Budget

Reliability must be "designed in" to the TMT. During system design, the top-level reliability requirements are allocated to subsystems by design engineers and system engineers working together. The goal is to minimize lost time due to failures and maintenance, both planned and unplanned. A more detailed approach to reliability is in the TMT Observatory Reliability and Availability Budget [20].

As prescribed in the Operations Concept Document (OCD) [21], the unscheduled technical downtime cannot exceed 3% of the time scheduled for science operations. However, an instrument or AO failure does not necessarily count as downtime, as long the scheduled observer's planned instrument is available (see [Fig. 7-18](#)). For the early light instrument suite, this plan results in manageable downtime allocations for WFOS, the Laser Guide Star Facility, and NFIRAOS, while the overall downtime meets the OCD requirement.

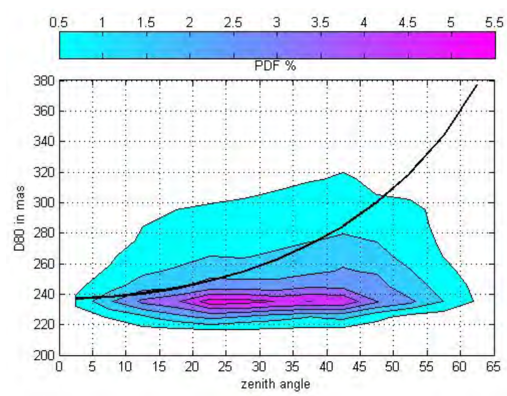


**Fig 7-17: $D_{80}$ conditional probability density function as a contour plot, compared to the zenith dependent error budget.**

**Table 7-6** shows the high level top-down partitioning of 3% technical downtime for the observatory, based on scheduled science time of 3000 hours per year. The arithmetic to combine downtime for critical and redundant subsystems is described in [20]. This budget is a function of Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) values estimated for the individual subsystems. The numbers are for random failures and (i) exclude "infant mortality," weeded out by burning-in components before installation, and (ii) assume proper maintenance, i.e. exclude "end of life" wear out effects. The project is in the process of verifying the allocations shown, through the evaluation of both MTBF and MTTR values. For example, based on segment actuator MTBF from Keck service data, actuator downtime fits comfortably in the share for Telescope control.

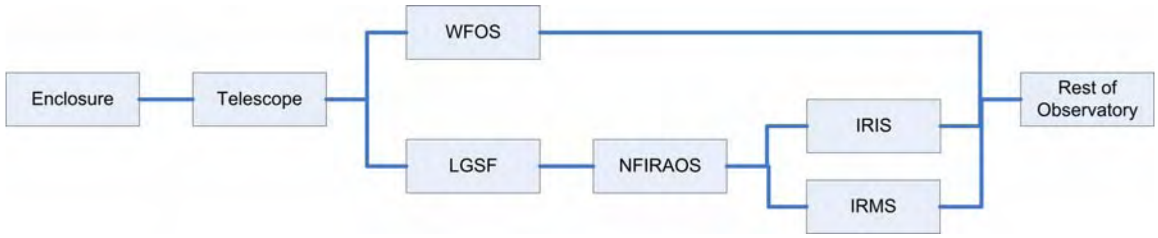


**Fig 7-18: Reliability block diagram of the observatory.**

**Table 7-6: Observatory top-down 3% unscheduled downtime budget.**

| Subsystem groups | Allocation [%] |
|---|---|
| Enclosure | 0.17 |
| Facilities | 0.02 |
| Telescope structure | 0.02 |
| Telescope optics (M1, M2, M3) | 0.13 |
| Telescope control and actuators, drives, encoders | 0.81 |
| Alignment and Phasing System (APS) | 0.17 |
| Telescope safety, sensors, power | 0.08 |
| AO, NFIRAOS, Laser Guide Star Facility | 1.00 |
| Scheduled Instrument | 0.5 |
| Observation Execution software | 0.15 |

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# 8 Observatory Description

In this chapter, we look in detail at the design of the Observatory. For each subsystem we present the requirements, the design description and options, function and component parts, the development tasks that are planned, and the work plan for implementation. The description begins with the facilities and enclosure, and includes the telescope, its structure, mirrors, controls, optics alignment and phasing, and optics installation and maintenance equipment. The chapter also covers observatory software, the early light adaptive optics, early light science instruments, and instrument development plans.

## *8.1 Summit and support facilities*

### 8.1.1 Overview

The Summit and Support Facilities are the infrastructure at and nearby the site that are required to operate TMT. Based on Cerro Armazones as the reference site, these facilities include (1) an access road to the site from a publicly maintained road, (2) the facilities at the summit, (3) support facilities near the base of the mountain, and (4) a construction camp, also at the base of the mountain, to provide boarding and lodging for contractor personnel during construction.

Also included in the Summit and Support Facilities are (1) the earthwork at the summit to provide the level platform for the enclosure, telescope and summit buildings, as well as the excavation for the facility foundations, utility trenches and other below-ground components, (2) the fixed base for the enclosure, (3) the telescope pier, and (4) utilities. The rotating enclosure is discussed separately in **Section 8.2** and the telescope is discussed in **Section 8.3**.

### 8.1.2 Requirements

The overarching requirements for the Summit and Support Facilities are to "provide adequate infrastructure for operations, including utilities, operational environment, and boarding, lodging [ORD]." More specific requirements for the Summit Facilities are derived from the telescope requirements for a range of items including the mirror storage, stripping and coating areas; and from the operations model for the control room, offices, laboratory and supporting areas; and from requirements for utilities from the telescope, instruments, rotating enclosure and other parts of the Summit Facility itself. The requirements for the Support Facilities are derived from the operations model and from requirements for utilities for the Summit Facilities and the Support Facilities themselves.

### 8.1.3 Conceptual Design Description and Options

#### 8.1.3.1 Access Road

A new 17 km access road will be constructed between the existing Paposo road and the TMT facilities at Cerro Armazones using the approximate route shown in **Fig. 8-1**. The new alignment will: (1) reduce the travel distance between Antofagasta and Armazones by approximately 20 km, (2) provide a driving surface wide enough for two vehicles to meet or pass without either vehicle to have to pull off the road, (3) provide a surface and alignment that will safely allow reasonable driving speeds, and (4) allow for future asphalt paving of the road surface.

A new road alignment will be constructed from the base of Armazones to the summit. The new alignment will be designed so that (1) there are no switchbacks and tight turns and (2) the grade does not exceed ten percent. The first kilometer of the road, starting from the summit, will be paved with asphalt for dust control.

#### 8.1.3.2 Construction Camp

A construction camp to provide the full boarding and lodging needs of contractors and TMT personnel will be provided nearby the location of the Support Facilities. This facility is needed due to the travel distance otherwise required for a daily commute back to Antofagasta and the need to minimize the impact on the desert environment that would result from each contractor constructing its own facility in separate locations.

The construction camp will be refurbished and kept in operating condition after the completion of the TMT facilities to provide overflow capacity for the accommodations facilities.

#### 8.1.3.3 Earthwork and Foundation Excavation

The summit of Cerro Armazones will be reduced from its current altitude at its high point of 3064 m to a level platform with an elevation of approximately 3052 m. The final elevation will depend on (1) the required footprint of the final design, (2) access for cranes and other equipment for the erection of the enclosure, and (3) the quality of the soil and rock. The estimated volume of material to be removed to provide the platform at 3052 m is approximately 72,000 cubic meters. A conceptual layout of the summit facility is shown in **Fig. 7-8**.

The earthwork will also include excavations on the summit for foundations, utility tunnels, and utility trenches.

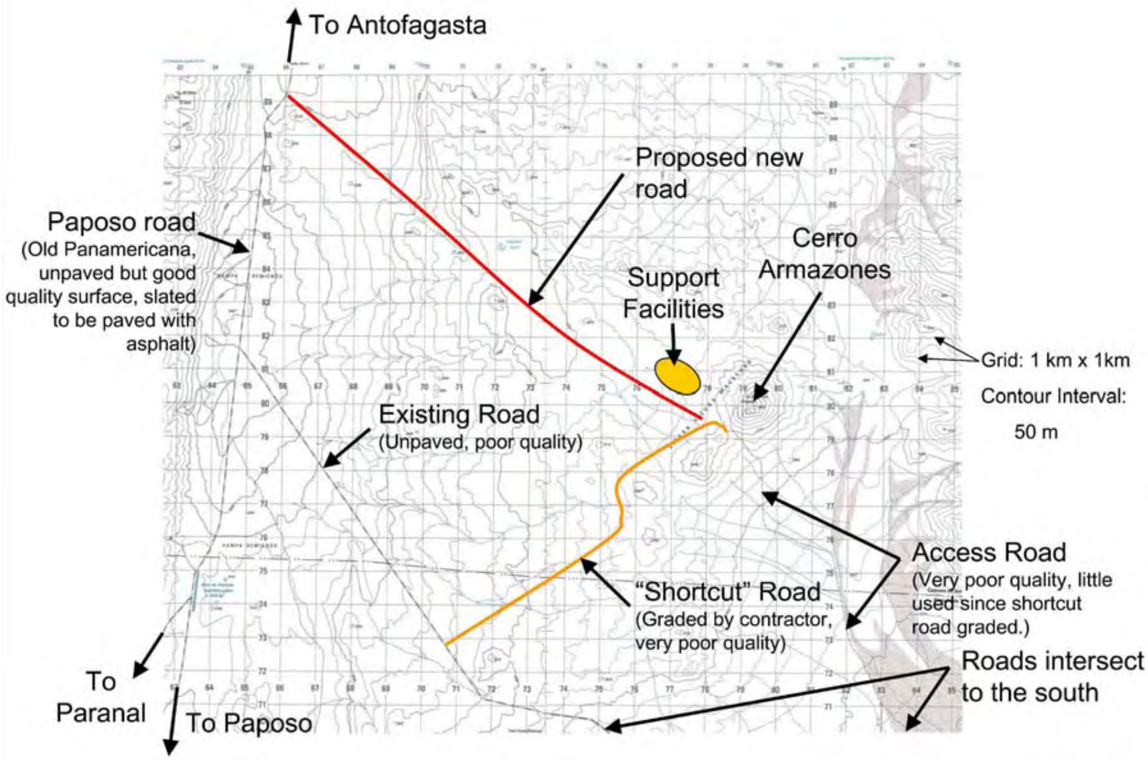



**Fig 8-1: Location of proposed new access road.**

#### 8.1.3.4 Telescope Pier

The concrete telescope pier will be constructed as a part of the foundation concrete work at the same time as the enclosure fixed base construction.

#### 8.1.3.5 Enclosure Fixed Base

The enclosure fixed base is the lower portion of the enclosure, and includes the utility tunnel to the cable wrap in the interior of the telescope pier, and provisions for power, signal, chilled water and other utilities required to operate the telescope, rotating enclosure, and the fixed base itself. The rotating enclosure is described in **Section 8.2**, with the interface between the fixed and rotating enclosure at the fixed base azimuth girder.

#### 8.1.3.6 Main summit facilities

The main summit facilities include the control room; computer room; conference room; office space; hydrostatic bearing equipment; electrical room; mirror stripping, coating and storage facilities; engineering and mechanical shops; safety equipment room and support services. A conceptual floor plan for the main summit facilities, with a table of room areas, is shown in **Fig. 8-2**.

#### 8.1.3.7 Utilities facilities

A separate utility building is located on the summit to house utilities that generate heat or vibrations. The utility building is physically separated from the main facilities to minimize the transfer of the vibrations to the telescope or heat plumes in the vicinity of the telescope. Equipment to be located in this facility includes the chillers, chilled water pumps, compressors, and main electrical switchgear.

#### 8.1.3.8 Support Facilities

The Support Facilities are located near the base of Cerro Armazones, and provide the services that are needed at the site, but do not need to be located on the summit. A conceptual layout of the Support Facilities using a campus-style arrangement is shown in **Fig. 8.3**. The Support Facilities are divided into four groups:

- Administrative, Laboratory and Shops. This facility includes offices, conference rooms, a lecture hall, mechanical shop, engineering laboratory, shipping and receiving, emergency vehicle garage, safety equipment room, lounge, kitchenette, and administrative area.
- Maintenance, Utility and Warehouse. This facility contains the electrical generation equipment, electrical distribution equipment, mechanical equipment for the support facilities, electrical shop, welding shop, mechanical shop, and a warehouse. This facility also includes a utility yard for water storage, chillers, fuel storage, and other equipment that does not need to be located within a building. An open storage yard and lay-down zone will also be located in this area.
- Dining Facilities. The dining facilities include a dining hall with seating for 60 people, a kitchen with the capacity to prepare and serve two seatings of 60 people, and the storage facilities in support of the kitchen.
- Accommodations. The accommodations consist of single-occupancy motel-style bedrooms with private bathrooms for 74 people. Each room is provided with a desk and internet access so that a person can work from the room. An accommodations support facility houses the logistical, mechanical and electrical services for the motel rooms and common areas such as personal laundry room, kitchenette, game and TV rooms.

### 8.1.4 Development Tasks

The Summit and Support Facilities are comprised of buildings, utilities, and civil work that are within common design methods and materials for this type of work, and do not require special development work.

### 8.1.5 Work Plan

#### 8.1.5.1 Road Construction

The road construction will start on the portion of the road from the base of Armazones to the summit. This portion of the road is required at the start of earthwork so that the heavy equipment required for the excavation of the summit can operate on this portion of the road. The remainder of the road, from the base of Armazones to the Paposo road, is not critical, as construction equipment can readily access the site using the existing, although poor quality, shortcut road.

#### 8.1.5.2 Construction Camp

The construction camp installation is the first part of construction to begin, as this facility will be required for construction personnel working on site. The road construction can start concurrent with the installation of the construction camp, with the road contractor either providing its own temporary construction camp, or commuting daily to Antofagasta.

#### 8.1.5.3 Summit Construction

The construction work plan for work on the summit follows the sequence of (1) installing the construction camp to provide boarding and lodging for construction workers, (2) construct the road from the base of Armazones to the summit to a level that heavy construction equipment can easily travel between the base of the mountain and the summit, (3) earthwork on the summit, (4) construction of the telescope pier and fixed enclosure base structure, (5) erection of the rotating enclosure, (6) completion of the enclosure fixed base and construction of the other summit facilities.

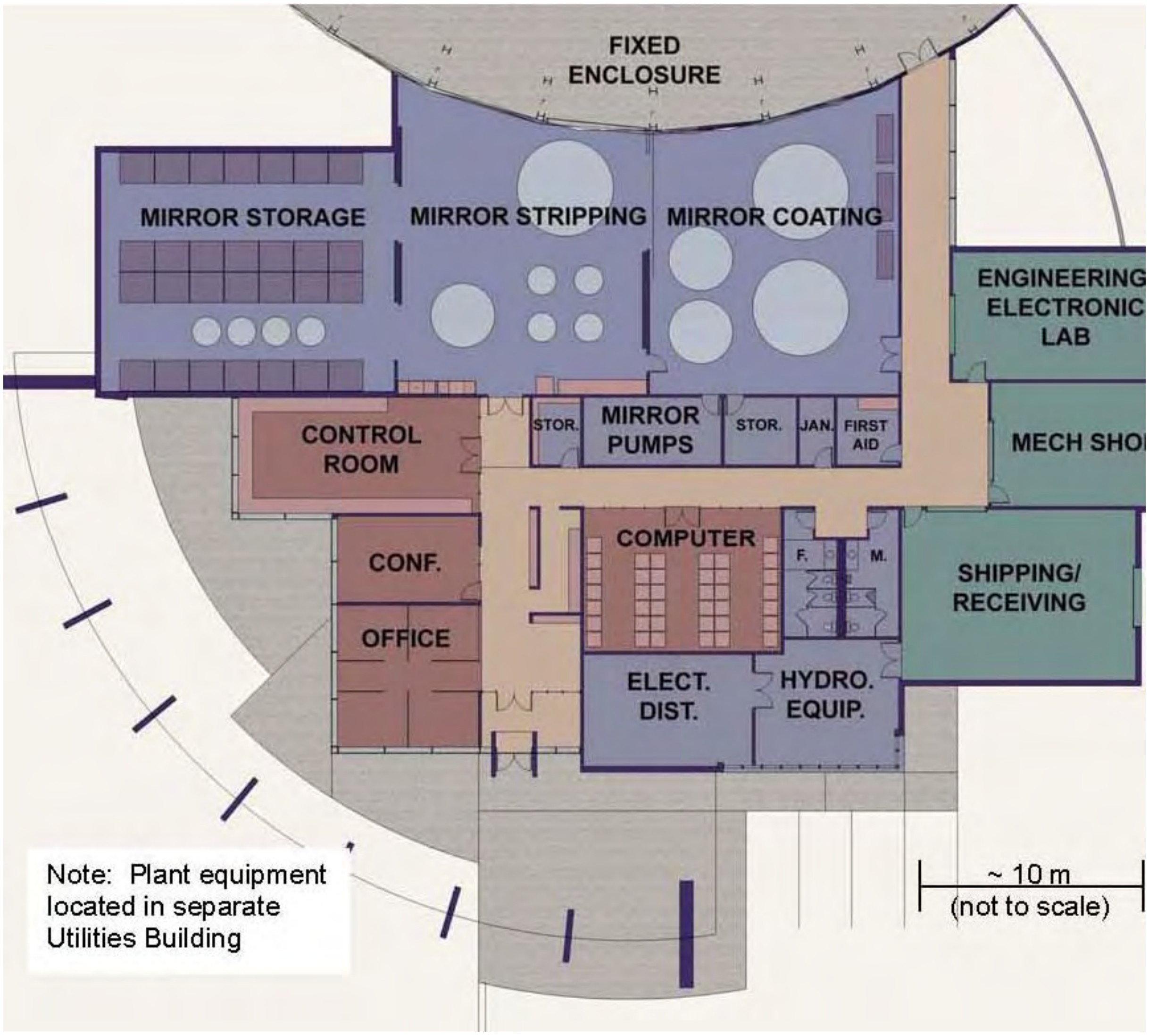
There is a break in the construction schedule after the erection of the structure for the enclosure fixed base and the start of the Summit Facilities so that (1) the enclosure contractor can access all sides of the enclosure with their equipment and (2) to avoid the risk of damage to the Summit Facilities from overhead work on the rotating enclosure. The telescope installation will start after the erection of the rotating enclosure.

#### 8.1.5.4 Support Facility Construction

In contrast to the specific sequence of work required for the summit construction, only selected parts of the support facilities need to be constructed in a certain sequence and timeframe. The construction work plan for the support facility starts with the installation of the construction camp, which provides boarding and lodging for construction workers. Critical path elements of the support facilities include the electrical power generation equipment, which is required for the acceptance testing of the rotating enclosure, and the provision of a warehouse, which is required for the telescope erection. Note that electrical power during construction will be provided by temporary diesel generators until the permanent electrical power system is installed. Other facilities can be constructed as funding profiles permit, with a goal of having the work completed at the start of Early Operations.

The construction at the support facility is independent of the road construction, as existing, although poor quality, roads may be used to access the site.

8.1.5.5




8.1.5.6

| Room | Room |
|---|---|
| Mirror Storage 189 m$^2$ | Janitor's Closet 5 m$^2$ |
| Mirror Stripping 187 m$^2$ | First Aid 12 m$^2$ |
| Mirror Coating 185 m$^2$ | Computer Room 76 m$^2$ |
| Mirror Coating Pumps 25 m$^2$ | Electrical Distribution Room 42 m$^2$ |
| Mirror Storage 13 m$^2$ | Hydrostatic Bearing Equipment 40 m$^2$ |
| Control Room 75 m$^2$ | Shipping and Receiving 108 m$^2$ |
| Conference Room 33 m$^2$ | Mechanical Shop 61 m$^2$ |
| Open Offices 54 m$^2$ | Engineering and Electronics Lab 76 m$^2$ |
| | |
| **Total Building Area (with corridors, etc.) ~ 1,200 m$^2$** | |

8.1.5.7

**Fig 8-2: Conceptual layout of the Main Summit Facilities.**


| Accommodations Facilities | Administration, Lab and Shop Facilities |
|---|---|
| 74 Rooms @ 16.7 $m^2$ each = 1,236 $m^2$ | Entry lobby 23 $m^2$ |
| **Total building area 1,612 $m^2$** | Open office space 262 $m^2$ |
| | 3 Offices @ 16 $m^2$ each = 48 $m^2$ |
| **Accommodations Support Facility** | 2 Conference rooms @ 28 $m^2$ ea. = 56 $m^2$ |
| Lobby 43 $m^2$ | Computer / IT room 26 $m^2$ |
| Kitchenette 28 $m^2$ | Mail lecture hall 87 $m^2$ |
| Quiet room and library 81 $m^2$ | First aid room 17 $m^2$ |
| Game and TV room 88 $m^2$ | Copy and printer room 23 $m^2$ |
| Laundry 13 $m^2$ | Receptionist 15 $m^2$ |
| Janitor's closet 8 $m^2$ | Janitor's closet 9 $m^2$ |
| Storage 24 $m^2$ | Administrative storage 10 $m^2$ |
| Electrical equipment room 34 $m^2$ | Lounge and Kitchenette 37 $m^2$ |
| Mechanical equipment room 34 $m^2$ | Mechanical shop and storage 74 $m^2$ |
| Men's toilet 20 $m^2$ | Shipping and receiving 97 m2 |
| Women's toilet 17 $m^2$ | Engineering, elect. lab & storage 100 $m^2$ |
| **Total building area 458 $m^2$** | Emergency vehicle garage 63 $m^2$ |
| | Women's toilet 21 $m^2$ |
| **Dining Facilities** | Men's toilet 21 $m^2$ |
| Dining hall 144 $m^2$ | **Total building area 1,335 $m^2$** |
| Serving area 46 $m^2$ | |
| Office 12 $m^2$ | **Maintenance, Utility and Warehouse** |
| General food storage 42 $m^2$ | Warehouse 420 $m^2$ |
| Kitchen 63 $m^2$ | Mechanical equipment 187 $m^2$ |
| Walk-in refrigerator 10 $m^2$ | Electrical distribution 187 $m^2$ |
| Walk-in freezer 10 $m^2$ | Power generation 240 $m^2$ |
| Janitor's closet 11 $m^2$ | Electrical shop 51 $m^2$ |
| Men's toilet 15 $m^2$ | Welding and Machine Shop 98 $m^2$ |
| Women's toilet 16 $m^2$ | Mechanical Shop 51 $m^2$ |
| **Total building area 440 $m^2$** | **Total building area 1,272 $m^2$** |

**Fig 8-3: Conceptual layout of Support Facilities with areas of rooms. Note: The Total Building Areas include the areas of corridors and other areas that are not listed as individual rooms.**

## 8.2 Enclosure

### 8.2.1 Overview

The TMT enclosure is a spherical structure housing the telescope. The principal functions of the enclosure are to protect the telescope from severe site environmental conditions, protect the telescope from wind buffeting, minimize the daytime thermal load, and provide a safe environment for observatory employees and visitors.

The TMT enclosure will be designed and manufactured by Empire Dynamic Structures, LTD (DSL), formerly AMEC Dynamic Structures (ADS), of Port Coquitlam, British Columbia. Previous DSL work includes enclosures for Gemini N & S (Hawaii and Chile), Subaru (Hawaii), Keck I and II (Hawaii), Starfire Optical Range (New Mexico), Sir William Herschel Observatory (Canary Islands), Canada France Hawaii Telescope (Hawaii), and Sir Isaac Newton Telescope (Canary Islands).

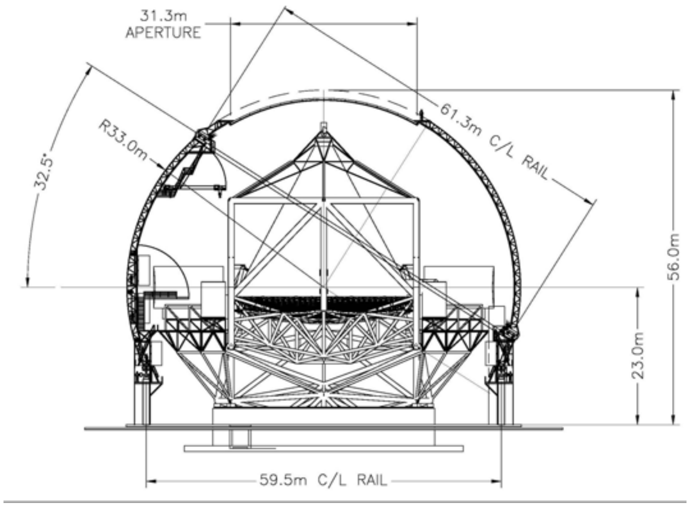



**Fig 8-4: Enclosure Cross-Section.**

### 8.2.2 Requirements

The TMT enclosure requirements are the result of an iterative process involving input from all the relevant disciplines within the TMT project, and from other observatories and industrial partners. Refinement of the requirements will continue, to enable an optimized and cost effective enclosure design.

The Enclosure Requirements Document (ERD) [1] provides an overall description of the enclosure system, its functions and constraints. High level TMT enclosure requirements are summarized below:

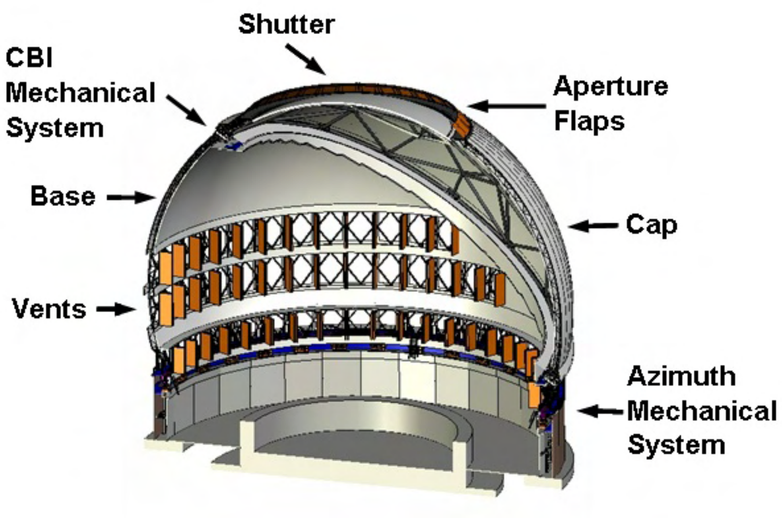



**Fig 8-5: Enclosure Systems.**

- Survival environmental loads: 78m/s wind load, 76mm ice load, 150kg/m$^2$ snow load, and seismic events applicable to the selected observatory site
- Protection of the telescope against environmental impact such as wind, snow or rain and dust
- Aperture position: zenith range 0° to 65°, continuous azimuth range, and slewing between any two points on the sky within 180 sec
- Shutter and vents: open or close within 120 sec
- Provide optimal observing aerodynamic conditions to minimize dome seeing, mirror seeing and wind buffeting
- Minimize daytime thermal influx from infiltration and conduction

### 8.2.3 Conceptual Design Description

The TMT enclosure configuration is referred to as a calotte design. The calotte configuration consists of three major structures: the base, cap, and shutter. The base and cap are a part of a continuous spherical shell split by a plane (Cap / Base Interface plane – CBI) inclined at 32.5° (half of the maximum observing zenith angle) relative to a horizontal reference plane. The base structure rotates about a vertical axis in the azimuth direction. The cap structure rotates about an axis perpendicular to the CBI plane. The cap incorporates a circular aperture opening that can be positioned to zenith angles from 0° to 65° and to all azimuth angles by combined rotation of the base and cap structures. The shutter structure consists of an open spherical frame inside the cap structure. One side of the shutter structure features a circular opening to enable viewing through the cap aperture, and the opposite side includes a circular plug closing and sealing the cap aperture. The shutter rotates about the same axis but independently of the cap structure. The aperture can be opened or closed by rotating the shutter 180° relative to the cap. Another significant feature of the enclosure design is that there are 98 vents, which provide a total venting area of 1,713 $m^2$, distributed in three horizontal rows on the base structure. Opening of vents enables natural ventilation of the enclosure interior during observation.

The calotte design was selected after extensive trade studies [2][3] performed during the initial phases of the TMT project. Various enclosure configurations found in existing observatories were evaluated for the TMT, including dome-shutter designs (such as Keck and Gemini), carousel, and co-rotating designs (such as Subaru). The calotte configuration provides a design that is both structurally and mechanically efficient due to the continuous spherical form and balanced moving components, thus minimizing costs. The spherical structure and circular aperture allow the enclosure size to be minimized while still providing the required telescope clearance and wind protection. Additionally, the structural design lends itself to modular construction methods that have been used successfully in existing large domed enclosures such as Keck and Gemini.

The following paragraphs include description of the major design features.

#### 8.2.3.1 Enclosure Structure

The components of the enclosure structural design are similar in concept to existing enclosures designed and built by DSL. The method of fabrication and construction has been developed to optimize structural efficiency, weather and thermal protection and construction efficiency, safety and security at a hostile site.

The enclosure shell is composed of a quadrilateral frame work of 1.0m deep trusses with a typical grid size of 2.5mx2.5m. Continuous rib trusses run in vertical planes (when the aperture is pointed to zenith), and are connected by smaller tie trusses running in lateral planes. The geometry allows a high degree of repetition in the fabrication of components. Larger openings in the structure are required in the vicinity of the ventilation openings, and the rib and tie structure is reinforced in these regions.

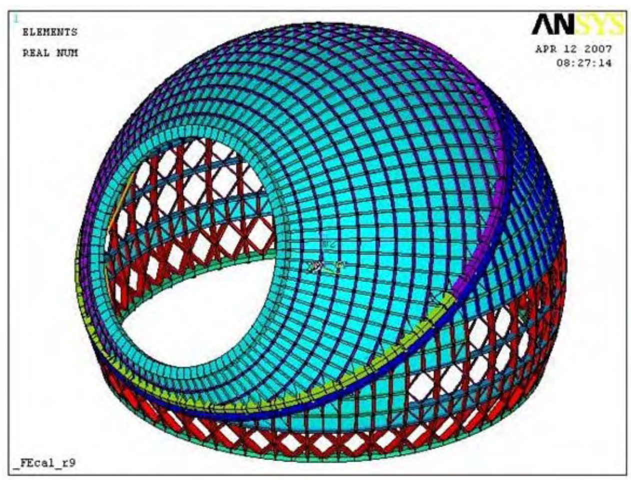



**Fig 8-6: FE Model of the TMT enclosure.**

The external skin consists of 5.0 mm thick plates, welded to the outside of the rib and tie structure. This approach provides a continuous and highly reliable weather barrier over the lifetime of the enclosure. The skin behaves as a structural membrane strengthening the enclosure. The enclosure is insulated with rigid insulation panels, fastened to the inside of the rib and tie structure. Insulation panels provide thermal insulation of the dome interior, and create a 1.0m deep interstitial space (between the external skin and the insulation) that can be ventilated to create an additional level of thermal insulation of the dome interior.

The cap and base shell structures are stiffened at their edges by ring girders utilizing a combination of box girder and truss construction. These ring girders provide the mounting surfaces for the azimuth and cap bogie and rail system, and thus their alignment is critical. The ring girder segments will be trial assembled at the fabricator in order to ensure accuracy of fabrication prior to site installation. Additionally, all components will be painted white prior to installation in order to minimize temperature related dimensional instability during on-site alignment.

The TMT enclosure structure was analyzed using the finite element model shown in Fig 8-6. Mechanical interfaces were modeled using spring elements representing the stiffness of individual bogie and guide roller elements. The survival loading conditions analyzed are given in the Section 8.2.2. Load combinations and safety factors were calculated per the American Society of Civil Engineers standard. The structural design was optimized under these survival conditions. Buckling and fatigue analyses were also carried out.

#### 8.2.3.2 Azimuth Mechanical System

The azimuth mechanical system provides the interface between the rotating enclosure and the fixed facility structure. The azimuth bogies are mounted on fixed base columns, and support the azimuth rail, which is mounted to the underside of the enclosure azimuth ring girder. There are a total of 32 bogies: 20 idler bogies, 6 brake bogies, and 6 drive bogies (50 HP each). In addition to the azimuth bogies, there are 64 lateral restraints attached to the fixed base structure to react lateral load. The azimuth bogie maintainability was an important factor in determining an optimal design solution. The proposed bogie and drive design is similar to the one used with considerable success on the JNLT (Subaru) enclosure. Fig. 8-7 shows azimuth bogie installation. The drive motors are located on the outside of the insulation in order to isolate heat generated by the drives.

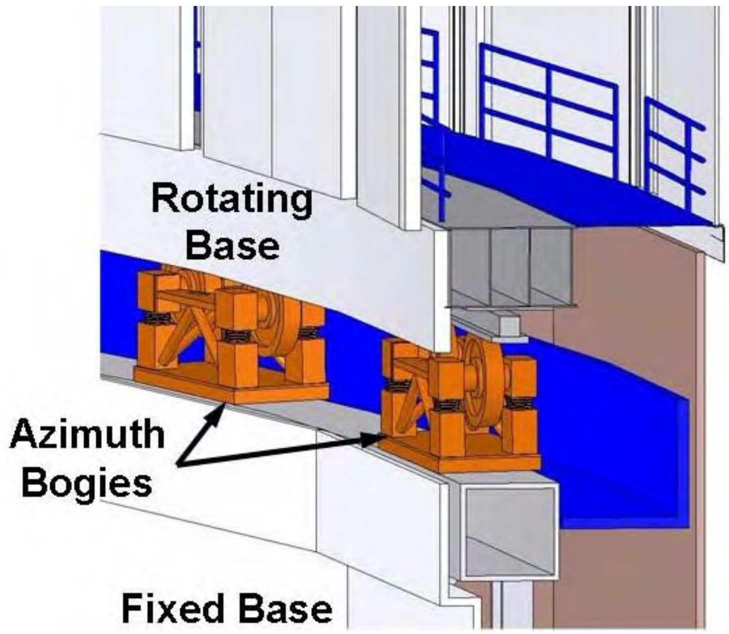



**Fig 8-7: Azimuth Bogie Installation.**

The proposed seal design utilizes an external seal maintaining continuity of the external skin weather barrier, and an internal seal enabling continuity of the insulation. The seal concept includes a sliding seal based on retrofits made at the Keck enclosures, which have proven to provide reliable sealing and minimal maintenance.

#### 8.2.3.3 Cap Mechanical System

The cap mechanical system at the inclined interface is a unique aspect of the TMT enclosure. A significant amount of design work and analysis resulted in the adopted design concept. The bearing system consists of 120 bogies mounted to the base structure. The bogies are oriented at either +45° or -45° relative to the CBI plane (60 in each direction). This arrangement enables optimized load distribution by concentrating the location and orientation of the bogies in the regions of highest load. The relatively small size of the bogies enables easy replacement and alignment.

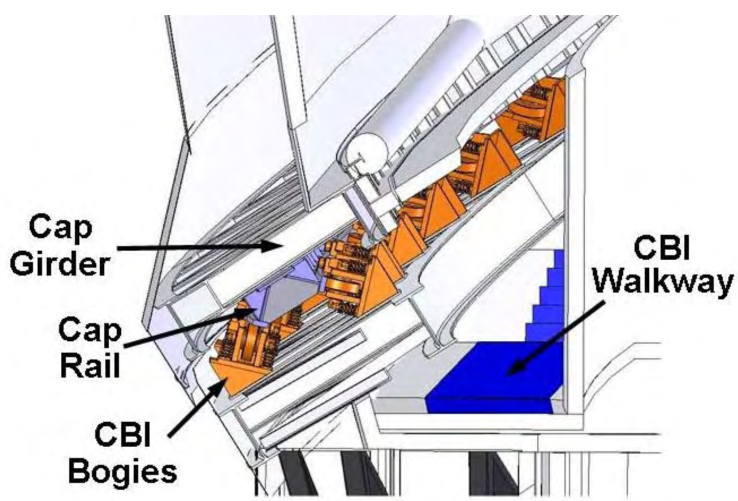



**Fig 8-8: Cap / Base Interface Detail.**

Cap motion is enabled by five, 40 HP drives attached to the rotating base. The drive system is a proven rack and pinion concept. The cap structure is balanced about its axis of rotation. Thus, the drive units are only required to overcome friction and inertia forces. **Figure 8-8** shows the CBI detail including cap bogies, cap and base ring girders, CBI walkway and cap rails. Access to the cap bogies is via an insulated walkway traversing the circumference of the cap bearing. A small maintenance station enabling tool and component transport is mounted to the cap structure, allowing the maintenance station to be rotated to any bogie location.

#### 8.2.3.4 Shutter

The shutter (**Figure 8-9**) consists of an open framework of steel tubing and nodes, supporting an aluminum plug structure. The shutter is supported by 16 bogies at its bottom edge, and rotates on a dedicated track attached to the cap ring girder. A rack and pinion drive system similar to the cap drive utilizes two, 40 HP drive units used to rotate the shutter between open and closed positions. The shutter structure is balanced about its axis. This feature enables the use of relatively modest size drive motors. The shutter is not moving relative to the cap during observation.

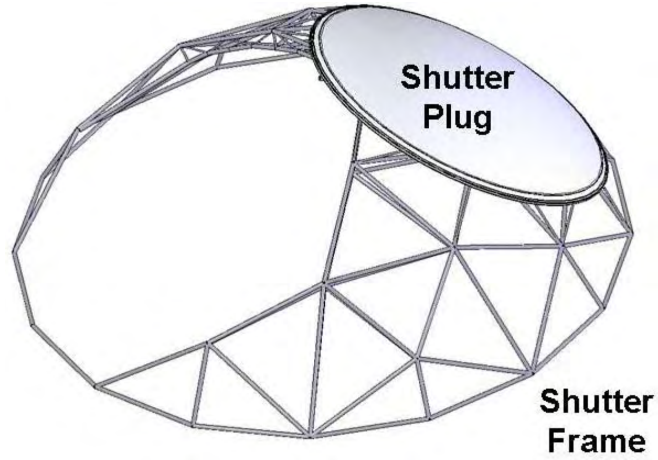



**Fig 8-9: TMT Enclosure Shutter.**

A dedicated lock mechanism was designed to reduce shutter structural mass. The shutter is secured in the closed position by a set of 10 latches attached to the cap structure. The latches are designed to react only to loads significantly exceeding operating loads effectively limiting plug deflections under such loads.

Shutter sealing is provided by P-seals attached to aperture flap planes. Any potential water leakage will be contained by a dedicated channel located at the shutter outer edge and drained overboard.

#### 8.2.3.5 Vent doors

Enclosure requirements specify the use of vents to provide night-time interior ventilation. The calotte configuration presented a significant challenge in terms of providing adequate ventilation area since there are no large openings allowing unobstructed movement of air during observation. A total of 98 vent modules have been incorporated in the enclosure design. The vents have been located in three horizontal rows: two upper rows of 54 x 5.0m x 4.4m openings, and a lowermost row of 44 x 4.0 x 4.0m openings. The number and location of vents have been determined by aerodynamic studies in order to enable optimal air movement inside the enclosure. Each vent module is independently controlled and could be opened or closed based on current interior ventilation requirements.

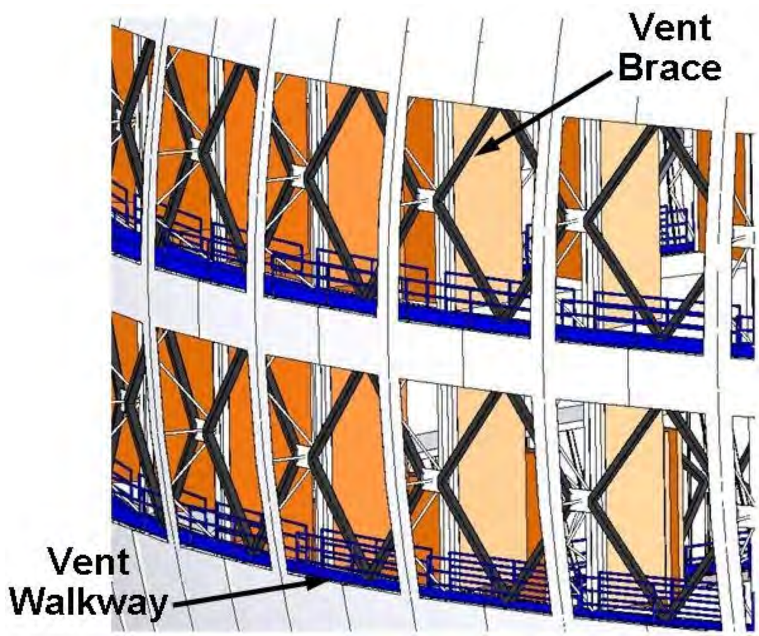



**Fig 8-10: TMT Enclosure Vents (Shown Open).**

Each vent opening consists of two sets of independently operated doors. Steel roll-up exterior doors provide weather protection against extreme windstorms. The interior doors are industrial freezer doors designed to maintain a continuous thermal barrier. Service access to interior and exterior vent doors has been enabled by a dedicated walkway in the interstitial space at each of three levels. Fig. 8-10 shows the vent layout on the enclosure.

#### 8.2.3.6 Aperture Flaps

One of the most important benefits of the calotte design configuration is superior wind protection of the secondary mirror in high wind conditions. The wind protection feature was further enhanced by adding a set of 36 aperture flaps designed to deploy during observation. This approach enabled a reduction of the overall enclosure size and significant cost savings. The aperture flaps are located at the outer edge of the aperture opening and are independently operated. Manual backup will enable flap retraction in case of actuator failure. A comprehensive shutter sealing system is included in the aperture flap design. Additional benefit of aperture flap concept is enhanced safety of maintenance operations. **Fig. 8-5** shows deployed aperture flaps and actuators.

### 8.2.4 Development Tasks

There are a few areas of elevated risk in need of added attention during the Design and Development Phase. These areas include cap mechanical system performance, vent door reliability and performance in a severe environment, sealing systems performance, aperture flap reliability and aerodynamic performance, ability to achieve required manufacturing tolerances and on-site construction issues. Each of the areas of concern represents a significant challenge and will be addressed in an appropriate manner. Risk reduction strategies include detailed component and system analysis during Design and Development Phase, component and system development tests and subsystem trial assembly at the fabricator's facility. Development of fabrication and construction methodologies is particularly important for achieving final as-built tolerances.

### 8.2.5 Workplan

Complex enclosure components will be fabricated at the DSL facility and, after a trial erection, shipped to TMT observatory site. Lower cost fabrication options including outsourcing have also been considered. Enclosure erection will be initiated upon completion of summit preparation, foundation pouring and fixed base erection activities. Completion of the enclosure shell and removal of dedicated falsework will enable start of telescope structure erection work. Final integration and acceptance of enclosure systems will be performed once facility power supply has been established.

## *References*

[1] Enclosure Requirements Document, TMT.ENC.DRD.05.003.DRF13.

[2] AMEC Enclosure – PP4 Midterm Review, TMT.ENC.PRE.05.024.

[3] Enclosure Down-Selection External Review, Overview and Aero-Thermal Presentation, TMT.ENC.PRE.05.022.

## 8.3 Telescope

### 8.3.1 Structure

#### 8.3.1.1 Overview

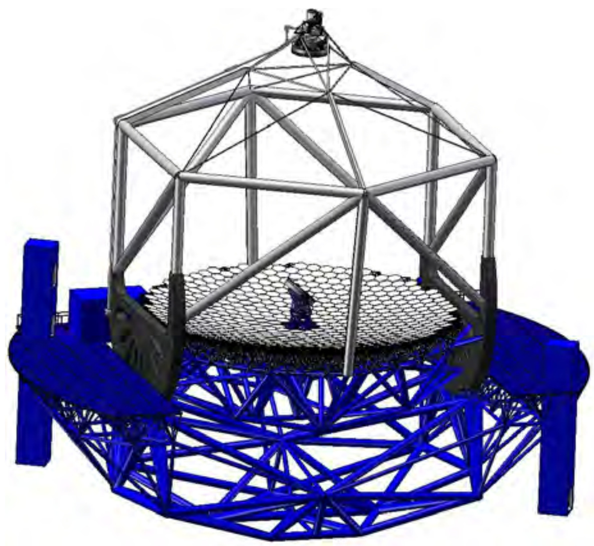


Fig 8-11: Telescope Structure System.

Empire Dynamic Structures, LTD (DSL) is providing the leading engineering support on the design of the telescope structure system. DSL has extensive experience in the design, fabrication and erection of telescope structures worldwide. The telescope structure system accommodates a Ritchey-Chrétien optical design [1, 2] and altitude-azimuth mount as described in **Section 7.2.2** Telescope Layout. The system consists of two major structural components: the azimuth and elevation structures, see **Fig. 8-11**. The elevation structure provides mounting for the telescope optics, 492 primary mirror (M1) segments with segment support assemblies, secondary (M2) and tertiary (M3) mirrors, and the Laser Guide Star Facility (LGSF), (**Section 8.5.2.2**). The azimuth structure supports the elevation structure and two large Nasmyth platforms where the observatory instruments and AO system are located, see **Fig. 8-13**. The telescope elevation axis is above the primary mirror. This enables an articulated M3 to direct science light to multiple instrument locations on both Nasmyth platforms. This M3 configuration provides flexibility and speed in instrument switching during astronomical observations by allowing multiple addressable focal plane positions on the Nasmyth platform.

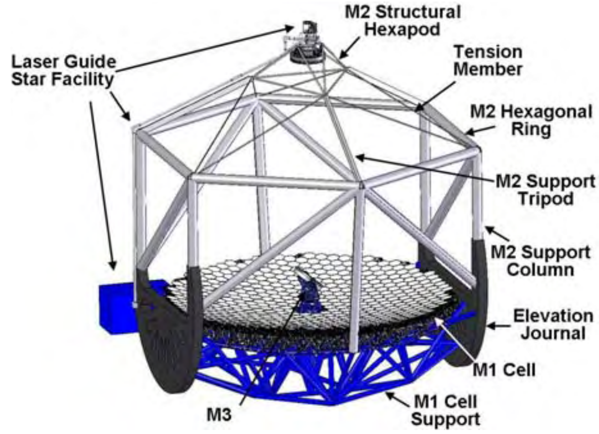



Fig 8-12: Elevation Structure Components.

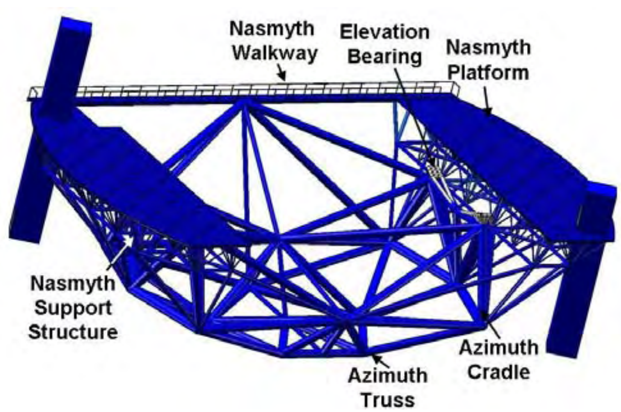



Fig 8-13: Azimuth Structure Components.

#### 8.3.1.2 Requirements

Functionally, the telescope structure system is required to provide support for the telescope optics and the associated astronomical instrumentation and supply the utilities that they require to operate. The optics support requirements can be further divided into shape and alignment controls over the operating environmental conditions. The shape control is specific to the mirror cell design, which supports the 492 M1 segments such that their motions are within the actuator stroke allotment, decenter and rotation tolerances as dictated by the image quality error budget [3]. The alignment control governs the allowable misalignment after active position controls of M2 and M3 with respect to M1and the instrument focal plane caused by the quasi-static disturbances due to gravity and thermal effects, and dynamic disturbances due to wind and vibration sources. The alignment requirements are also dictated by the delivered image quality in the error budget. The utilities required to operate the telescope-mounted systems include power, coolant, cryogen, data and communication, and they are provided through cable wraps placed between the telescope pier, azimuth and elevation structures.

In addition, the telescope structure is required to serve as a platform for safe access to service and maintain the telescope-mounted systems. Therefore the placement and design of walkways, stairways, elevators and lifts to allow efficient access are another aspect of the requirements.

The telescope structure system is an integral part of the mount control system, which provides coordinated azimuth and elevation motion control such as pointing, tracking, nodding, offset and guiding during observation. The telescope structure system is responsible for the dynamic characteristics of the structure and mechanical systems required for generation and control of the required range of azimuth and elevation motions to the requisite precision. The motions include acceleration, deceleration, motion feedback, over-travel and loss of power protections etc. All motions driven by the telescope structure system must be compatible with the telescope safety system in terms of interlock, to safeguard against harm to personnel and equipment.

The top level performance requirements are expressed as error budgets in terms of image qualify, pointing and pupil alignment accuracy in the OAD [4]. The image quality error budget is defined in both encircled energy and RMS wavefront error, and it is composed of contributions from dome and mirror seeing, optical design, optical surface quality, blur and jitter caused by misalignments. The last three contributions correspond to the aforementioned shape control, quasi-static and dynamic misalignments requirements, respectively.

The requirement flow-down and traceability development, which subdivides the top level requirements into the telescope structure system requirements, is underway and it is described in **Section 6.2** Requirements Flow Down and Traceability. Examples of requirements flow-down are listed in **Section 7.5**

Performance Estimates. Integrated modeling simulation is used extensively to predict the overall system performance with an objective to understand the performance drivers and design requirements at the lower level such as the telescope structure system. **Fig. 8-14** shows the flow-down and traceability from the top level error budget to the telescope structure system and subsystems requirements.

The telescope structure system has additional interface requirements with the telescope-mounted optics and instrumentation, mount control system, active optics alignment control systems, enclosure and summit facilities. The primary interface parameters such as mass properties, space, volume, stiffness and mounting configuration requirements have been established for the optics assemblies, laser guider star facility and telescope pier. In addition, the interfaces for major utilities and their requirements have been established with the summit facilities group.

#### 8.3.1.3 Conceptual design description and options

The basic telescope structure dimensions are shown in **Figure 7.2**, as defined in the OAD [4]. Given these basic dimensions, the structural concept is governed primarily by the telescope 'light path' configuration, particularly by the usage of the articulated M3 to feed the instrumentation on the two Nasmyth platforms. The clearance required for the light path from M3 to the Nasmyth instrument stations constrains the structural options within the design space.

**Elevation structure**

The focal plane at the on-axis instrument position has a diameter of 2.62 meters, which corresponds to a 20 arcminute Field Of View (FOV) [4]. M3 has the capability to direct the science beam to a large portion of the Nasmyth platforms, over the steering range described in **Section 7.2.3** Nasmyth Platform, see **Fig. 8-15**.

Furthermore, this range of instrument positions must be accessible over the operating zenith angle range of -1° to 65°. The swept-volume of the beam from M3 to the Nasmyth platforms, shown as yellow conical cylinders in **Fig. 8-15**, determines the structural support placement. Firstly, the primary support structure has to be placed below the elevation axis in order to create a direct and efficient load path towards ground, since any structure near the elevation axis would result in vignetting. Secondly, the large beam swept-volume is not compatible with using compact trunnion bearings to support the elevation structure on its axis of rotation. A pair of large circular journals with an open annulus arc centered on the elevation axis, supported by hydrostatic bearings mounted on the azimuth structure is the obvious alternative. The minimum arc length and radius of the elevation journals are set by the -1° to horizon pointing zenith angle range. More importantly, the journal length and geometry are also restricted by the requisite light beam clearance incident on M1, shown as yellow conical cylinder in **Fig. 8-16**. The geometry of the elevation journals is also illustrated in **Fig. 8-16**. Thus the governing journal geometric parameters are bounded by both light path constraints along with the need to balance the elevation structure about its axis of rotation.

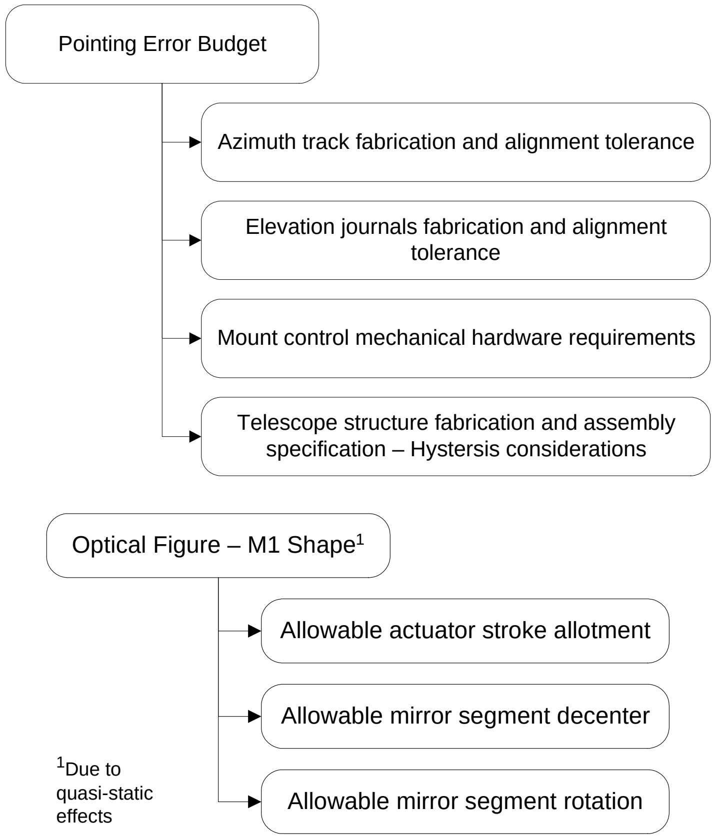



**Fig 8-14: Examples of Requirements Flow-Down.**

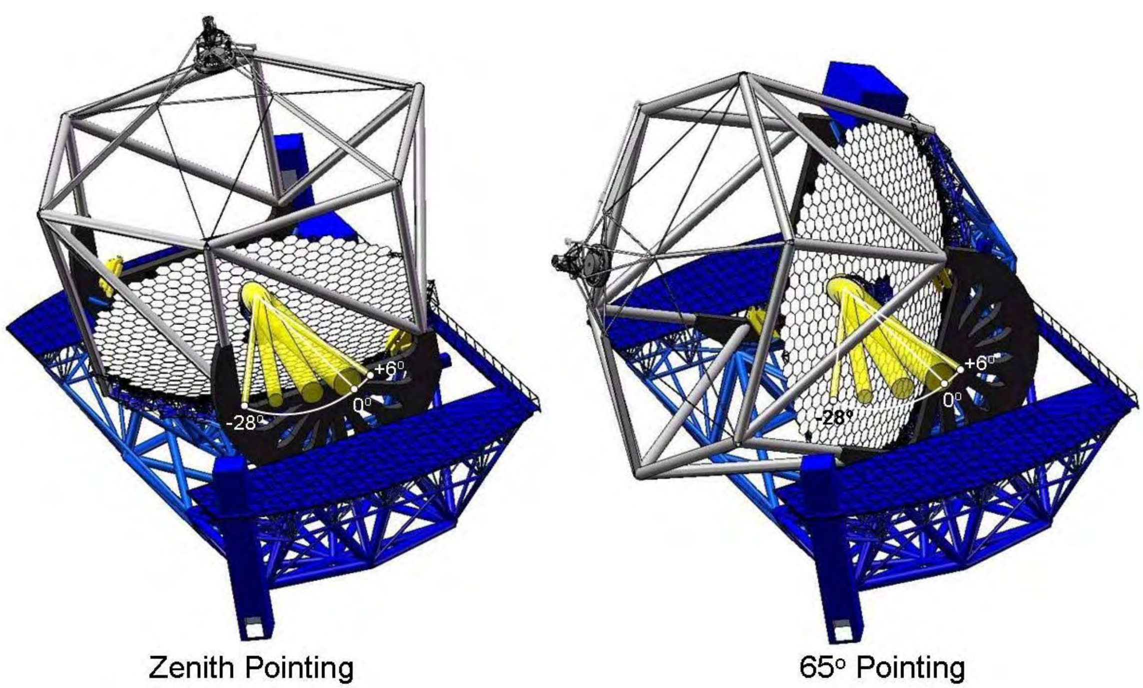



**Fig 8-15: Structural Placement for Light Path Considerations - M3 to Nasmyth Platform, yellow cylinders represent the FOV at different instrument positions.**

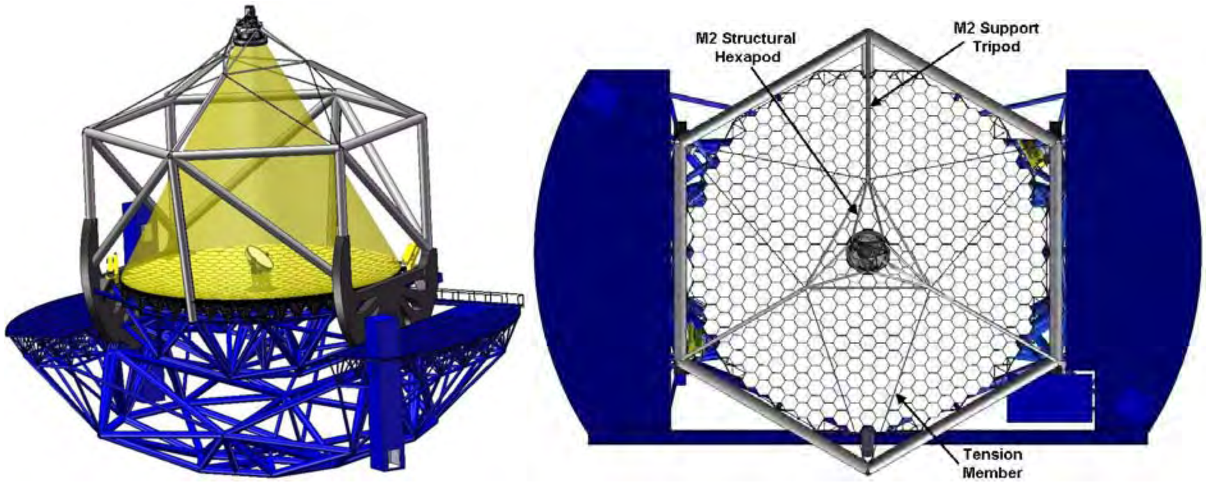



**Fig 8-16: Structural Placement for Light Path Considerations – M1.**

Having the elevation axis above the primary mirror, the distributions of the supported optical elements are not “naturally” balanced about this axis. The mass moment due to the 144-tonne primary mirror system 2.9 m below the elevation axis is only reduced by less than half by the moment created by the 7-tonnes of secondary mirror (M2) system and laser guide star components located at the top end, 25 m above the elevation axis; see Table 8-1. The structural elements required to support the M1 mirror cell[2] and tie the elevation journals together are all located below the elevation axis, further adding to the imbalance. Moreover, trade studies have shown that in order to support the M1 segments in the mirror cell to within its quasi-static alignment requirements over the zenith angle range, it requires two substantial elevation journal structures. The requirement to balance the elevation structure about its rotation axis implies a design solution different from the minimum mass configuration. In other words, the balancing requirement requires the structural mass of the elevation structure to be redistributed from areas where it could work more efficiently to areas where it can help balance the telescope, e.g. the elevation of the M2 support hexagonal ring is influenced by mass balance.

The remaining M2 support elements such as the tripod legs and tension members are designed to be as slender as possible, given buckling considerations, in order to minimize top-end obscuration and wind cross-section, also illustrated in **Fig. 8-16**.

**Table 8-1: Mass and location of the telescope mounted optical components.**

| Optical Assembly | Mass, tonnes | Location from the elevation axis |
|---|---|---|
| M1 | 144 | -2.9 m |
| M2 and laser guide star components | 6.9 | 25.0 m |
| M3 | 9.7 | 2.0 m |

[2] The mirror cell is a 2 m deep truss structure with a fine top chord fitting the segment-triangulation scheme, i.e. with equilateral triangular openings matching the vertices of hexagonal mirror segments when projected in plan view. Each M1 segment is attached via its segment support assembly at the 2/3 point of each side of the triangular opening and its neighboring “triangles” are not occupied. Diagonal trusses transition the load paths into a coarser bottom chord at 2 m below. This configuration allows practical access through the mirror cell. The segment-triangulation results in a less dense top chord, compared with actuator-triangulation which requires smaller openings, for better mirror segment servicing access. The mirror also has a six-fold symmetry, i.e. six identical 60° sectors, in order to reduce fabrication complexity.

**Azimuth structure**

The azimuth structure is formed by having the tubular azimuth cradles tied together by a central truss arrangement inboard and the Nasmyth platforms attached outboard to the cradles. The two elevation-axis hydrostatic bearings are mounted on the top of each azimuth cradle. Between the bottom of the azimuth cradles and the azimuth track are six hydrostatic bearings, three on each side. They support the entire weight of the telescope. This structural arrangement provides efficient and direct load paths between the elevation structure and ground. The azimuth structure geometry and the elevation bearing positions are illustrated in **Fig. 8-13**.

The Nasmyth platforms are 7 m below the elevation axis, and each instrument is supported on a purpose-built instrument support structure, which raises the instrument to the correct elevation in order to "receive" the science beam according its size and geometry. The instrument support structures are attached to a grid of 2 m by 2 m hard points on the deck structure of each Nasmyth platform. An additional finer grid of 1 m by 1 m is available to support a deck grating system for personnel and equipment traffic, as well as for the electronic cabinets and servicing equipment associated with each instrument. The deck grating is design for light manufacturing loads[3]. The instrument support structures also provide attachment points for removable stairs and walkways for serving of instruments. An elevator is incorporated into each Nasmyth platform, which carries personnel and small tool cart from the base of the platform to the Nasmyth platform deck and instrument walkway levels. In addition, a walkway at the telescope back side connects the two Nasmyth platforms.

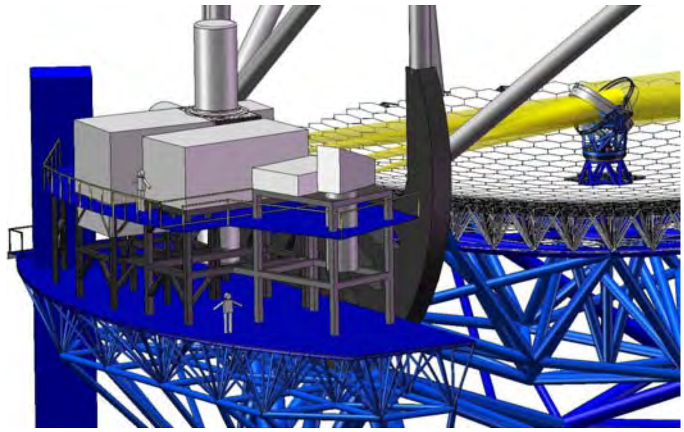


**Fig 8-17: Conceptual layout of access infrastructure for the final instrument locations.**

The overall Nasmyth platforms configuration [6] has been derived from aero-thermal CFD studies, which predicted the mirror seeing from the effects of instrument blockage on mirror flushing [7,8], the instrument configuration issues [9] and instrument support requirements [10]. **Fig. 8-17** illustrates the conceptual layout of one of the platforms with the full suite of first decade science instruments supported on their instrument support structures, walkways and elevator.

**Mechanical System – Mount Control Hardware**

The baseline mount control hardware is hydrostatic bearings, Direct Drive Linear (DDL) motors and optical tape encoders for both azimuth and elevation axis motions [11]. This hardware combination provides the requisite accuracy and resolution to meet the mount control motion requirements. The conceptual design is based on a system of hydrostatic shoe bearings (HSBs) [12], DDL motors [11] and optical encoders [13] to generate and provide feedback of the mount control motions. The azimuth axis uses six HSBs, three under each azimuth cradle with two master bearings at the corners and a slave bearing in the centre; the DDL system is a ring of 584 magnet segments mounted around the azimuth track with two groups of seven forcers attached on the azimuth structure; a 3 m diameter central hydrostatic pintle bearing provides lateral restraint. A feasibility study is in progress for a similar size encoder ring as the pintle bearing with a minimum of four equally spaced read heads. The elevation axis uses four HSBs, two on each elevation journal positioned at 25° symmetrically about the centerline and a lateral restraint guide pad is incorporated in each HSB; the DDL system is a 104° sector of 101 magnet segments mounted vertically inboard of each elevation journal, and three forcers are attached symmetrically about the centerline atop each azimuth cradle; the encoder system is a 10 m encoder tape covering a sector of 150° with three equally spaced read heads and work is in progress to determine whether encoding is required on both journals.

It is recognized that the cable wrap friction can impede the mount control motion. In order to minimize this effect, the azimuth cable wrap [11] is motor driven, synchronized to the azimuth rotation. In addition, all bend-radii are kept to be as large as practical and the major lines such as hydraulic hoses, power cables, coolant

[3] IBC 2003, 125 psf distributed, 2,000 lb concentrated.

lines and cryogenic hoses are stacked vertically and compartmentalized in order to minimize rubbing. The elevation cable wrap is a cable carrier supported by a fixed cable tray. The cable tray is located on the centerline of the azimuth structure below the elevation structure. The elevation cable wrap is given the same design considerations to minimize friction.

**Fig. 8-18** shows the implementation of the safety hardware [12] such as brakes, shock absorbers and limit switches for the azimuth axis inside the telescope pier. In addition, an elevation axis counterbalance system composed of coarse static ballasts and fine active control will be implemented along with a

locking pin system that holds the structure for servicing an unbalanced telescope.

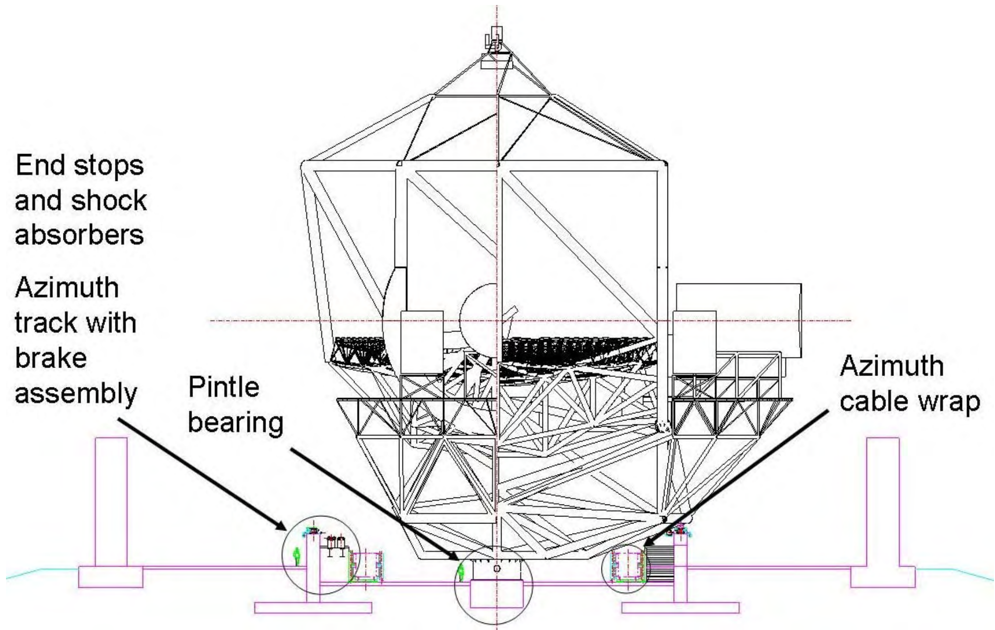



**Fig 8-18: Azimuth Axis Mount Control Hardware – Split View (Left -Side View, Right- Back View).**

#### 8.3.1.4 Development tasks

The development tasks are divided into three categories based on performance, cost and risk mitigation. Going beyond the standard finite element analysis (FEA) structural analysis technique, the performance based tasks develop integrated analytical tools to guide the design by predicting the telescope structure system performance in terms of image quality. Examples of integrated model simulation development are described in **Section 7.5** Performance Estimates. These tools ensure the quasi-static performance [13] and dynamic performance of the integrated structure and control system, including the mount control and active optics control for M1, M2 and M3. Moreover, CFD and complementary wind-tunnel testing are utilized to validate the overall aero-thermal performance. The cost based tasks are cost reduction studies. Two cost based studies are planned; a fabrication and alignment tolerances trade study, based on the Keck telescope experience, and a feasibility study of using alternate fabricators in South America. The first study will determine the optimal fabrication and alignment tolerances by balancing the costs associated with each. The second study will determine the cost benefits against risks of having the telescope structure fabrication work distributed between North and South America. The risk mitigation tasks are technical studies to retire risks. Two studies are planned to address performance uncertainties in the mount control system, one for the DDL motor system and the other for the azimuth cable wrap system.

#### 8.3.1.5 Work plan

The current work plan assumes DSL will continue to be the prime contractor and commercial partner. The detailed design phase will commence at their site following the Design and Development Phase (DDP), and they will produce the shop drawings, bill-of-material and integration procedure required for fabrication and assembly of the entire telescope structure system. Procurement of the mount control mechanical hardware and steel fabrication will proceed after the detailed design phase review. When fabrication is complete, a partial trial assembly of the telescope structure will be conducted before packing and shipping. The level of trial assembly will be based on the cost versus risk trade analysis by comparing the trial assembly cost against the probable risk cost of rework on-site. It is possible that work will be conducted at multiple fabrication sites, pending the findings of the aforementioned feasibility study, and coordination will also be an integral part of the work plan. After arrival on-site, where possible mechanical system installations will progress in parallel with structural erection in order to minimize the time spent on-site, which has the highest unit cost in terms of labor and the associated support. Once erection is complete, the telescope structure system will undergo acceptance tests according to the procedures established by the TMT project.

The telescope structure system erection sequence is closely related to the development of other TMT systems. For example, the telescope structure cannot ship until the warehouse facility is available, its erection cannot start until the staging facilities are ready, and the actual on-site erection cannot begin until the enclosure is weather tight. Similarly the telescope structure system affects its 'successor' tasks such as the mount control system installation, optics installation and instrumentation installation. They cannot commence until the telescope structure system is working reliably and has been acceptance tested. Once the on-site erection starts, the telescope structure system will be on the critical path of the overall assembly, integration and verification schedule.

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[2] Ritchey-Chretien Baseline Design, TMT.SEN.SPE.06.001.

[3] TMT Image Size and Wavefront Error Budgets, Volume 1 - TMT.OPT.TEC.07.001, Volume 2 - TMT.OPT.TEC.07.002., and Volume 3 - TMT.OPT.TEC.07.003.

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[6] Nasmyth Platform Structural Design Concept, TMT.STR.TEC.06.043.

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[9] Nasmyth Platform Configuration Issues TMT.SEN.TEC.06.026.

[10] Nasmyth Instrument Support Requirements Document, TMT.SEN.DRD.06.003.

[11] Mount control and mechanical hardware, TMT.STR.PRE.06.014.

[12] Telescope Azimuth Lateral Restraint Configuration, TMT.STR.PRE.06.38.

[13] S. Roberts, S. Sun and D. Kerley, "Optical performance analysis and optimization of large telescope structural design", Proc. SPIE **5867**, 586700 (2005).


### 8.3.2 Primary Mirror

#### 8.3.2.1 Overview

The TMT primary mirror (M1) builds on the successful experience of the W. M. Keck Observatory in constructing and operating two 10 m diameter telescopes that currently are the largest optical-infrared telescopes in the world.

**Keck Heritage**

The Keck telescopes were the first large telescopes to be built with segmented primary mirrors, and their technical and scientific success has made them the prototypes for other large segmented-mirror telescopes in use or under construction around the world.

TMT has benefited greatly from the lessons learned on the Keck Telescopes. Many TMT staff members worked on the Keck project and current Keck Observatory staff members have been generous with their time, serving as advisors and reviewers for TMT. TMT is particularly drawing on Keck experience in the design of the primary mirror.

The Keck primary mirrors use 1.8 m hexagonal segments. Each segment's reflecting surface is an aspheric, off-axis portion of the global primary mirror. The gaps between segments are only 3 mm wide (the optical gap is about twice that if you include the edge bevels), resulting in a >99% filled aperture.

The optical performance of the segment is sensitive to three of the rigid body degrees of freedom: piston, tip and tilt. These are “out-of-plane” motions. It is not very sensitive to the other three degrees of freedom: X and Y translation and “clocking” rotation about the center. These are “in-plane” motions. Therefore, the support system controls the in-plane motions passively and controls the out-of-plane motions actively with precise feedback from edge sensors.

Each segment has three actuators that allow it to be aligned (in tip and tilt) and phased (in piston) to form an accurate, continuous surface. The Keck Phasing Camera System (PCS) uses starlight to provide feedback for aligning and phasing the segments. The relative positions of the segment edges are measured by edge sensors; the shape of the primary mirror can be maintained for weeks by maintaining the same edge sensor readings.

The PCS also provides information about the optical figure of each segment. Each segment support incorporates a warping harness. Using the PCS measurements, the warping harness can correct low-order aberrations such as focus and astigmatism by means of 30 moment actuators.

TMT has evaluated the Keck designs and has reviewed the fabrication, alignment and maintenance methods used on the Keck telescopes. Many features of the Keck primary mirror designs have been retained, including general control algorithms and the whiffletree axial support and diaphragm lateral supports. The functionality of the Keck PCS has been included in the design for the TMT Alignment and Phasing System (APS), described in **Section 8.3.6.4**. However, the designs have been modified somewhat because of the scale of TMT, the need for rapid segment calibration due to the large number of segments, and to reduce costs.

**Design Philosophy**

The design philosophy for the TMT primary mirror (M1) is based on the philosophy that guided the scientists and engineers who built Keck. By breaking the aperture into segments of manageable size, many of the difficulties involved in the construction of large telescopes are reduced, including fabrication, testing and transportation of the large mirrors and mirror cells. The need for large handling equipment, high-capacity handling cranes and large vacuum coating chambers is also greatly reduced. Some risk issues are also mitigated. For example, breakage of a segment would not be nearly as catastrophic as breakage of a traditional telescope primary mirror.

Moderate-sized segments can be fabricated at moderate cost and can be mounted on support systems of moderate complexity. It is also possible to keep the glass in the segment thin, which reduces the overall mass and thermal inertia, and allows the glass temperature to follow the changing ambient temperature to minimize mirror seeing effects.

The focal ratio of the TMT M1 is faster than Keck (f/1 vs. f/1.75). This leads to segments that are more aspheric for a given size; therefore, we have chosen to make the TMT segments 20% smaller than the Keck segments. The smaller segments can also be thinner.

### 8.3.2.2 Requirements

The optical prescription for M1 is described in **Section 7.2.1**. M1 is a hyperboloid with a conic constant of -1.0009535 and a paraxial radius of curvature of 60 meters. The aperture outer diameter is 30 meters.

The M1 functional requirements are driven primarily by system architecture choices. The performance requirements are driven primarily by the error budgets described in **Section 7.4**. These requirements are summarized below.

**Functional requirements**

M1 incorporates 492 hexagonal segments, as described in **Section 7.2.1**. The segmentation pattern is shown in **Figure 8-19**. There are 82 unique types of segments. The pattern of segment types repeats every 60 degrees around the aperture. One spare segment of each type will be provided to allow immediate replacement when a segment is removed for recoating. This means that each segment will be installed in a different sector of the mirror each time it is recoated. Therefore, each segment must have alignment features that position it in precisely the correct position and orientation when it is substituted into the array.

It isn’t possible to divide a curved surface into regular hexagons of uniform size. TMT has developed a scaling approach [1] that minimizes the differences in segments to a few millimeters. To accommodate the different sizes, the Segment Support Assemblies (SSAs) must incorporate features that divide the support forces differently for each type of segment.

To allow the segments to be removed for recoating, the SSA design incorporates a provision for installing a lifting jack that can raise the segment to a level where it can be safely grabbed by a lifting mechanism attached to a Segment Handling Crane (see **Section 8.3.7**). No part of the segment assembly, including its support and edge sensors, may be allowed to extend under a neighboring segment.

The polisher will mount each segment on its respective SSA for final optical testing and figuring. The SSA must be compatible with the optical testing configuration and must work properly as a stand-alone system. When suitably packaged, the segments and their attached SSAs must be able to withstand the transportation environments (temperature, vibration and shock) encountered in moving the mirrors from the polisher to the telescope site.

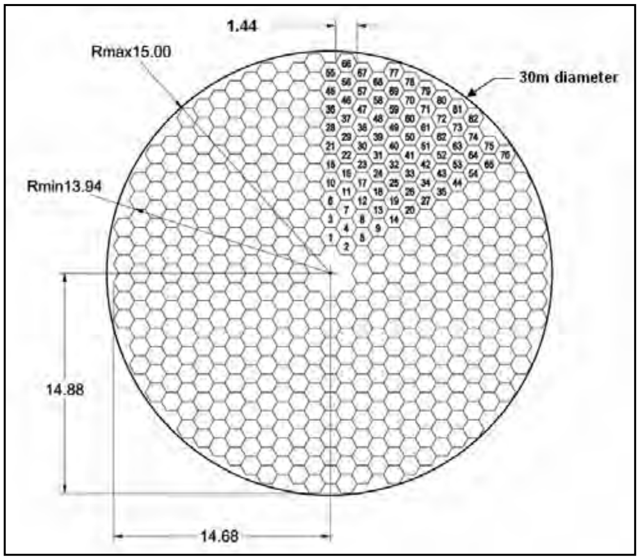



**Fig 8-19: Hexagonal pattern for the TMT primary mirror.**

On the telescope, the segment positions will be initially set using surveying techniques (see **Section 8.3.6.2**). To accommodate this during installation in the telescope, the segment subcells must have a provision for mounting dummy segment weights and must incorporate accurate alignment targets that will be visible from multiple surveying instruments (without blockage from the dummy weights).

The large quantity of segments drives the need for reliability, maintainability and serviceability. In case of failure of a warping harness actuator or M1CS position actuator, it must be possible for a person working in the mirror cell to replace the actuator from below without the need to remove the segment. All components of the M1 and the M1CS must have a high mean time between failures (MTBF). Each of the potential TMT sites is in a strong earthquake zone, therefore it is important for all equipment to be designed so that it can be quickly inspected after an earthquake to assess any damage; this is particularly an issue for M1 because of the large number of segments.

The periodic recoating of the segments imposes additional requirements. The requirement for minimum recoating intervals is 2 years with a goal of 5 years. The segment and the portions of the SSA that will stay with it in the coating chamber must be compatible with the vacuum and coating environment. The segments will be mounted face-down in the coating chamber to reduce coating pinholes caused by dust particles; therefore segment supports must work in this orientation.

All designs must ensure safety of personnel and must safeguard the telescope equipment as well as the rest of the observatory, even in case of a strong earthquake.

**Performance Requirements**

The TMT image size error budget is described in **Section 7.4.2**. The budget for M1 shape errors drives several requirements. Each segment must be polished to the correct aspheric shape and must be accurately tested. The specification document for the polished segments is reference [2]. The error budget requirements must be met at all operational zenith angles. This drives the requirements for the Segment Support Assemblies (SSAs).

The error budget requirements must also be met at all temperatures within the performance conditions (see **Table 6-1**). This places requirements on the design of the segment support assemblies (SSAs) and on the coefficient of thermal expansion (CTE) of the material in the segment blanks [3], summarized in **Table 8-2**.

Each segment must be controlled in tip, tilt and piston – this places requirements on the position actuators and edge sensors of the M1 Control System (M1CS), described in **Section 8.3.5**. The segment support must also be stiff (10 N/μm) and must have a high fundamental resonant frequency (35 HZ) to maintain segment phase in the presence of disturbances, such as wind and ambient vibrations.

Low-order segment figure errors can be compensated by the SSA warping harnesses (see **Table 8-3**). The segment error budgets relate to the residual errors after warping-harness correction.

The TMT AO-corrected wavefront error budget is described in **Section 7.4.3**. To meet this budget, the wavefront errors of M1 must be correctable by the facility AO system, NFIRAOS (see **Section 8.5**) to less than 40 nm RMS. This correctability is limited in spatial frequency and amplitude by the characteristics of available deformable mirrors, described in **Table 8-21**. Therefore, the optical surface formed by the segments must minimize discontinuities and other high spatial frequency errors, and the total amplitude of wavefront errors must be limited. These considerations impose requirements on the segment polishing, the SSA design, the segment material properties, and on the Alignment and Phasing System (APS) (described in **Section 8.3.6.4**) and the M1CS.

**Table 8-2: Material property requirements for the segment blanks.**

| | | |
|---|---|---|
| Average CTE: | 0 ± 40 x 10-9/°K | |
| CTE Variation within the Blank: | 0 ± 10 x 10-9/°K | relative to average CTE of blank |
| Maximum CTE Gradient in the Z Direction: | < 2 x 10-9/°K | |
| Stress in Blank Material: | < 0.2 MPa | anywhere in the blank |

**Table 8-3: Warping harness correction requirements.**

| Aberration | Correction Range* | |
|---|---|---|
| (nm P-V) | Correction Factor | |
| Focus: | 1,000 nm | < 1/15 |
| Astigmatism: | 2,000 nm | < 1/15 |
| Coma: | 200 nm | < 1/5 |
| Trefoil: | 400 nm | < 1/5 |
| * Per each orthogonal Zernike term. | | |

The TMT pointing error budget is described in **Table 7-4** and the pupil alignment budget is described in **Table 7-5**. To meet these budgets the global position and tilt of M1 relative to the telescope structure must be repeatable as a function of zenith angle. This primarily imposes requirements on the mirror cell structure and on the M1CS. M1 must also incorporate alignment features (retro-reflectors) that allow its global position to be accurately measured by the Global Metrology System (GMS) described in **Section 8.3.6.5**.

Requirements on system emissivity, described in **Section 6.1.5.6**, and diffraction effects that scatter energy out of the center of the image, impose limits on the effective width of the gaps (nominally 3.5 mm) between the segments, including the physical gap (nominally 2.5 mm) as well as the edge bevels on the optical surfaces (0.5 mm each side).

Errors in the global shape of M1 can cause spatial and temporal variations in the image scale. The global shape is controlled by the M1CS.

#### 8.3.2.3 Conceptual Design Description

The segments will be attached to the top chords of the mirror cell, which is described in **Section 8.3.1.3**. Servicing of the segment support equipment will be performed by staff working in the mirror cell. The segments, SSAs and mirror cell are shown in **Figure 8-20**.

**Segment Support Assembly (SSA)**
The segment support design is based on the successful Keck approach, with a statically-determinant whiffletree axial support and a central diaphragm lateral support. The TMT mirror cell will have larger fabrication tolerances and structural deflections than the smaller Keck cell, which requires a larger adjustment range in the Subcells and a larger travel range in the actuators and SSA. To minimize stress in the central

diaphragm, the axial and lateral supports are mounted to a moving frame that is controlled in piston and tip/tilt by the position actuators. **Figure 8-21** is a schematic of the SSA.

Each segment is mounted to a Subcell that is attached to the mirror cell structure. To ensure proper alignment of the segments, during installation, the Subcells will be installed on the telescope and adjusted as described in Section 8.3.6.2.

The moving frame is laterally supported by a flexure on a central column that is aligned, with pins, to the fixed frame. Axial support of the moving frame is provided by three actuators attached to the Subcell that control piston, tip and tilt of the segment with respect to the Subcell.

The segment axial support is a two-level whiffletree connected to the segment by 27 flex rods. **Figure 8-22** illustrates the SSA conceptual design.

The warping harnesses incorporate twenty one linear actuators (driven by stepper motors) that can be used to introduce a set of bending moments to adjust the shape of the segment.

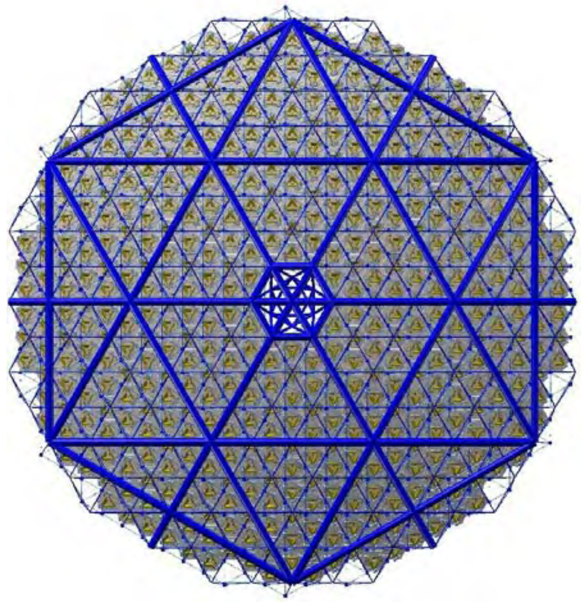


**Fig 8-20: The M1 segments, SSAs and mirror cell, viewed from below.**

**Segments**

There are several potential suppliers of the segment blanks. Possible substrates include fused silica and low expansion glass ceramics.

The thickness of the segments is based on design trades that involve mirror support, thermal inertia and total

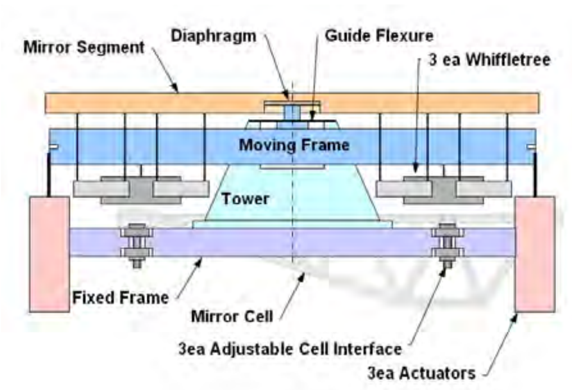



**Fig 8-21: Schematic of the SSA design.**

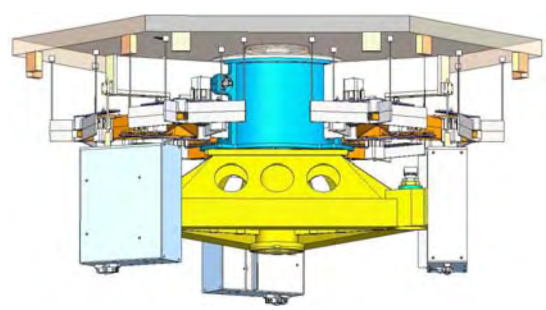


**Fig 8-22: Conceptual design of the SSA.**

mass. Reducing the glass thickness reduces the total mass and the thermal inertia, but requires more support points. For a 27-point axial support, the thickness of the segment can be reduced to 45 mm for a zero-expansion glass-ceramic segment or 50 mm for a zero-expansion fused silica segment.

The finished segments will conform to the parent hyperboloidal shape. From the center to the outer edge of the primary mirror the segment radius of curvature increases from 60 to > 63 meters and the segments go from being almost spherical to having 230 microns peak-to-valley of asphericity (mostly astigmatism).

Each finished segment will have a cylindrical pocket ground into the back side of the segment for the central diaphragm. All surfaces, except the optical surface, will have a commercial grade polish to remove subsurface damage. The optical surface will have a smoother polish and an accurate figure. The SSA will be mounted to the segment prior to final figuring and the acceptance test. This will ensure that the segment figure measured in the optics shop is the same as it will be in the telescope.

Retro-reflectors (e.g. “cat-eyes”) will be mounted at the inner corners of the type 2 segments and at the outer corners of the type 82 segments (the segment types are shown in **Figure 8-19**). These 12 targets will be measured by the GMS to determine the position of M1 relative to the other telescope optics.

**Primary Segment Assemblies**

The combination of the glass segment, SSA, Subcell, edge sensors and attached cabling is called a Primary Segment Assembly (PSA) **Figure 8-23** illustrates one of the PSAs, shown from below, surrounded by its adjacent PSAs. The total mass of the 492 M1 PSAs is 116 metric tonnes. The actuators, which are part of the M1CS, add 11 metric tonnes.

All indications are that the PSAs will meet their functional and performance requirements. A summary of analysis results can be found in reference [4].

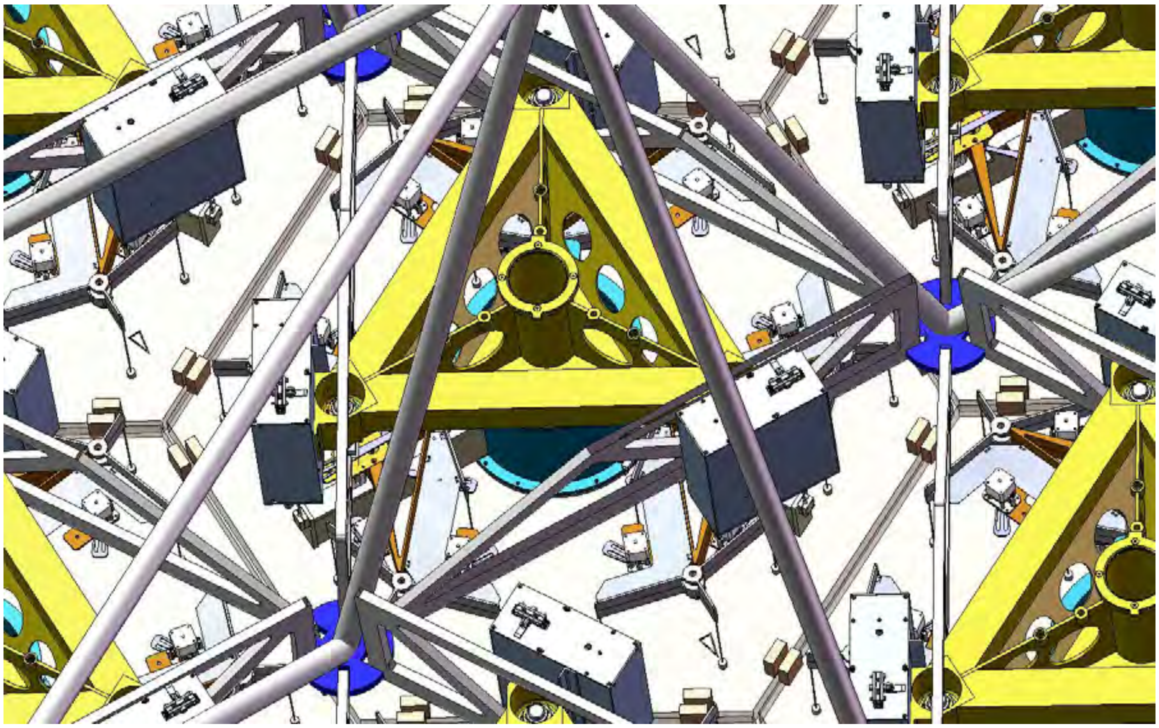


**Fig 8-23: A PSA and its neighbors, shown from below (cables not shown).**

### 8.3.2.4 Development Tasks

**SSA design**

The SSA is being developed by IMTEC, Inc. The preliminary design will be completed and reviewed at the SSA PDR, scheduled for fall 2007. Following the SSA PDR, IMTEC will produce a prototype SSA mounted to an aluminum segment. They will use this initial prototype to evaluate the SSA design prior to the manufacture of additional prototypes. Several copies of the second-generation prototypes will be supplied to the polishers doing the studies described in the following section. Based on the feedback from the polishers, further design changes will be incorporated before completing the final design.

IMTEC will work with the polishers to develop SSA assembly fixtures and procedures.

**Engineering and Manufacturing Design Studies**

TMT has been working with polishing firms to develop segment production methods. In 2005-2006 three contractors – Sagem, Zygo and a team of ITT and Tinsley – conducted Engineering and Manufacturing Design (EMD) studies. These studies included: investigation of production and testing techniques; technology development and risk reduction studies; preparation of production plans and facility layouts; and generation of cost estimates.

In 2007, TMT is initiating a second round of studies that are referred to as EMD2. These studies will include: further developmental activities to reduce technical and schedule risk; evaluation of blank material properties;

development of an optical test bed to measure SSA print-through and warping harness performance, production of 4 prototype segments mounted on SSAs (one for the optical test bed and three for the three segment test assembly described in **Section 8.3.5.3**), and creation of updated production plans, schedules and cost estimates.

It is anticipated that these studies will lead to the initiation of low-rate initial production of segments by at least one polisher before the end of the project Design and Development Phase.

#### 8.3.2.5 Work Plan

**Fabrication of Segment Blanks**

TMT will purchase the segment blanks from a single supplier chosen by a competitive selection process. TMT has requested that all 574 blanks be supplied within 55 months after receipt of order. All four glass suppliers have indicated they can deliver blanks meeting the TMT specification, on that schedule.

The blanks will be generated and ground to the required meniscus shape by the blank supplier.

**Fabrication of Finished Segments**

TMT will down-select to one or two polishers to produce the finished segments. Use of two polishers would reduce technical, schedule and contractual risk, but would incur the cost of setting up two production facilities. TMT has requested that the first 492 segments be delivered within 72 months after receipt of order. One of the goals of the EMD2 program is to prepare at least two of the polishers to be able to meet this schedule by the start of the TMT construction phase.

**Fabrication of SSAs**

The SSA components will be fabricated, partially assembled, and supplied to the polishers in kit form in time for the start of segment production.

The Subcell components will be fabricated, assembled and shipped directly to the observatory.

**Integration at the Observatory**

The assembly, integration and verification (AIV) of the PSAs at the observatory will involve the following steps:

1. Installation of the Subcells onto the mirror cell and attachment of dummy weights;

2. Surveying and adjustment of the Subcells in six degrees of freedom (see **Section 8.3.6.2**);

3. Incremental installation of the M1CS actuators, ahead of the segment installation

4. Preparation of the PSAs, including:

    4.1. Unpack, clean and inspect;

    4.2. Install edge sensors (see **Section 8.3.5.3**);

    4.3. Apply reflective coating (see **Section 8.3.7.1**);

5. Installation of the segments, starting from the center;

6. Verification of the alignment of the initial 120 segments with the prime focus camera (PFC) (see **Section 8.3.6.3**);

7. Alignment and phasing of the segments with the APS (see **Section 8.3.6.4**).

### *References*


[1] TMT M1 Segmentation Database, Eric Ponslet, March 6, 2007, TMT.OPT.SPE.07.006.

[2] Specification for Finished 1.44-m Primary Mirror Segments, B. Platt & L. Stepp, March 7, 2007, TMT.OPT.SPE.07.004.

[3] Specification for Primary Mirror Segment Blanks, B. Platt & L. Stepp, January 26, 2007, TMT.OPT.SPE.07.001.

[4] TMT SSA Preliminary Design Overview - Interim Report, E. Williams, May 10, 2007, TMT.OPT.PRE.07.015.

### 8.3.3 Secondary Mirror Assembly

#### 8.3.3.1 Overview

The secondary mirror (M2) reflects the light from the f/1 primary mirror and converts it to an f/15 beam for the science instruments. The mirror is a large, convex hyperboloid.

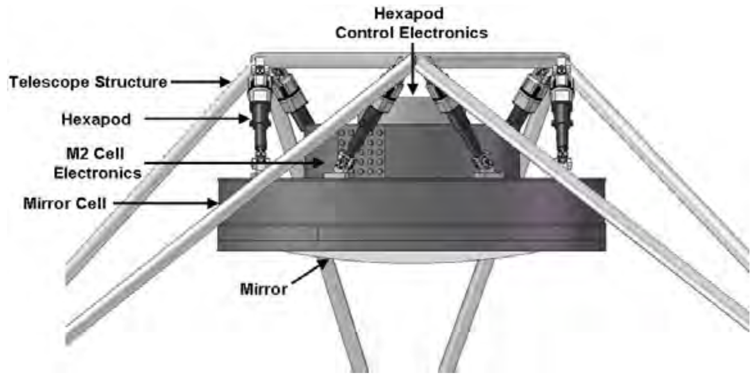



**Fig 8-24: Configuration of Secondary Mirror Assembly (Laser Launch Telescope removed for clarity).**

The secondary mirror assembly includes the mirror, cell, positioner, control electronics, and software, along with the associated interfaces to the telescope structure. The cell is a steel weldment structure that contains the axial and lateral supports for the mirror. The mirror supports are active and can correct low-order aberrations including residual polishing figure errors and the effects of changing zenith angle (gravity) and temperature. The hexapod positioner is used to control five rigid body degrees of freedom of the M2. The hexapod will be used to correct telescope structural deformations due to gravity and temperature.

The control electronics and software provide the local servo control loops for the hexapod positioner and the mirror support. The Telescope Control System (TCS) provides the high level control for the positioner and mirror support systems.

An annotated schematic of the Secondary Mirror Assembly is shown in **Figure 8-24**.

#### 8.3.3.2 Requirements

The optical prescription for the M2 is described in **Section 7.2.1**. The M2 is a convex hyperboloid with a conic constant of -1.31822813 and a paraxial radius of curvature of 6.22768 meters. The clear aperture outer and inner diameters for a 15 arc minute field of view are 3.025 and 0.210 meters, respectively.

**Functional Requirements**

The M2 must maintain the correct optical shape and remain aligned with the other telescope optics. The focus adjustment of the telescope is accomplished by moving the M2 in the Z- direction. The M2 Positioner must be able to control the M2 position and orientation in five degrees of freedom (rotation about the optical axis has no optical significance). Retro-reflectors at the edge of the M2 will allow measurements of the mirror position by the Global Metrology System (GMS), described in **Section 8.3.6.5**.

To minimize flexure of the relatively thin members in the upper telescope structure, the mass of the M2 Assembly must be limited – the total mass has been specified to be < 6,000 kg.

To limit the obscuration of the telescope entrance pupil by the M2 Assembly, the diameter of the M2 Assembly shall be less than 3.6 meters. All components of the mirror cell, positioner and control electronics will be inside this diameter. This is similar in size to the seven segments left out of the center of M1.

Because it is close to the enclosure entrance aperture, the M2 Assembly will be subjected to relatively high air flow velocity. To minimize wind shake of the telescope, the cross sectional area of the M2 Assembly must be limited, and the external surfaces must be streamlined to reduce drag. The specified cross-sectional area for the M2 Assembly, in combination with the Laser Launch Telescope mounted above it, is < 10 square meters from any orientation. The average drag coefficient of the M2 Assembly will be less than 1.5, from any orientation.

The design of the M2 Assembly must ensure safety of personnel and must safeguard the telescope and other equipment of the observatory. Because of its high position in the telescope, two concerns are particularly important: avoiding hazards from falling parts; and limiting damage from an earthquake whose accelerations may be amplified by coupling to the resonances of the telescope structure. Particular attention will be paid to providing safety restraints and making all service panels and fasteners captive.

The M2 Assembly will be designed for reliability, maintainability and serviceability. All components that are likely to fail in service shall be replaceable from the back side of the mirror cell with the telescope horizon pointing. The M2 Assembly design will be compatible with in-situ $CO_2$ snow cleaning and water-detergent washing of the M2, with catchment trays to prevent fluids from dripping during washing. The M2 and mirror cell will be compatible with all equipment and processes involved in stripping and replacing the reflective coating.

**Performance Requirements**

The performance requirements are driven by the error budgets described in **Section 7.4.2**. TMT is a complex integrated system and the connection of the M2 performance to the error budgets is similarly complex.

Rigid body motion of the M2 will cause: (1) image jitter; (2) static wavefront errors (primarily focus, coma and astigmatism); (3) telescope pointing errors; (4) pupil instability; and (5) image scale errors.

The M2 optical surface figure must satisfy: (1) the image size budget; (2) the AO-corrected wavefront error budget; and (3) the image scale budget.

Temperature changes of the M2 system will cause: (1) thermal distortion of the M2 optical surface figure (M2 shape errors); (2) local seeing effects due to heat transfer from the mirror or mechanical surfaces to the air.

Many of the errors of the M2 system will be corrected by compensating adjustments. The active optics control architecture of the telescope is described in **Section 7.3.1** and **Section 8.3.5.1**. In general, the error budgets identify the residual errors after active and adaptive corrections have been applied.

In seeing-limited mode, M2 optical surface figure errors can be corrected by: (1) the active optics capabilities of the M2 mirror support system; and (2) adjustments of M1 figure by the M1 Control System (M1CS). Correcting M2 errors in M1 will introduce field-angle-dependent errors, but for low-spatial-frequency errors these effects will be small.

In AO-corrected mode, M2 optical surface figure errors can also be compensated by the deformable mirror (DM) in the adaptive optics systems.

The M2 mirror support active optics system will operate in an open-loop mode with look-up tables for zenith angle and temperature, based on calibration runs with the Alignment and Phasing System (APS) (see **Section 8.3.6.4**). Compensation by the M1CS will be based (in the seeing-limited mode) on a low-order wavefront sensor in the instrument, with the exception that focus and coma errors will be corrected by rigid-body motions of the M2. In the AO-corrected mode, compensation by the M1CS will be based on off-loading of the corrections from the AO DM.

M2 positioning control will be open loop with look-up tables based on measurements by the APS. In addition, closed-loop adjustments will be made to compensate for focus and coma. These must be done in a manner that doesn't affect pointing accuracy or pupil stability. See **Table 8-7**.

The following tables include some of the key performance requirements. The numbers are preliminary and reflect work in progress. **Table 8-4** includes a set of wavefront error allocations for the M2 mirror surface, before active optics and adaptive optics corrections, expressed in nm RMS. The correspondence between these wavefront error allocations and the image size error budget assumes a distribution of spatial frequencies with the same PSD as a Kolmogorov turbulence model of the atmosphere. **Table 8-5** includes a set of requirements for the M2 Positioner.

#### 8.3.3.3 Conceptual Design Description

The secondary is a 3 m diameter convex mirror. To put this in context, this is about the same size as the primary mirror of the Shane telescope at Lick Observatory on Mt. Hamilton. Thus, the initial design of the cell assembly and support system were patterned after primary mirrors of similar diameter. The major difference is the orientation, face down at zenith pointing.

A key design decision is the type of mirror substrate. Options include a lightweight structured mirror, a segmented mirror, and a uniform-thickness meniscus mirror. The meniscus mirror was chosen because it will have smooth support print-through bumps and no edge discontinuities, therefore the print-through on its surface can be almost completely compensated by the adaptive optics systems.

**Table 8-4: Preliminary Wavefront Error Budget Allocation for M2 Mirror Figure, before active optics and adaptive optics corrections.**

| Error Source | Wavefront Error Budget Allocations (RMS, nm) | |
|---|---|---|
| | At Zenith | At 65 degrees Elevation |
| Mirror supports | 57 | 73 |
| Polishing Error | 83 | 83 |
| Thermal Effects | 38 | 38 |
| Coatings Effects | 14 | 14 |
| Look-up Table Error | 25 | 25 |
| **Total (RSS)** | **112** | **122** |

**Table 8-5: Preliminary requirements for M2 Positioner.**

| Parameter | Value | Units |
|---|---|---|
| Z Range (focus) | ± 15 | mm |
| X, Y Range | ± 15 | mm |
| Control Resolution | 1 | micron RMS |
| Tilt Range | ± 2 | mrad (at M2) |
| Control Bandwidth | < 1 | Hz. |
| Capacity | 5,000 | Kg |

The conceptual design uses an axial support with 60 actuators in a hexapolar pattern and 24 passive lateral supports distributed around the edge of the mirror as shown in **Figure 8-25**. Finite-element analysis results for 1-g print-through cases for the axial and lateral supports are shown in **Figures 8-26** and **8-27**, respectively [1] However, the support print-through will be polished out at the zenith-pointing position (i.e. face down). As the telescope moves away from the zenith, the inverse of the axial support print-through will increase with zenith angle as (1 – cos(Z)) and the lateral support print-through will increase as sin(Z), where Z is the zenith angle.

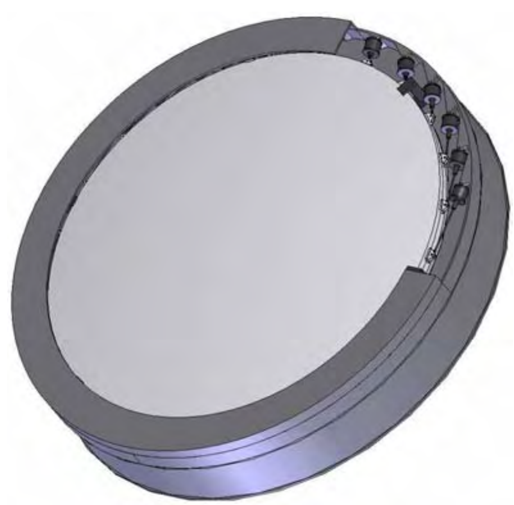


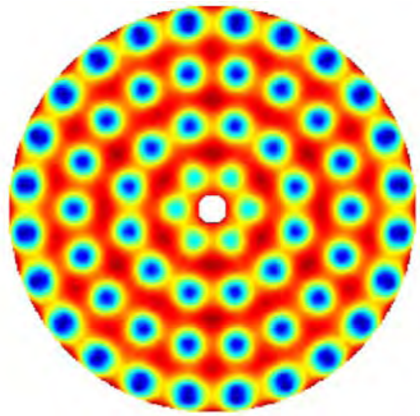
**Fig 8-25: M2 Cell Assembly, with part of the aperture cover removed to show the edge lateral supports.**

The M2 positioner is a hexapod, i.e. a six-legged Stewart platform. A conceptual design of the M2 positioner has been developed [2] by CSA Engineering, Inc, http://www.csaengineering.com/ . The design, developed from commercially available components, was optimized to meet the requirements for payload capacity, stiffness and motion resolution. **Figure 8-28** shows the hexapod geometry recommended by CSA.

The Alignment Plan for M2 is described in **Section 8.3.6**.

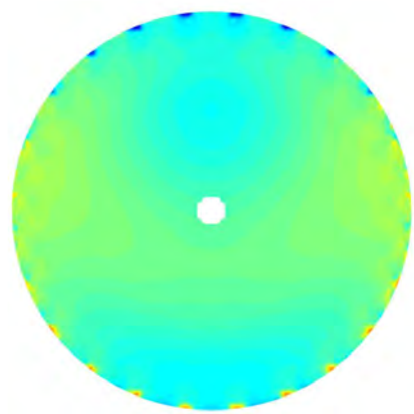
The cell and positioner are controlled by two independent low level control systems. It is envisioned that these low level control systems will be provided by the suppliers of the M2 assembly and the positioner respectively. The Telescope Control System (TCS) will provide a software adaptor around each system as well as providing the required high level control. See **Section 8.3.5**. The bandwidth of the low level M2 support control system will be less than 0.1 Hz and the bandwidth or the hexapod will be less than 1 Hz.

The local M2 control systems will be packaged in thermally insulated enclosures and will utilize the observatory supplied chilled coolant system to actively remove the thermal load.



P-V: 49 nm surface; RMS: 10 nm surface

**Fig 8-26: M2 Axial support print-through, with 60 axial supports, at horizon pointing (print-through is polished out at zenith).**



P-V: 14 nm surface; RMS: 2 nm surface

**Fig 8-27: M2 Lateral support print-through, with 24 edge lateral supports, at horizon pointing.**

**Coating**

There will be a coating chamber large enough to coat the M2 at the observatory. The baseline coating orientation is face down, to reduce the number of pinholes caused by particles on the surface of the mirror during the recoating process.

A dome-mounted crane and service platform will be used to remove the M2 Cell Assembly from the telescope structure and lower it to a cart on the floor. The assembly will be moved to the cleaning and stripping room, where the mirror will be prepared for re-coating. After re-coating it will be moved back to the dome floor where it will be lifted and re-installed in the telescope structure. The coating chamber and mirror handling equipment are described in **Section 8.3.7**.

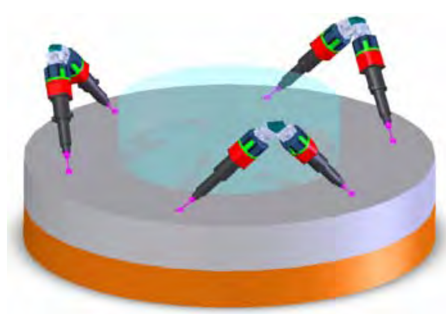


**Fig 8-28: Illustration of the hexapod geometry evaluated by CSA Engineering for the M2 Positioner.**

#### 8.3.3.4 Development Tasks

Key development tasks include: development of prototype axial and lateral support actuators; and studies to develop the method of testing the large convex secondary mirror. Optical testing of large convex mirrors requires specialized auxiliary optics, and can require stitching together of multiple interferograms to encompass the full optical surface. These tasks will be carried out by contractors as described below.

#### 8.3.3.5 Work Plan

The initial conceptual design of the M2 Assembly was created and analyzed by the AURA New Initiatives Office. Further design work will be performed by contractors.

After an RFP process, two contractors will be selected to develop preliminary designs for the M2 Cell Assembly (not including the positioner). As part of this work, they will prepare a detailed cost estimate and schedule for the design and fabrication of the M2 Cell Assembly, and will perform the study mentioned above to develop the method to be used in testing the large convex mirror.

There will subsequently be a down-select to a single contractor for the final design and fabrication of the M2 Cell Assembly. The contract for the M2 Cell Assembly will include polishing and testing the mirror, design and fabrication of the mirror cell, and integration of the assembly in the optics shop.

TMT plans to contract separately for the mirror blank and for the M2 positioner, with a competitive vendor selection process for each.

### *References*


[1] TMT M2 Performance prediction, Ritchey-Chrétien design, May 11, 2007, TMT.OPT.PRE.07.019.

[2] Secondary Mirror Positioner Concept Design, Michael Cash and Greg Pettit, CSA Engineering, Inc., February 28, 2006, TMT.OPT.CDD.06.002.


### 8.3.4 Tertiary Mirror Assembly

#### 8.3.4.1 Overview

The Tertiary Mirror (M3) is a large, optically-flat mirror that is used to direct the telescope image to the multiple instruments on both Nasmyth platforms. The M3 must be able to switch among the science instruments rapidly and precisely, and it must be able to track in two axes to keep the beam aligned with the instrument as the telescope changes zenith angle. One of these axes (the "rotation" axis) is coincident with the M1 optical axis, and the other (the "tilt" axis) is perpendicular to that axis. The optical surface of the M3 passes through the intersection of the telescope elevation and azimuth axes and rotates and tilts about that point.

The M3 Assembly, shown in **Figure 8-29**, includes the mirror, cell, positioner, control electronics, cables, cable wrap and software, along with the associated interfaces to the telescope structure.

The cell is a steel weldment structure that contains the axial and lateral supports for the mirror. The mirror supports are active and can correct low-order aberrations including residual figuring errors and the effects of changing zenith angle (gravity) and temperature.

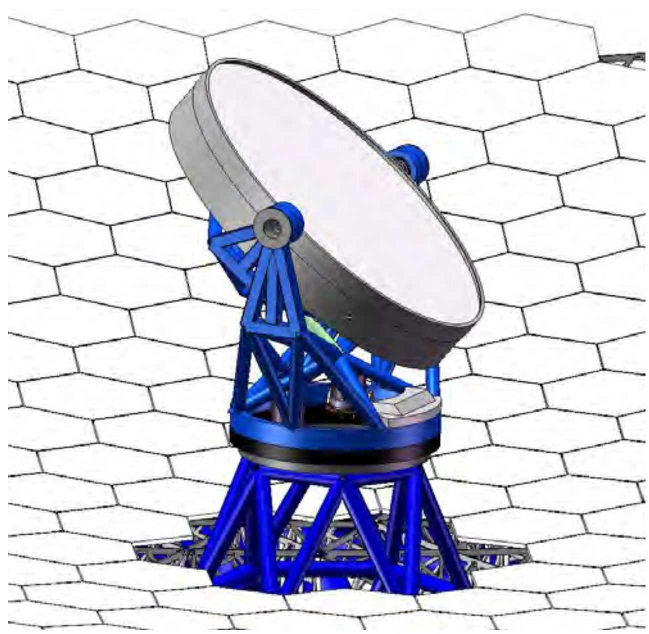


**Fig 8-29: Tertiary Mirror (M3) Assembly.**

The control electronics and software provide the local servo control loops for the M3 positioner and the mirror support. The Telescope Control System (TCS) provides the high level control for the positioner and mirror support systems.

#### 8.3.4.2 Requirements

**Functional Requirements**

As stated in **Section 7.2.1**, the clear aperture of the M3 optical surface is an ellipse with minor axis of 2.450 m and major axis of 3.508 m, providing a 15 arc minute unvignetted field of view.

The M3 Assembly must be able to direct the science beam to any instrument within the range of instrument positions specified in **Section 7.2.3**. To address all the instruments and to meet servicing needs, the M3 Positioner must have a rotation range of ±180 degrees. The tilt range of motion is from 32 to 48 degrees, with this angle measured between the M1 optical axis and the M3 surface normal vector.

The M3 must remain flat and meet surface figure specifications at all operational orientations. The support of the M3 is more complex than typical alt-az telescope mirrors. The gravity vector has changing components in all three orthogonal directions in the M3 local coordinate system. Active optics control of the M3 figure is required to compensate for support errors and uneven thermal expansion.

To minimize M3 misalignment caused by deflection of its supporting structure, the mass of the M3 Assembly must be minimized – the total mass has been specified to be < 8,000 kg.

The entire M3 Assembly must fit within a 3.50 m diameter cylinder centered about the M1 optical axis, at all observing orientations, to avoid obscuration of the telescope entrance pupil.

Retro-reflectors at the edge of the M3 will allow measurements of the mirror position by the Global Metrology System (GMS), described in **Section 8.3.6.5.**

The M3 Assembly will be designed for reliability, maintainability and serviceability. All components that are likely to fail in service will be replaceable from the back side of the mirror cell with the telescope zenith pointing. The M3 Assembly design will be compatible with in-situ $CO_2$ snow cleaning and water-detergent washing of the M3, incorporating catchment trays to prevent fluids from dripping during washing. The M3 and mirror cell will be designed to allow safe and efficient removal and replacement for recoating and will be compatible with all equipment and processes involved in the stripping and deposition of the optical coating.

The design of the M3 Assembly must ensure safety of personnel and must safeguard the telescope and other equipment of the observatory. The M3 assembly will be serviced with the telescope zenith-pointing, by personnel who ascend into the center of the assembly through the rotation bearing of the M3 positioner. The cable wraps will leave adequate room for this access. The control electronics will be mounted in accessible locations. Because of the proximity to M1 segments, particular attention will be paid to providing safety restraints and making all service panels and fasteners captive. The overall dimensions of the M3 Assembly must also leave adequate clearance for the segment handling cranes to reach the innermost segments (see **Section 8.3.7.3**).

**Performance Requirements**
The performance requirements are driven by the error budgets described in **Section 7.4**.

Rigid body motion of the M3 will cause: (1) image jitter; (2) telescope pointing errors; and (3) pupil instability.

M3 optical figure errors will cause: (1) an increase in the image size; (2) an increase in the AO-corrected wavefront; and (3) a change in image scale.

Temperature changes of the M3 system will cause: (1) thermal distortion of the M3 optical surface figure; and (2) local seeing effects due to heat transfer from the mirror or mechanical surfaces to the air.

Many of the errors of the M3 system will be corrected by compensating adjustments. The active optics control architecture of the telescope is described in **Section 7.3.1** and **Section 8.3.5.1**.

In seeing-limited mode, M3 optical surface figure errors can be corrected by: (1) the active optics capabilities of the M3 mirror support system; and (2) adjustments of M1 figure by the M1 Control System (M1CS). Correcting M3 errors with M1 will introduce field-angle-dependent errors, but for low-spatial-frequency errors these effects will be small.

In AO-corrected mode, M2 optical surface figure errors can also be compensated by the deformable mirror (DM) in the adaptive optics systems.

Key performance requirements for the M3 Assembly are listed in **Table 8-6**. The correspondence between wavefront error allocations and the image size error budget assumes a distribution of spatial frequencies with the same PSD as a Kolmogorov atmosphere.

#### 8.3.4.3 Conceptual Design Description and Options

The conceptual design for the M3 Assembly was developed by a team at the National Optical Astronomy Observatory [1]. It incorporates a large rolling-element bearing for the azimuth rotation axis and smaller trunnion bearings for the tilt axis. The current design has been reduced in size from the original concept because of the adoption of the Ritchey-Chrétien optical design. The M3 is currently 2.506 x 3.522 meters, including margin around the edge of the clear aperture.

The mirror substrate is a 100-mm thick solid mirror of zero-expansion glass. The solid mirror was chosen over other potential types of substrates because it will produce only smooth support print-through bumps and no edge discontinuities in the aperture. This facilitates compensation of mirror figure errors by the AO system.

The mass of the mirror itself is 1.75 metric tonnes.

The mirror support has 60 combined axial-lateral support actuators in a stretched hexapolar pattern. The support mechanisms are attached to the back of the mirror. **Figure 8-29** presents results of finite-element analyses [2] for self-weight load cases with gravity in three orthogonal directions.

The positioner uses a dual-motor helical gear drive on the rotation axis, and a linear actuator to drive the tilt axis. The mechanisms are different because of the different ranges of motion.

The mirror supports and positioner will be controlled by low level control systems, developed by the supplier of the M3 Assembly. The mirror support active optics system will operate in an open-loop mode with look-up tables for zenith angle and temperature, based on calibration runs with the Alignment and Phasing System (APS) (see **Section 8.3.6.4**). M3 positioning control will be open loop with look-up tables based on pointing tests and measurements by the APS and GMS. See **Table 8-7**.

The Telescope Control System (TCS) will provide a software adaptor around each system as well as providing the required high level control, as described in **Section 8.3.5**. The bandwidth of the low level M3 support control system will be less than 0.1 Hz and the bandwidth of the positioner will be less than 1 Hz.

The local control systems will be packaged in thermally insulated enclosures and will utilize the observatory supplied chilled coolant system to actively remove the thermal load.

**Table 8-6: Key Requirements for M3 Assembly**

| **Parameter** | **Requirement** |
|---|---|
| **Positioner** | |
| Rotation range | ± 180 degrees |
| Tilt range | 40 ± 8 degrees |
| Time to switch beam between instruments | < 3 minutes |
| Maximum tracking velocity (rotation axis) | 7 arcsec/sec |
| Maximum tracking velocity (tilt axis) | 3.5 arcsec/sec |
| Pointing repeatability (rotation axis) | < 2.5 arcsec |
| Pointing repeatability (tilt axis) | < 5 arcsec |
| Tracking error | < 65 mas RMS at M3 |
| Positioner capacity | 8,000 kg |
| **Mirror** | |
| Polishing figure error over one beam footprint* | 46 nm RMS surface** |
| Support figure error over one beam footprint* | 10 nm RMS surface** |
| Support thermal effects* | 46 nm RMS surface** |
| * At zenith, before AO correction.<br>** Wavefront error after reflection at 45° is √2 x the surface error. | |

**Coating**

The coating chamber at the observatory will be large enough to coat the M3. The baseline coating orientation is face down, to reduce the number of pinholes caused by particles on the surface of the mirror during the coating process.

Removal of the M3 for recoating will be done with the telescope locked at a zenith angle of 45 degrees and the M3 rotated to face upwards in that position. A mobile crane will extend its boom upwards from floor level to suspend a lifting harness above the M3 cell, as shown in **Section 8.3.7**. Connection of the lifting harness to the M3 cell will be semi-automatic. The cell will have deployable bars that guide the lifting harness into position and actuators that make the connection. Disengagement of the M3 cell from the positioner will also be by means of actuators.

#### 8.3.4.4 Development Tasks

Key development tasks include: development of prototype support actuators; studies of bearing smoothness under load; and studies to develop a cost-effective method of testing the large flat tertiary mirror. These tasks will be carried out by contractors as described below.

#### 8.3.4.5 Work Plan

After a selection process, two contractors will be chosen to develop preliminary designs for the M3 Assembly. As part of this work, they will prepare a detailed cost estimate and schedule for the design and fabrication of the M2 Cell Assembly, and will perform the studies mentioned above.

There will subsequently be a down-select to a single contractor for the final design and fabrication of the M3 Assembly. The contract will include polishing and testing the mirror, design and fabrication of the mirror cell, support system, positioner, cable wrap and control electronics, and integration of the assembly in the contractor's shop.

TMT plans to contract separately for the mirror blank.

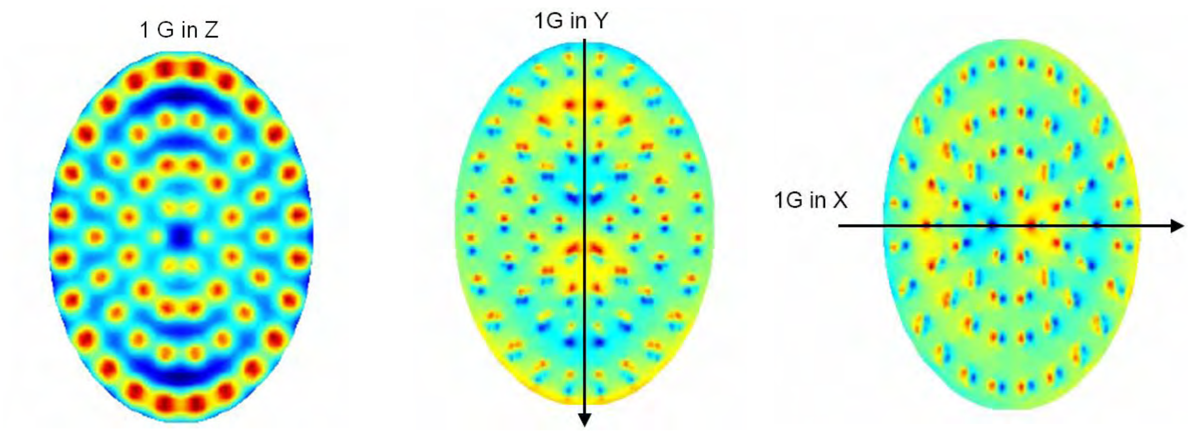



**Fig 8-30: Print-through of the M3 supports for three orthogonal gravity directions. Indicated values are surface (rather than wavefront) and are for a single star footprint. At zenith-pointing, the combined print-through will be 70% of the superposition of Cases 1 and 2. At the horizon, the print-through will be equal to Case 3.**

## References

[1] D. Blanco, M. Cho, L. Daggert, P. Daly, J. DeVries, J. Elias, B. Fitz-Patrick, E. Hileman, M. Hunten, M. Liang, M. Nickerson, E. Pearson, D. Rosin, M. Sirota, L. Stepp, "Control and support of 4-meter class secondary and tertiary mirrors for the Thirty Meter Telescope", *Optomechanical Technologies for Astronomy*, ed. E. Atad-Ettedgui, J. Antebi and D. Lemke, SPIE Proc. 6273, 2006; TMT.OPT.JOU.06.002.

[2] M. Cho, TMT M3 Performance prediction, Ritchey-Chrétien design, May 11, 2007, TMT.OPT.PRE.07.018.

### 8.3.5 Telescope Controls and Software

#### 8.3.5.1 Overview

Telescope Controls and Software consists of the systems listed below[4].

- Telescope Control System (TCS)
  - o The TCS includes adaptors and high level control for the M2, M3, and enclosure systems[5]

[4] Although the Alignment and Phasing System (APS) is contained under the WBS for Telescope Controls the APS is described in Section 8.3.6.4 due to its unique functionality and critical importance.

[5] The M2 and M3 systems (mirrors, support systems, rigid body positioners, and low level controls) are envisioned to be procured as turn key systems. The WBS and the organization of this construction proposal reflect this vision therefore the low level control of M2 and M3 is described in Sections 8.3.3 and 8.3.4 rather than in this section. Telescope Controls and Software will provide the necessary wrappers, adaptors, and high

- M1 Control System (M1CS)
- Mount Control System (MCS)
- Test Instrument Control (TINC)
- Telescope Safety System (TSS)
- Engineering Sensors (ESEN)
- Commissioning Acquisition and Guiding System (CAGS)
- Power Lighting and Grounding (PL&G)

The TMT is the first ground based observatory to be designed from conception with fully integrated active optic systems, adaptive optic systems, laser guide star systems, and instrument systems. Although the system decomposition and associated interfaces are optimized to minimize unnecessary inter-system coupling, the architecture and design explicitly acknowledges that TMT is a complex system-of-systems. Telescope Controls alone is responsible for over 30,000 I/O channels and nearly 12,000 degrees of freedom (DoF).

The TMT active optics (aO) system consists of the Mount, M1, M2, M3 systems; the Alignment and Phasing System (APS); and the wave front sensing functionality that is embedded within the instruments, AO systems, and the APS. See **Figure 7-9**. The Telescope Controls and Software provides the functionality required to coordinate and control the telescope including, but not limited to, the mount, enclosure, and the M1, M2, and M3 control systems. **Figure 8-31** illustrates the various telescope control systems from a functional perspective.

The aO architecture consists of several nested control loops, which work in combination to minimize image jitter, image blur, and pupil motion. The inner control loops are typically closed on a local encoder or transducer; for example an encoder in the case of the mount. The inner loop receives commands from a look up table (LUT)[6]. The middle control loop refreshes the LUT set-points, often with on-sky optical measurements, on time scales of days, weeks, or months. The outermost control loop is closed in real time with on-sky, optical measurements. The update times for the outermost control loops are in the range of fractions of seconds to minutes.

The M1, M2, and M3 systems each contain the functionality to control rigid body DoF as well as higher order modes via shape actuators. Rigid body control of M1 is via three actuators per segment (see **Section 8.3.2**), M2 rigid body control is via a Hexapod (see **Section 8.3.3**), and M3 rigid body control is via a two axis positioner (see **Section 8.3.4**). The TCS, M1, M2, and M3 control systems include rigid body LUTs that contain the required set-points. The rigid body LUTs are created offline by the TCS based on APS measurements, complemented with data gathered by surveying or the Global Metrology System (GMS). The LUTs will support functions of zenith angle (gravity) and temperature. The initial data for the M1 rigid body segment LUT is determined by a calibration process during sensor installation. Initial data for the M1 global tip/tilt piston LUTs are determined via surveying. Initial data for the M2 and M3 rigid body LUTs are based on surveying.

M1 shape control is accomplished via warping harnesses. See **Section 8.3.2**. Control of M2 and M3 shape is accomplished via their respective support systems. See **Sections 8.3.3** and **8.3.4**. The M1, M2, and M3 control systems include shape LUTs that contain set-points for their respective "shape" control systems. The shape LUTs are created offline by the TCS based on measurements by the APS. The LUTs will support functions of zenith angle (gravity) and temperature. Initial data for the M2 and M3 shape LUTs will be determined by the vendors who supply the respective systems. Initially, prior to APS measurements, the M1 warping harness LUTs will be set to the unloaded condition.

The APS will be used to align and phase M1 every time new segments are installed. The APS alignment and phasing measurements can be accomplished in parallel for all 492 segments; hence all M1 rigid body and shape LUTs can be updated every time APS is used - approximately every ten to twenty days when newly coated segments are installed. The zero points for the M2 and M3 rigid body LUTs will be updated on a time scale that is similar to that of M1 updates; LUT updates for gravity and temperature will occur every one to two

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level control necessary to interface the vendor supplied systems to the telescope control systems. The same is true of the enclosure system.

[6] The definition of LUTs includes analytic expressions as well as explicit n-dimensional tables. Typically LUTs are functions of one or more variables, most often zenith angle and temperature, although additional dependencies are possible. The LUTs typically contain set-points for a closed loop control system. The LUTs are updated on time-scales of days, weeks or even months in contrast to the much faster time-scales of true real time control systems.

years. The M2 and M3 shape LUTs will also be updated every one or two years. It will take APS approximately two hours, using star-light, to align and phase M1 and determine the zero point corrections for M2 and M3. In order to minimize the loss of observing time, APS can be used in twilight to make these measurements.

The azimuth and elevation telescope mount commands will be based on the time and the right ascension and declination coordinates of the selected science object. Corrections to the idealized telescope will be made via a TCS LUT (pointing model). Pointing models will be updated on a monthly basis. Once the M1, M2, and M3 LUTs are determined and a pointing model is built it will be possible for the telescope systems to run without the outermost real time control loop. On the other hand without real time optical feedback from an on instrument wave-front sensor (OIWFS) or off-loads from the AO system, performance is not expected to be adequate as a result of un-modeled errors and drifts.

In seeing limited operation, wave front tip/tilt, focus, coma, and low order radial modes will be measured via an OIWFS. The TCS will utilize these measurements to correct tip/tilt image motion errors via the mount, coma errors via M2 decenter and/or tip/tilt, focus errors via M2 piston; low order radial modes will be corrected via M1. The process of correcting tip/tilt errors on the mount has historically been called guiding. The M3 control baseline is to operate without any real time optical feedback, although the control design will support pupil corrections via feedback from the instruments or APS. During AO observations the aO corrections will be based on the time-averaged position of the AO tip/tilt stage and the time-averaged position of the AO deformable mirror (DM); up to 100 modes can be offloaded. The characteristics of each of the nested aO loops are listed in **Table 8-7**. Additional corrections to the M2 LUTs, beyond those described **Table 8-7**, may be implemented via FEA and thermal models.

The APS (see **Section 8.3.6.4**) contains an acquisition camera and a low order WFS. Together these components will act as a surrogate instrument from the perspective of the telescope. The acquisition camera and WFS will be used to integrate and verify telescope pointing and aO loop performance prior to telescope integration with an instrument or AO system. In addition the APS acquisition camera and WFS will be utilized throughout the life of the observatory for engineering and performance improvements of acquisition, pointing, and the aO loops.

**Table 8-7: Characteristics of the nested active optic loops**

| | | Inner Control Loops Local Encoder Feedback | | | | | | Middle Control Loop LUT Feedback | | Outer Control Loop Real Time Optical Feedback | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | | DOF | Actuators | Sensors | Sample/ Update Rate (Hz) | Loop BW (HZ) | LUT(ZA,T)[7] Command Rate[8] (HZ) | LUT(ZA,T)) Source | LUT(ZA,T) Refresh Rate | Sensor | Sample/ Update Rate (Hz) | Loop BW[1] (Hz) |
| Mount | Azimuth & Elevation | 2 | DDL motors[9] | Tape encoder | ≥ 40 | ~ 1 | 20 | Pointing tests | Monthly | OIWFS[10] | 5 | ~ 0.3 |
| M1 | Global Tip, Tilt, Piston | 3 | Segment actuators | Actuator sensors | 20 | ~ 0.5[11] | 0.1 | Surveying | >>1 year | No outer control loop | | |
| | Segment Tip, Tilt, Piston | 1476 | Segment actuators | Edge sensors | 20 | ~ 0.5[5] | 0.1 | APS | 2 to 4 weeks[12] | OIWFS[13] | 0.1 | 0.001 to 0.01 |
| | Warping Harness | 10,332 | Warping harness | Strain gauge | na[14] | na[8] | On average < 10x/night | APS | 2 to 4 weeks | No outer control loop | | |
| M2 | De-center | 2 | Hexapod | Local encoders | 20 | < 1 | 0.1 | APS/GMS[15] | See note[16] | OIWFS[17] | 1.0 | 0.01 to 0.1 |
| | Tip/Tilt | 2 | Hexapod | Local encoder | 20 | < 1 | 0.1 | APS/GMS[9] | | | | |
| | Piston | 1 | Hexapod | Local encoder | 20 | < 1 | 0.1 | APS/GMS[9] | 2 to 4 weeks | OIWFS[18] | 0.1 | ~ 0.01 |
| | Shape | 82 | Hydraulic Actuators | Load cells | 1 | < 0.1 | 0.1 | APS | > 1 year | No outer control loop | | |
| M3 | Tilt | 1 | DC drive | Local encoder | 20 | < 1 | 0.1 | APS & surveying | > 1 year | No outer control loop[19] | | |
| | Rotation | 1 | DC drive | Local encoder | 20 | < 1 | 0.1 | APS & surveying | > 1year | No outer control loop[13] | | |
| | Shape | 120 | Hydraulic Actuators | Load cells | 1 | < 0.1 | 0.1 | APS | > 1 year | No outer control loop | | |

[7] In general look up tables are functions of zenith angle (ZA) and temperature (T); additional dependencies are also possible.
[8] The actual command rate may be faster as a result of required profiling and trajectory control
[9] Direct drive linear motor
[10] WFS Tip/Tilt (image motion) will be corrected via the mount (guiding). In AO mode the outer loop image motion feedback is not based on the OIWFS but rather via an offload of the time averaged position of the AO tip/tilt stage.
[11] The global M1 control bandwidth is 0.5 Hz. The control bandwidths of the individual segments will be approximately 20 Hz; individual actuator bandwidths will be 30 to 50 Hz.
[12] Zero point only. Zenith angle and temperature dependence will be updated on approximately a yearly basis or whenever M2 and M3 are recoated (~ every 2 years).
[13] In seeing limited mode low order radial modes will be corrected on the M1. In AO mode the outer loop feedback is not based on the OIWFS but rather on an offload based on the time averaged shape of the AO deformable mirror (DM); up to ~ 100 modes will be offloaded.
[14] Warping harness will be adjusted as a function of zenith angle and temperature. A bandwidth requirement is not relevant.
[15] The GMS may be used on a nightly basis to correct the zero point drifts of the M2 LUTs as a result of un-modeled (primarily temperature) error sources.
[16] On a 2 to 4 week basis (based on the frequency of segment exchanges) APS will realign focus and two of the remaining four M2 DOF. The remaining two degrees of freedom will be measured by APS on approximately a yearly basis or whenever the M2 is recoated. The selection of which two DOF will be measured by APS more frequently is TBD.
[17] Coma will be corrected on M2 via tip/tilt, de-center, or rotation about the neutral point. The optimum approach is TBD; the architecture will easily support any of these three possibilities.
[18] Focus will be corrected via M2 piston
[19] The instruments and the APS will have the ability to slowly control pupil position via M3 tilt.

#### 8.3.5.2 Telescope Control System

**Overview**

The TCS is responsible for the coordination and control of the various systems that make up the telescope system. **Figure 8-31** illustrates the TCS relative to the other telescope control systems. **Figure 7–10** illustrates the context of the TCS relative to the other principal systems within the OES. The TCS is one of the systems within the Observatory Execution System (OES); the OES is described in **Section 8.4.3** The TCS consists of control software and associated off the shelf computer processing hardware. **Figure 8-31** illustrates the use of adaptors to interface and reconcile differences between vendor supplied software and core observatory software.

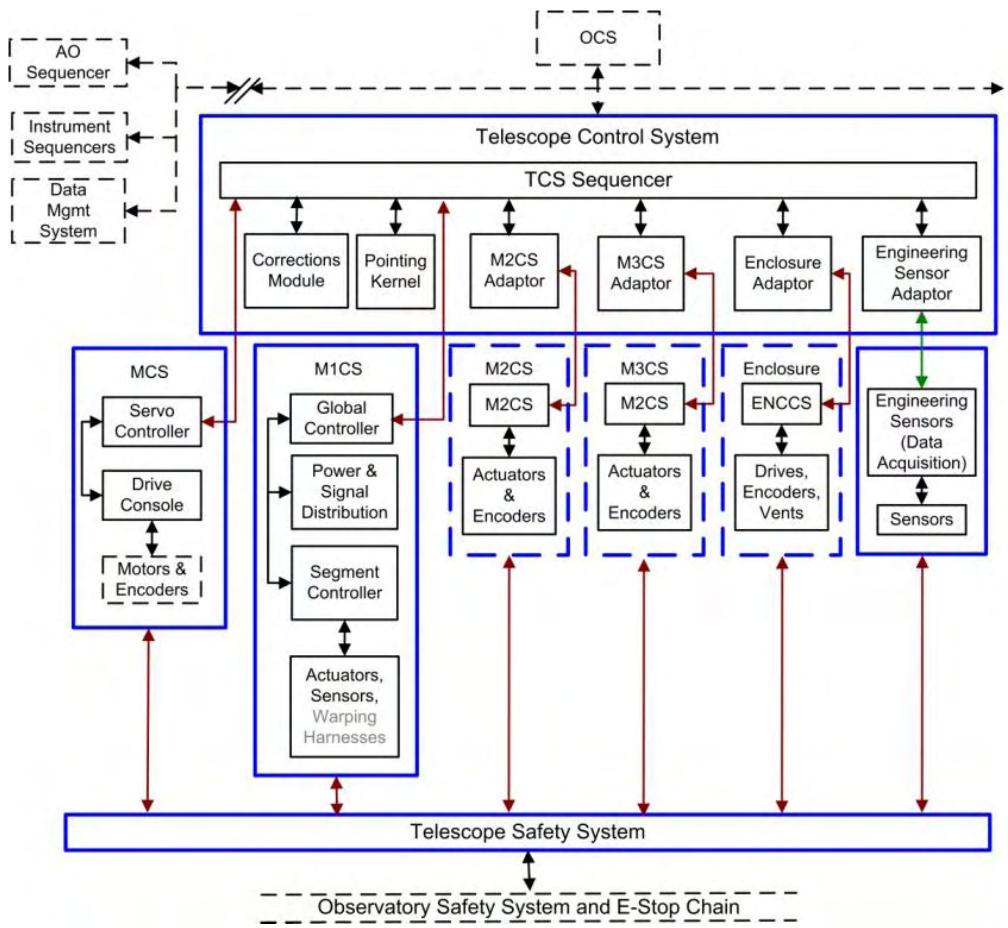


**Fig 8-31: An illustration showing the functional relationships between the various systems that fall under Telescope Controls. Dashed lines and/or grey text indicate systems that are shown for reference only and are not contained within Telescope Controls. The lines connecting the various systems are illustrative of a hierarchical control relationship but do not imply communication paths. Communication paths are better illustrated by Figure 8-52 (OES Integration Architecture).**

**Conceptual Design Description and Options**

The TCS design will be based on the sequencing strategy described in **Section 8.4** and illustrated in **Figure 7–10**. A premise of the sequencing strategy is a clear distinction between control/command and data paths [1].

The TCS consists of a Sequencer and Status/Alarm Monitor, a Pointing Kernel, a Corrections Module, and several adaptors. The Sequencer and the Status/Alarm Monitor controls and coordinates the telescope systems based on commands received from the Observatory Control System (OCS) and expert user interfaces [2].

The TCS Sequencer and Status/Alarm Monitor provides high level control of the mount, M1, M2, M3, and the enclosure (cap, base, shutter, vents). The enclosure vents will be controllable individually or via pre-set configurations; the design will provide the hooks enabling automated control of vent configurations based on environmental conditions.

The TCS pointing kernel converts target positions (right ascension and declination) into pointing and tracking demands in the appropriate coordinate system for the telescope mount; instrument and AO WFS probes, atmospheric dispersion correctors, rotators; and the enclosure cap and base. This is accomplished through the use of a number of virtual telescopes. A virtual telescope is the astrometric building block used to construct the pointing kernel. The virtual telescope is an ideal telescope that responds instantaneously to new demands. The demands can be in the form of a changed sky target or image position [3,4].
In seeing limited operation the correction module receives and processes focus, tip/tilt, coma and low order radial corrections from an OIWFS that have been reconstructed and rotated into telescope mount, M1, and M2 coordinates. In diffraction limited mode (AO) the corrections are based on an offload of the time averaged position of the AO tip/tilt stage and the DM; up to 100 modes can be offloaded in this configuration. The corrections module also processes data from the GMS for use by the M1, M2 and M3 systems. See **Section 8.5**. The corrections module is also responsible for the creation and management of the M1, M2, and M3 rigid body and shape LUTs.

The TCS contains several adaptors to handle differences between vendor and commercially supplied software systems and the core observatory software systems. There will be adaptors for the M2, M3, Enclosure, and Engineering Sensor systems.

**Key Development Tasks**
The TCS technical risk level is low. The differences of the TMT TCS relative to control systems for existing 8 to 10 meter telescopes are driven by “lessons learned”, the maturation of complex software system frameworks, and an evolution of software standardization. There hasn’t been a revolution of new ideas and concepts since the last generation of telescopes; the TMT TCS will be built on past principles and design concepts that have been demonstrated successfully. As a goal the re-use of existing designs and collaborations with similar projects will be pursued whenever practical.

**Work Plan**
The operations staff must be intimately familiar with the observatory software in order to efficiently address the persistent desire to improve system performance, add new capabilities, maintain complex interfaces, and keep pace with evolving technology. A demonstrated successful approach (as per Keck) to developing the requisite familiarity is to develop the core software components in house and to ensure a smooth transition to operations of the knowledge base and staff at the end of the construction project. This is the baseline approach for TMT. Other than for unique processes such as the pointing kernel the majority of the software effort will be accomplished within the Project Office and by TMT partner institutions.

#### 8.3.5.3 M1 Control System

**Overview**
The M1 Control System (M1CS) is responsible for maintaining the overall shape of the segmented M1 mirror despite structural deformations caused by temperature and gravity and disturbances from wind and vibrations (observatory generated and seismic). Properly supported, the mirror segments (see **Section 8.3.2**) can be treated as rigid bodies; hence, their positions can be described by six parameters. The three in-plane motions are controlled passively via the Segment Support Assembly (SSA). The three out-of-plane motions (piston, tip, tilt) are actively controlled by the M1CS via three actuators and two sensors per inter-segment edge. In total the M1CS contains 1476 actuators and 2772 sensors. In addition to actuators and sensors the M1CS includes the algorithms, software, electronics, and communication buses necessary for control of the primary mirror. The M1CS also provides the local control of the warping harnesses.

The M1CS can be considered a stabilization system that works to maintain the shape of M1 based on previously determined set-points. The set-points vary as a function of gravity (zenith angle) and temperature. The APS is responsible for aligning M1 by making measurements using starlight from which the set-points can be determined (see **Section 8.3.6**). The APS also takes the data to determine the proper set-points for the warping harnesses. In addition, the M1CS has the capability to utilize data from an OIWFS or the AO system (see **Section 8.5**) to make real time corrections to the overall mirror shape.

The starting point for the design of the TMT M1CS is the design of the M1 control system used on the successful Keck telescope and more recent work done for The California Extremely Large Telescope CELT [5,6,7]. The M1CS description that follows starts off with a statement of requirements and then leads into a description of each of the primary M1 components culminating with a description of the control algorithm and remaining development activities. **Figure 8-31** illustrates the context of the M1CS within the overall group of telescope control systems.

**Requirements**

The conceptual design of the M1CS is requirement driven. The Level 1 error allocations for M1 shape drive the noise requirements on sensors, actuators, and the APS derived set-points. The operating wind environment drives the required pseudo static stiffness of the actuators, SSAs, and the mirror cell as well as the control bandwidth of the M1CS. The requirement on M1CS bandwidth is also driven by the disturbance forces that the air flow over M1 produces. Air flow is maintained over M1 in order to meet the Level 1 error allocation for telescope and dome seeing. In addition the telescope and dome seeing error allocations drive towards a M1CS design with low power dissipation and the need to remove unacceptable thermal loads. The level-1 requirements to minimize disturbances due to vibrations, in particular from rotating machinery, drive the design requirement to push excitable resonances above 35 Hz and to choose a baseline actuator design than can provide damping.

The M1 aperture size coupled with the 1.4 meter segment size results in a design with many M1CS components; hence, reliability, maintainability, and cost are important. The large number of segments also drives the duration of the Assembly, Integration, and Verification (AIV) process. The M1CS will be designed to handle the continually evolving M1 configuration during AIV.

Level 1 requirements on observatory availability drive requirements on the maximum observing time allowed for M1CS alignment, which in turn drives requirements on drift at the M1CS component level. The fifty year observatory lifetime requirement directly drives an actuator and sensor design, which can be maintained, via repair and replacement, for at least fifty years. In addition it drives a software/electronics design that pushes industry standards deep into the system, enabling cost effective future upgrades driven by obsolescence and technology evolution.

The error budget terms for the active alignment of M1 are listed in **Table 8-8**. Key M1CS derived requirements are listed in **Table 8-9**.

**Table 8-8: The error budget terms for active alignment of M1. Grey entries are beyond the direct scope of the M1CS but impact alignment of M1.**

| Error Source | 80% Enclosed Energy arc-seconds | | |
|---|---|---|---|
| Segment alignment and stabilization - active | | | 0.064 |
| Desired edge sensor readings | | 0.035 | |
| Edge sensor readings | | 0.045 | |
| thermal effects | 0.005 | | |
| gravity effects | 0.000 | | |
| temporal effects | 0.033 | | |
| sensor noise | 0.030 | | |
| Desired OIWFS readings | | TBD | |
| Instrument wavefront sensor centroids | | TBD | |
| Atmospheric disersion compensation | | TBD | |
| Actuators | | 0.020 | |
| Uncontrolled frequencies | | 0.022 | |
| wind | 0.020 | | |
| seismic | 0.006 | | |
| equipment | 0.006 | | |

**Conceptual Design Description and Options**

A functional block diagram of the M1CS is shown in **Figure 8-32**. The sensors located on each inter-segment edge measure a linear combination of height difference and the dihedral angle between adjacent segments. These 2772 measurements are compared with the set-points determined by the APS. The difference between the sensor measurements and the desired sensor readings are processed by the control algorithm at a 20Hz rate to determine the actuator commands necessary to maintain the correct shape of the primary mirror. There are 1476 degrees of freedom to control including the global tip, tilt, and piston of M1; since there are 2772 measurements there is nearly a factor of two in redundancy. A description of each of the M1CS major elements (Actuators, Sensors, Segment Controller and Cables, Power and Signal Distribution, Global Controller) is contained in the following sections.

The core requirements on M1CS actuator performance are listed in **Table 8-9**. The most demanding design requirements are tracking error, low sensitivity to wind loads and structural vibrations, large dynamic range, low operating power, reliable operation, and low unit cost. The required actuator stroke results from a system level trade study involving telescope structure mass and dynamics, segment installation and alignment tolerances, and actuator cost. The large number of actuators drives the aggressive cost and reliability targets and hence a design that departs from that used on the Keck telescopes. A number of potential actuator technologies have been investigated [8]. Voice coil technology was chosen based on its ability to damp vibrations, to deliver high accuracy, and to deliver a long potential lifetime due to low wear. It is interesting to note that the European Southern Observatory (ESO) Extremely Large Telescope (ELT) Project is also leaning towards voice coil based actuators.

**Table 8-9: Key derived M1CS requirements.**

| | **Requirement** |
|---|---|
| **System** | |
| Bandwidth | 0.5 Hz |
| Power dissipation on segment | ≤ 2 watts/meter$^2$ RMS |
| **Actuators** | |
| Total Stroke | 4.3 mm |
| Tracking Error | ≤ 5 nm RMS |
| Axial Load | 610 Newtons |
| Axial Stiffness @ 35 Hz | ≥ 10 N at 35 Hz |
| Max Tracking Rate | 150 nm/sec |
| Slew Rate | ≥ 50 µm/second |
| Power (segment mounted) | ≤ 0.2 Watts/actuator RMS |
| Weight | ≤ 7 Kgs |
| MTBF | ≥ 300,000 hours |
| Orientation (performing) | 0 to 115 degrees |
| **Sensors** | |
| Noise | 4.9 nm RMS, 5.5 nm/ (Hz)$^{1/2}$ |
| Temporal effects | 1 nm week (assumes re-alignment every 5 weeks) |
| Gravity and thermal effects | 1 nm RMS each |
| Humidity effects | 3.2 nm RMS |
| Gap range | 2.5 +/- 0.6 mm |
| Delta gap in operation | +/-0.3 mm |
| Range for performance | +/-100 µm |
| Range for operation | +/- 2.5 mm |
| Orientation | non interlocking |
| Vacuum compatible | Yes |
| Power (segment mounted ) | ≤ 0.3 Watts/sensor RMS |

### Actuators

The TMT actuator concept is an evolution of an actuator design first developed for the CELT project [9,10]. The actuator relies on techniques that achieve the required accuracy while providing a substantial amount of vibration attenuation and damping. The actuator development plan consists of building a series of prototype actuators (P1 through P4) to verify cost, reliability, and performance prior to the initiation of mass production. The build, and initial test of the first TMT prototype (P1) is complete; the demonstrated performance indicates that the design can meet the most demanding performance requirements [11].

P1 evaluation continues to be followed by a P2 design effort. **Figure 8-33** is an illustration of the Primary-mirror Segment Assembly (PSA), Subcell, and the top layer of the telescope mirror cell including pictures of the P1 actuators and sensors.

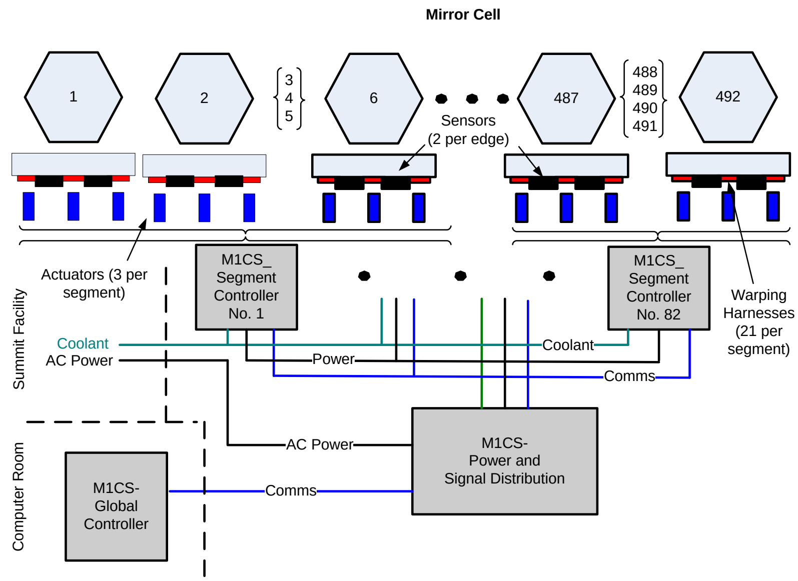


**Fig 8-32: M1CS functional block diagram. The 82 segment controllers and the power and signal distribution system are mounted to the mirror cell floor. The signal distribution consists of a tree structure of network switches.**

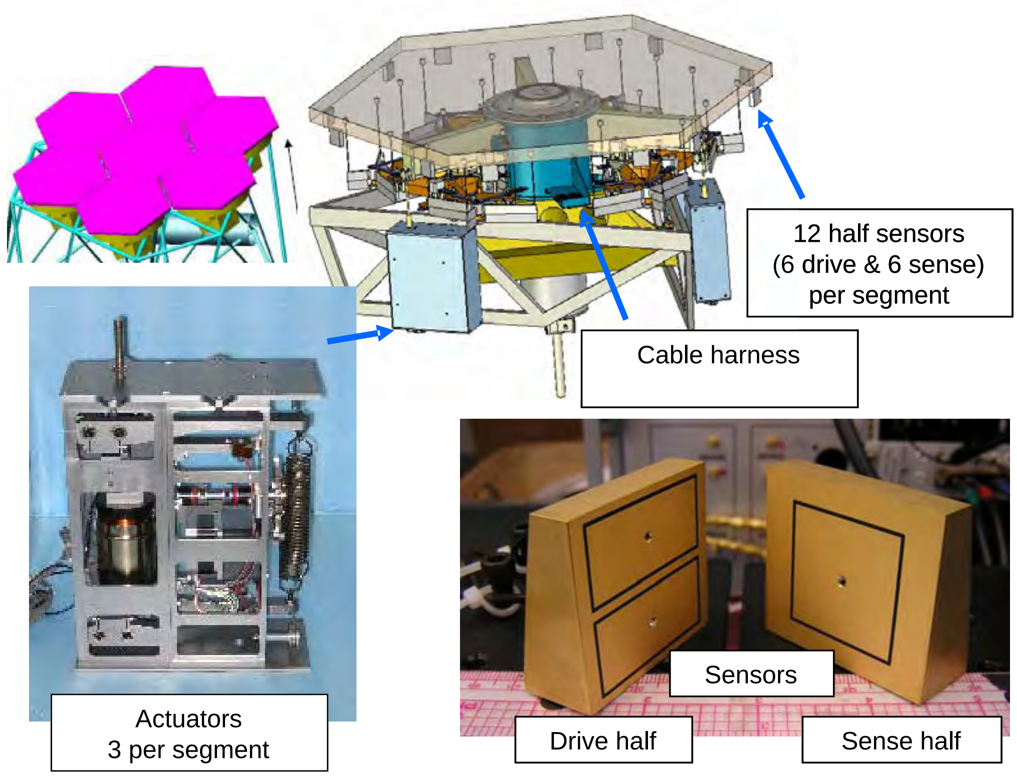


**Fig 8-33: An illustration of the PSA, Sub-cell, and top layer of the mirror cell. The segment jack can also be seen. Pictures of the P1 actuator and the P1 sensors are shown. The P1 actuator is shown with its covers off.**

The actuator design is based on a parallel combination of a relatively fast 50 Hz control loop closed on a voice coil using an accurate commercially available optical sensor for fine positioning and an offload loop that works to minimize the power dissipation in the voice coil [12,13]. The offload loop uses a stepper motor in combination with a lever and spring mechanical system to provide the pseudo static force required to support the weight of the mirror at all zenith angles with near zero power dissipation. The voice coil loop control laws create equivalent stiffness and damping properties that achieve high positioning accuracy even in the presence of external disturbances such as wind.

The off-loader mechanism has a number of gears, bearings, rotating parts and cables. A single accelerated life-time test (41 years) of the off-loader was run with only two failures. The common failure mode was identified and a fix installed. Although this single test is statistically insignificant it does provide some confidence that a reliable actuator that is based on P1 design concepts is realizable. Comprehensive reliability, lifetime, and stress tests will be run on the P2, P3, and P4 actuators.

The production actuator will be designed to so that it can be re-built with relative ease in order to support a 50 year observatory life time. The fine position control mechanism of the actuator has no sliding or rotating parts, does not require lubrication, and relies only on flexural systems that can be designed to operate for essentially infinite lifetime. A few examples of the initial test results are illustrated in **Fig. 8-34**.

**Sensors**

The requirements on the sensors are listed in **Table 8-9**. Two critical top level requirements drove a sensor design that diverged from that used at Keck. The Keck design is described in reference [14]. First, due to the large number of sensors, the cost target for the TMT sensor is approximately one tenth the cost of a Keck sensor. An equally important design driver is the requirement on ease and efficiency of the segment exchange process. When a Keck mirror segment is removed for re-coating the interlocking sensor drive paddle needs to be swung away to allow the mirror segment to be lifted out of the telescope. This is a delicate and time consuming operation. The sensors for the baseline TMT design are non-interlocking and only require the disconnection and connection of cables during a mirror segment exchange.

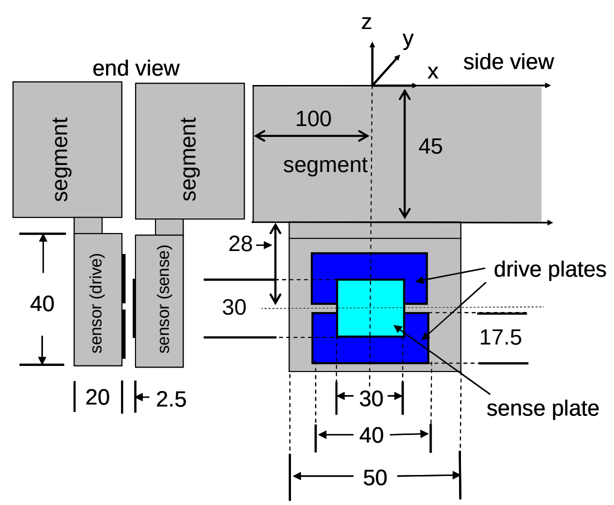


**Fig 8-34: A cross section view or the TMT edge sensor showing critical dimensions in millimeters.**

The TMT baseline design, although capacitive based, is quite different in detail from the Keck design. The decision to use capacitive technology was principally based on the success of the Keck sensors. Although inductive technology has the benefit of additional immunity to humidity and dust these benefits were not considered great enough to outweigh TMT's institutional knowledge and past success with capacitive sensors.

The aggressive sensor cost target is being addressed by reducing the number of parts from eight plus attachment hardware for the Keck sensor to only two for TMT. In addition the TMT sensors are smaller than the Keck sensors and will bond directly to the back of the segments with low CTE glue. Small variations in segment thickness will be carefully equalized via the glue joint. This approach further reduces cost by removing the need for additional machining on the backside of the segment and/or the use of custom made sensor parts or shims.

Keck sensors determine differences in height between adjacent segments by measuring a change in capacitance resulting from a differential gap change between parallel capacitive plates. In contrast the TMT sensors measure the differential overlap between capacitive plates to determine the change in relative height. This difference in TMT sensor geometry from that of the Keck geometry adds significant complexity as described below [15].

The geometry of the TMT sensor is illustrated in **Figure 8-35**. Ideally the sensors would only sense differences in height and dihedral angle between adjacent segments and have insignificant sensitivity to in-plane segment motions. A measurement of dihedral angle is important because without it a specific form of primary mirror focus mode would not be controllable. In practice the combination of the TMT sensor geometry and considerable TMT in-plane segment motion (predicted by FEA) results in significant sensitivity to in-plane segment motions. Therefore it will be necessary to calibrate the sensors as a function of the in-plane segment positions.

Calibration will be accomplished by designing the sensors to include an independent measurement of gap between adjacent segments. Based on simulations it has been shown that gap measurements can be used to determine the in-plane positions of M1 segments [16].

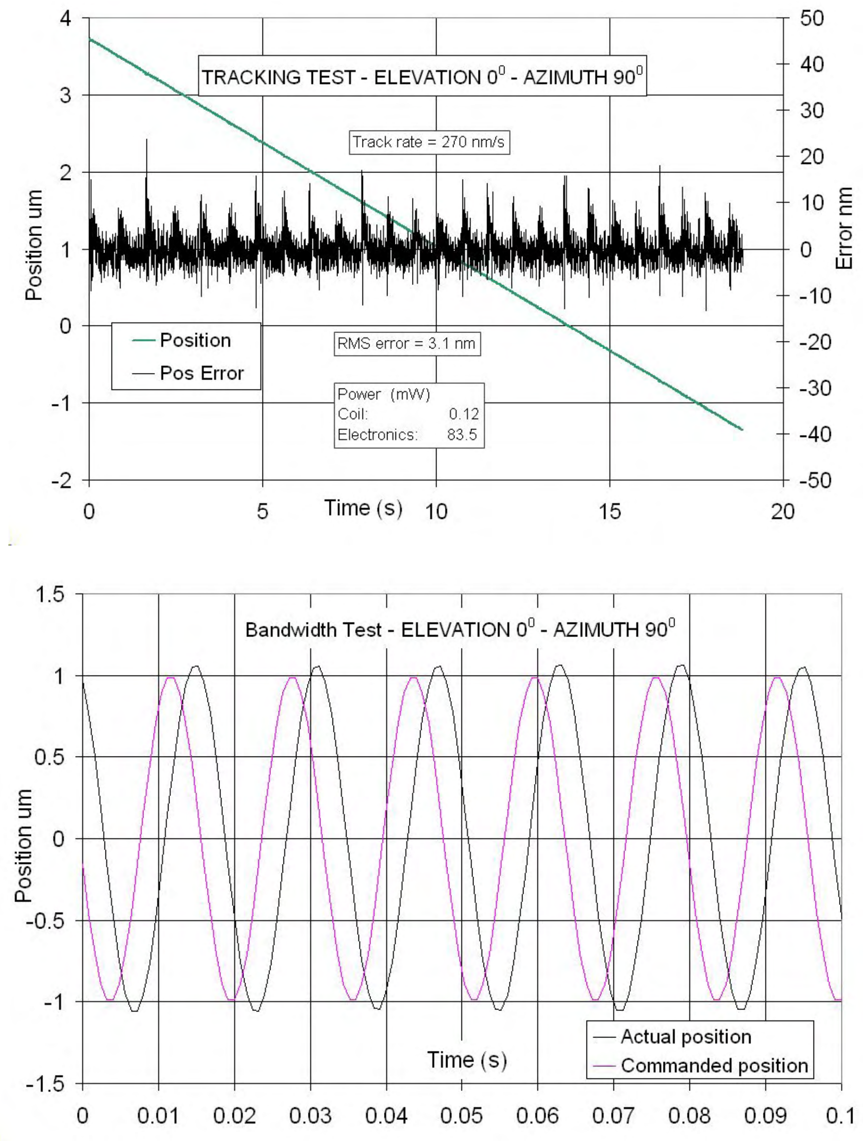


**Fig 8-35: The top figure illustrates the actuator tracking error at a track rate of 270 nm/sec. The tracking error is 3.1 nm RMS and meets the 5 nm RMS requirement identified in Table 8-9. The measured power dissipated at the actuator is extremely low due to the use of an off-loader. The bottom figure illustrates that the actuator bandwidth, defined by a 90 degree phase lag between the command and output is greater than 50 Hz. Both of these tests were run with a 450 Newton load on the actuator.**

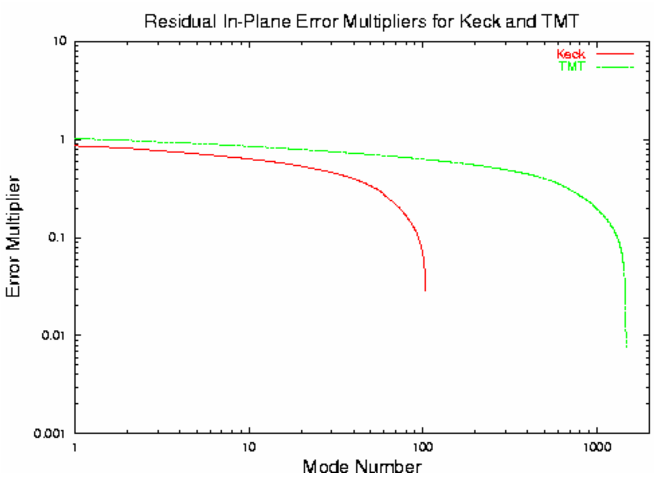


**Fig 8-36: Residual in-plane error multipliers for Keck and TMT are shown. The residual multiplier includes the multiplier for the indicated mode and all higher modes. Note that due to the geometry of the gap measurements there is little magnification of in plane errors.**

Once the in-plane positions of the segments are determined it is possible to calibrate the sensors via data gathered by the APS at different elevation angles and at different temperatures [17].

**Figure 8-36** compares the residual in-plane error multipliers on gap measurements for both Keck and TMT. The residual error multiplier gives the multiplier for the indicated mode and all higher modes. Thus the residual error multiplier for mode 1 is analogous to the total noise multiplier. It is worth noting that little, if any, in-plane error magnification occurs. This is not unexpected since motions normal to a segment edge are directly measured. Although motions parallel to a segment edge are not directly measured the combination of sensors on adjacent edges and redundancy provide a good measure of these motions as well.

In-plane measurements were not required at Keck as a result of the Keck sensor geometry per the description above. **Figure 8-36** also indicates, via comparison of the TMT and Keck curves, that the in-plane error multipliers are only weakly dependent on the total number of segments.

Similar to the actuators, the sensor development plan consists of building a series of prototype actuators (P1 through P4) to verify cost, reliability, and performance prior to the initiation of mass production. The build and initial test of the first TMT prototype (P1) is complete and initial evaluations are complete. A picture of the P1 sensor is included in **Figure 8-33**.

An electrostatic model and study of the sensor was completed prior to the build of the first prototype. One of the key results of this initial study was that the sensor needs to be fully shielded to reduce cross talk despite the desire to do otherwise for cost considerations. **Figure 8-37** illustrates the favorable comparison between measured P1 (shielded) performance and an electrostatic model of the sensor. **Figure 8-37** also illustrates that the sensor is linear over a ±4mm range - a larger range than is required. A P2 will be built and tested after the analysis of the in and out-of-plane coupling has been completed. Additional electrostatic modeling will also be completed as the design matures to include interactions of three sensors near a segment edge, attachment characteristics, and cable bonding characteristics.

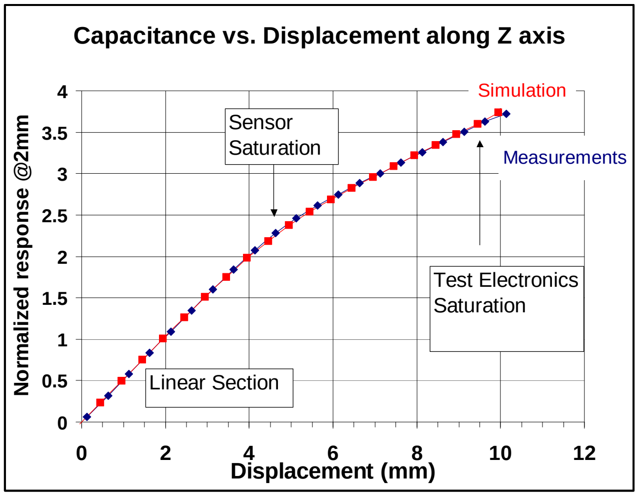


**Fig 8-37: A comparison of measured and simulated P1 sensor data for relative height (Z) displacements.**

The proposed sensor calibration approach is in the development stage, and until proven, poses considerable risk to the project. As part of a risk mitigation plan the status of an inductive sensor under consideration for the ESO ELT remains under consideration as a TMT alternative. It may be possible to develop an inductive sensor with favorable cross coupling characteristics and little sensitivity to humidity.

Optical sensors have been researched and have shown certain benefits but at a relatively high cost. The section below on development tasks discusses the sensor risk mitigation activities in more detail.

**Segment Controllers and Power/Signal Distribution**
The Segment Controllers include the distributed electronics and associated cabling required to control the actuators and warping harnesses and to read out the sensors. The design is driven by requirements on minimizing power dissipated near each segment, support of efficient segment exchanges, maintainability, reliability, low cost, and lifetime. As mentioned previously, the Level-1 fifty year lifetime requirement drives a design that pushes industry standards as deep into the system as practical to support future upgrades.

The Segment Controller electronics will be mounted in approximately 94 industry standard insulated enclosures located on the floor of the mirror cell; each enclosure can support the electronics necessary to control up to six segments. The heat generated by the Segment Controllers will be actively removed by the facility provided coolant system. Components mounted directly to the M1 segments, including actuators, sensors, and warping harnesses will be designed to dissipate less than 2 Watts/Meter$^2$ doing away with the need to run coolant to each individual segment. The mirror segment cable harness will be designed to minimize the number of connections and disconnections that need to be made during a segment exchange and will utilize robust connectors suitable for frequent make or break connections.

Several power distribution racks will be located throughout the floor of the mirror cell. The power distribution racks will receive facility provided AC power and distribute 48V DC power to each of the Segment Controllers. The Segment Controllers will utilize DC to DC converters to generate additional voltages as required.

All communication between the Global Controller and the Segment Controllers will be via industry standard Ethernet.

**Global Controller**
The M1CS Global Loop Controller (GLC) consists of the core and ancillary control software for the M1CS and the associated computer processing hardware. The control algorithm used at Keck, modified for the increase in the number of segments, segment geometry, and sensor geometry as described above, is the starting point for the TMT M1CS control algorithm. The mathematical basis for control of the TMT M1 is described in detail in references [6] and [7]. The Keck software implementation is described in reference [18]. The heart of the GLC is a Multiple Input Multiple Output (MIMO) control algorithm that converts the difference, between the LUT that contains the set-points for the sensors as determined by the APS and the corrected sensor readings, into actuator commands. The LUT is a function of gravity and temperature; the corrected sensor readings are calculated using the raw sensor readings and the gap measurements as described above.

An important characteristic of the M1 control system is the propagation of sensor errors. **Figure 8-38** compares the residual out-of-plane error multipliers for Keck and TMT. As described for **Figure 8-36** for in-plane errors, the residual error multiplier gives the multiplier for the indicated mode and all higher modes, thus the residual error multiplier for mode 1 is analogous to the total noise multiplier. As expected, and in contrast to the propagation of in-plane errors, the multipliers scale with the square root of the number of segments.

In **Figure 8-38** the modes are ordered from the highest to the lowest multiplier, which is mostly consistent with an ordering in spatial frequency from lowest to highest. The reason for this correspondence is due to the fact that low-spatial-frequency modes have small edge discontinuities that are difficult for the sensors to detect and therefore for the active control system to control. The error propagation characteristics of M1 geometry were taken into account as part of the overall system level error budgeting exercise.

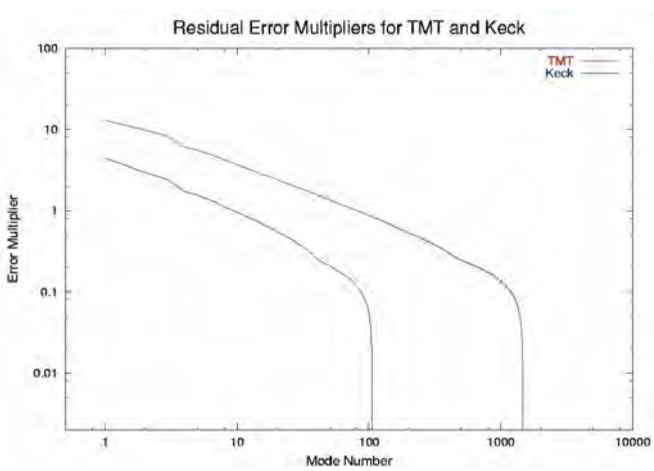


**Fig 8-38: A comparison of the residual out-of-plane error multipliers for Keck and TMT.**

The dynamic characteristics of the M1CS are as important as the static stabilization characteristics. The required bandwidth for the TMT M1CS is 0.5 Hz. This is driven by the requirement to reject wind disturbances, which are characterized by the wind model coupled with the wind attenuation properties of the enclosure (see **Section 7.5**). In comparison, the achieved Keck M1 bandwidth, with only 36 segments, is less than 0.1 Hz. Although achieving a 0.1 Hz bandwidth at Keck was not a particular challenge achieving a 0.5 Hz bandwidth on TMT may be more difficult. The difficulty results from dynamic interactions between individual segments that can be ignored at lower bandwidths. This phenomenon is commonly known as the controlled structure interaction effect (CSIE). Activities associated with mitigation of the CSIE risk are described in the Key Development Tasks section below.

In addition to performing the core processing for the MIMO control system the GLC is responsible for the following:

- Control of the global tip, tilt, and piston of M1
- Control of the segment warping harnesses
- Filtering and correction of measured sensor data
- Management of the sensor set point LUTs
- Management of the warping harnesses LUTs
- Overall configuration control of the M1CS
- Interfaces to the following
  - Telescope Control System
  - Alignment and Phasing System
  - Data Management System
  - Adaptive Optics Systems
- Expert user interfaces
- Diagnostic and data visualization tools
- Segment maintenance procedures
- Alarm and fault handling
- Data logging

It is important to note that implementing the required computer power for the Keck M1CS was a major challenge and risk; the same is not true for TMT. The advancement of processing power over the last two decades far exceeds the additional processing power required to control 492 segments.

**Key Development Tasks**

The key development tasks are driven by risk. The largest risks are associated with the sensors, the CSIE effect described above, and the unknowns associated with integrating a large and complex system.

The first of two significant sensor risks is associated with the ability to calibrate the sensors adequately to remove errors due to in-plane segment motions. Calibration performance is dependent on the utilization of the appropriate sensor geometric model, noise in the gap measurement, sensor installation and fabrication tolerances, the magnitude of the in-plane motions, and the ability to adequately affect in-plane segment motions for calibration purposes. On going mitigation efforts include analysis, electro-static and noise propagation models; and timely prototyping and testing of the sensors, installation tools and processes. It is expected that a full control simulation of the in and out-of-plane sensitivities including the significant noise sources will be developed to adequately mitigate the associated risks.

A second risk related to sensors has to do with the humidity sensitivity of capacitive sensors. Significant effects, hundreds of nanometers at 70% relative humidity and above, have been observed in laboratory tests with both Keck and TMT style sensors. It is interesting to note that there hasn’t been a noticeable degradation of performance at Keck correlated with humidity.

Mitigation efforts include investigations and testing of coatings and/or cleaning processes that can be used effectively to decrease the sensitivity to humidity. Lab testing can be accomplished quite easily, which is an advantage. In addition, the specific humidity characteristics of the candidate sites will be taken into account in writing the humidity sensitivity requirements for the sensors. Past and present Keck data are being analyzed to determine if the effect exists at Keck but is masked by other error sources.

The CSIE risk is associated with dynamic coupling between segments and can compromise the ability to deliver the M1CS bandwidth necessary to meet the disturbance rejection requirements [19,20,21]. CSIE is driven by the characteristics of the combined SSA - actuator - mirror cell dynamics. Mitigation efforts have begun with stand alone analysis and simulations of the actuator to SSA dynamics; over time integrated models will be used to determine the global performance of the M1CS including disturbance rejection. In addition, early hardware testing of the actuator to SSA dynamics will be initiated on a Single Segment Test Assembly (SSTA) followed by system testing on a Three Segment Test Assembly (TSTA).

Additional system level risks will be addressed via testing on the SSTA and TSTA. The SSTA will consist of a dummy (aluminum or similar) segment, an SSA, and three actuators and associated control electronics. The TSTA will consist of three SSAs each with a segment made of a low CTE material, three actuators, sensors, cables, and control electronics. The three SSAs will be mounted on a truss structure that mimics the characteristics of the mirror cell. The SSTA and the TSTA will include metrology equipment as required to measure important performance characteristics.

**Figure 8-39** provides a high level vision of how the SSTA and TSTA will be utilized in the context of the overall M1CS development path.

**Maintenance and Reliability**
Maintainability of the M1CS and of segment reflectivity via re-coating is driven by Level 1 requirements. The M1CS design will include diagnostic and data visualization tools to support the location of faults, particularly sensors, actuators, and electronics. The diagnostic tool set will complement the hardware design so that faults can be traced to assemblies that can be easily and quickly replaced in-situ. This philosophy follows the rigorous Line Replaceable Unit (LRU) model that is used in the aerospace and defense industries. Automated test stands will be provided to support off-line repair of all M1CS printed circuit board assemblies (PCBA), sensors, cables, and actuators.

The M1CS design supports the segment exchange process by using non-interlocking sensors, convenient SSA to actuator connections and disconnections, reliable and easy cable connections, and by avoiding coolant connections. In addition the sensors, segment mounted cable harnesses, and warping harnesses will be vacuum compatible to minimize the number of components that need to be removed from the segment prior to stripping and re-coating.

M1CS reliability is also driven by Level 1 requirements and is included in the design process from the start. Due to the relative low cost of the M1CS components, reliability testing of prototypes will be utilized extensively to complement reliability analysis. Reliability testing of early prototypes will include HALT (Highly Accelerated Lifetime Testing) and HAST (Highly Accelerated Stress Testing). Software reliability will be addressed using code walk throughs, module level testing, and industry standard verification tools.

**Work Plan**
The development of the actuators, sensors, segment control electronics and cabling, and software will utilize a series of evolving prototypes. This approach, coupled with appropriate analysis, is optimum for the development of a system that consists of a large number of relatively inexpensive components. As part of this approach, bench test sets and test beds (SSTA and TSTA) will be built to support component and system level testing. At the appropriate points multiple components will be built to support reliability, stress, and accelerated lifetime testing. **Figure 8-39** provides a graphical representation of this model.

Much of the organizational infrastructure required for the M1CS design and build is not needed in the long term for TMT operations. Recognizing this, the TMT Project Office has made a conscious decision to collaborate with a National Laboratory (NL) or similar organization on the M1CS during the Design and Development Phase (DDP), with the aim of transitioning the overall effort over to the NL by the beginning of construction. During construction the NL will act similar to a prime contractor. This approach removes the need for the Project Office to build up the required construction phase infrastructure. In addition, this approach enables the DDP technology development products of the Project Office to be transferred to the NL for inclusion into the final system in a cost effective manner. The approach also enables leveraging the Keck knowledge base that exists within the Project Office, partner institutions, and at the NLs under consideration.

An important feature of the work plan is the goal of a smooth transition between the project and operational phases of the observatory. During construction, TMT staff members who expect to remain with the project into operations will be embedded into the design team located at the NL. In addition the NL will support AIV of the M1CS at the observatory site, providing training to TMT staff members during the process. Both of these transition mechanisms were used successfully at the Keck Observatory.

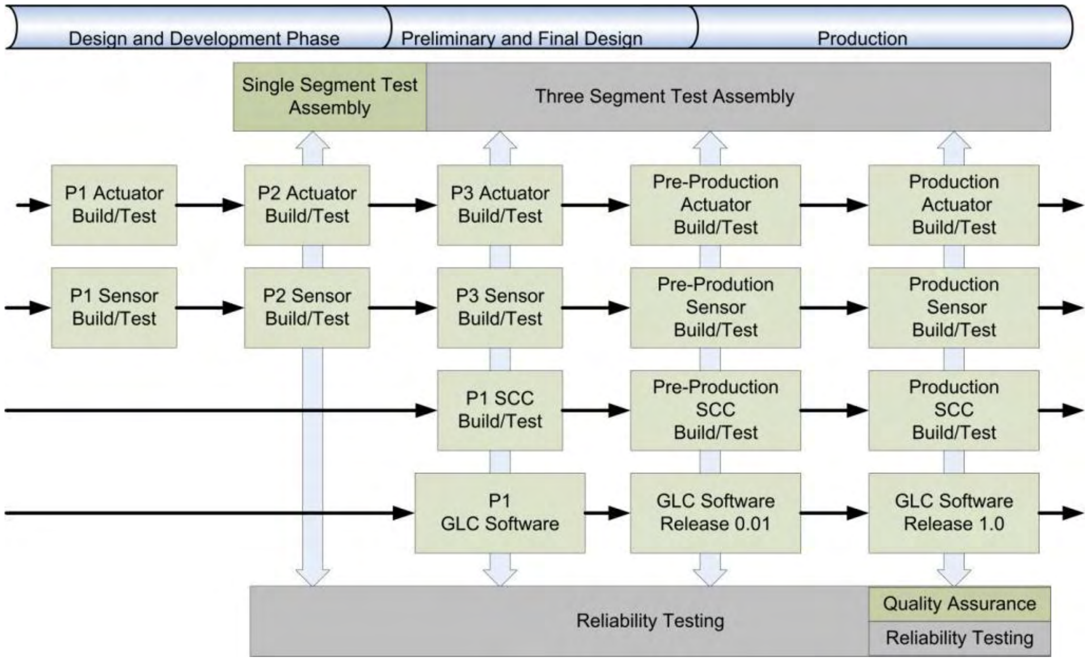


**Fig 8-39: A graphical representation of how successive M1CS prototypes will be used for risk mitigation and reliability testing.**

### 8.3.5.4 Mount Control System

**Overview**

The MCS provides servo control of the mount azimuth and elevation axis. The MCS closes a position loop around telescope mounted motors and encoders. The MCS receives azimuth and elevation pointing and tracking commands from the TCS. The commands are based on the output of the pointing kernel blended with tip/tilt (guide) corrections as measured by an OIWFS or offloaded by the AO system. The MCS will be designed to support pointing and acquisition, open loop tracking, closed loop tracking (guiding), offsetting, and nodding processes. Figure 8-31 illustrates the context of the MCS relative to the other Telescope Control subsystems.

**Requirements**

The core performance requirements levied on the MCS flow down directly from the Level 1 requirements and error budgets. The most notable are listed below:

- One arc-second RMS pointing over the entire accessible sky
- Three minute maximum slew time between any two points on the accessible sky
- Offsetting of up to 1 arc minute to an accuracy of 50 milli-arcseconds RMS
- Nodding up to amplitudes of 1 arcsecond with less than 1 second lost to moves.
- Nodding up to amplitudes of 10 arcseconds with less than 2 seconds lost to moves.
- A maximum of 10 milli-arcseconds RMS (25 milli-arcseconds $D_{80}$) image jitter (1 dimensional) due to wind.

**Conceptual Design Description and Options**

The MCS will utilize traditional proportional – integral – derivative (PID) servo control laws and customized structural filters. A minimum time control strategy coupled with feed forward will be used to meet the nodding requirements. Azimuth and elevation torques will be supplied by linear motors mounted at the base of the telescope and on the elevation rockers respectively. Elevation motors will be located on both the left and right elevation rockers. Position feedback will be via tape encoders mounted around the base of the telescope and along both rockers. See Section 8.3.1. Velocity feedback will be calculated via the derivative of the position feedback supplied by the tape encoders

**Key Development Tasks**

The key development tasks are driven by technical risk and cost. The largest technical MCS challenge is achieving the required image jitter performance over the range of operational wind conditions, while keeping the telescope as light as possible to minimize cost.

Design and performance prediction is accomplished via modeling and simulations. This work is ongoing as the structural design evolves and as additional non-linear effects such as friction, sampled data delays, and quantization errors are added to the model.

The ability to meet the 10 milli-arcsecond RMS one dimensional image jitter requirement looks feasible. **Figure 8-40** illustrates the telescope image jitter in response to a nominal wind disturbance (5.5 m/s median wind, 30 degrees zenith, 0 degrees azimuth) on M2 and 1.5 m/sec air flow over M1 via the enclosure vents. The illustration includes the PSD and cumulative responses. Also illustrated is the nominal wind spectrum. From the figure one can see that the majority of the image jitter occurs near the limit of the mount control bandwidth; approximately 1 Hz.

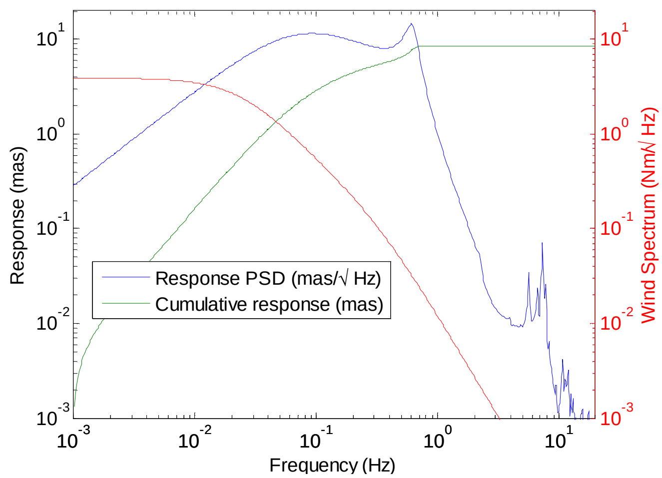


**Fig 8-40: Telescope image jitter during nominal wind conditions. The cumulative image motion is 10 milli-arcseconds RMS and the PSD peaks near the limit of the mount control bandwidth of 1 Hz. The majority of the motion is in the elevation direction.**

Achieveing the 1 arcsecond RMS pointing requirement will also be a challenge. Doing so will require the utilization of a telescope structural thermal model with a level of fidelity that has not been previously required for ground based astronomy. Development of this model will be initiated during the DDP.

**Work Plan**

The MCS motors and encoders will be delivered by the telescope structural contractor. The drives and associated logic will be accomplished via a contract to the motor supplier or a vendor that has worked closely with the motor supplier in the past. The servo control software and associated computer processing hardware will be accomplished by the Project Office or at a partner institution.

#### 8.3.5.5 Test Instrument Control

A simple prime focus camera (PFC) will be mounted on the telescope prior to the installation of the M2 and M3 systems. See **Section 8.3.6.3**. The PFC will be used to verify that the initial 120 segments have been installed correctly. The PFC will also be used to conduct early pointing and tracking tests. The interface with the PFC will be made identical to that used for acquisition and aO feedback during operations.

A Global Metrology System (GMS) is under consideration for use during operations. See **Section 8.3.6.5**. During operations the GMS could be used to update the rigid body LUTs for M2 and M3. GMS measurements would take place at the beginning of the night and as part of the science object acquisition process. The GMS interface with the Telescope Controls would be automated and invisible to the user.

#### 8.3.5.6 Telescope Safety System

The Telescope Safety System (TSS) provides for personnel and telescope equipment safety. The TSS will be a stand alone system, based on a Programmable Logic Controller (PLC), and will provide safety via hard wired interlocks and the issuance of alarms. The TSS will interface with the observatory safety system and emergency stop (E-stop) system. Examples of the conditions that the TSS will monitor include over speeds, over travel, crane stowed, and out-of-balance conditions.

#### 8.3.5.7 Engineering Sensors

The Engineering Sensors (ESEN) system will provide an array of temperature, wind speed, acceleration, and seismic sensors mounted to, and near by, the telescope. The ESEN system will include the hardware and software necessary to make the data available on a real time basis via the Observatory Data Base

#### 8.3.5.8 Commissioning Acquisition and Guiding System

The APS (see **Section 8.3.6.4**) contains an acquisition camera and a low order WFS. Together these components will act as a surrogate instrument from the perspective of the telescope. Collectively these components, including the associated electronics, and software, is called the Commissioning Acquisition and Guiding System (CAGS). The CAGS will be used to integrate and verify telescope pointing and the mount, M1, M2, and M3 aO loop performance prior to telescope integration with an instrument or AO system. In addition the acquisition camera and WFS will be utilized throughout the life of the observatory for engineering and performance improvements for acquisition, pointing, and aO loops. CAGS is an ancillary function of the APS.

#### 8.3.5.9 Power, Lighting, and Grounding

The Power, Lighting, and Grounding system (PL&G) will distribute dedicated and general purpose AC power throughout the telescope structure. Both clean and dirty power will be distributed. Clean power will be conditioned and backed up via Uninterruptible Power Supplies (UPS). Dedicated primary power will be made available, at a minimum, for the following systems; Instruments and AO systems, Telescope Drives, Laser Room, Cable Wraps, Laser Launch Telescope, M1, M2, and the M3 systems; and the Beam Transfer Optics. General power will be made available via industry standard keyed and color coded power outlets. Single and Three Phase power will be available; voltages and frequency characteristics are dependent on the site location. Dedicated isolated grounds will be utilized for sensitive equipment.

Spot and emergency lighting will be available on the mirror cell, Nasmyth Platforms, and walkways.

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### 8.3.6 Optics Alignment and phasing

#### 8.3.6.1 Overview

This section describes the initial alignment of the telescope optics during integration, as well as the alignment and phasing system (APS) and the global metrology system (GMS) that will be used to set and maintain alignment of the optics and phasing of M1 segments during operations.

As the M1 segments, secondary mirror (M2) and tertiary mirror (M3) are installed in the telescope, their initial alignment will be accomplished with surveying instruments. A prime focus camera (PFC) will be used to check the alignment of the first 120 segments before the M2 and M3 are installed. The PFC will also be used for early telescope pointing tests. Once the M2 and M3 are in place, the APS will be used to align and phase the segments as they are installed.

The GMS will provide a rapid independent measurement of the positions of M1, M2 and M3 as a function of zenith angle.

#### 8.3.6.2 Initial alignment by surveying

As the telescope structure is erected, the positions of the M1 mirror cell structure and the mounting interfaces for the M2 and M3 assemblies will be measured using surveying instruments and carefully adjusted by shims and other means. Dummy weights will be installed to represent the M2 assembly, the M3 assembly and each M1 segment. The telescope zenith pointing elevation position will be established, and the centers of the M1 mirror cell and the M2 interface structure will be aligned with the telescope azimuth axis at zenith pointing. The positions of M1, M2 and M3 relative to the elevation axis will be measured at different zenith angles, and shims will be adjusted so that each mirror is in the optimum location to minimize actuator stroke as the zenith angle changes.

Each M1 segment support assembly (SSA) will have a subcell that is attached to the mirror cell structure by three adjustable attachment points (AAPs) (see **Section 8.3.2**). Each AAP interface point on the mirror cell will be positioned during telescope erection within 5 mm of the correct position in X, Y and Z. The SSA subcell will have three surveying targets, one associated with each AAP.

Fixed reference targets will be mounted at the center and around the perimeter of the mirror cell. The position of each SSA target will then be measured relative to the reference targets by multiple theodolites or total stations (a total station is a surveying instrument that incorporates an electronic theodolite and an electronic distance measuring (EDM) system).

The AAPs will be adjusted and the target positions will be surveyed again. This will allow each corner of each SSA subcell to be positioned within ±200 microns of its correct position. This process of surveying and adjusting the 492 subcells will take several weeks, so to ensure a uniform thermal environment the surveying will be done at night, with the adjustment of AAPs done during the day.

#### 8.3.6.3 Prime focus camera

The prime focus camera (PFC) will be a simple star-stacking camera located at the prime focus. It will be used to check the alignment of the first 120 segments installed at the center of M1, and to perform early telescope pointing tests. The PFC will be removed when the M2 assembly is installed.

The PFC must have adequate resolution to allow the segments to be tilted to align their images within an arc second and adequate field of view to capture star images formed by the segments, considering the anticipated accuracy of initial segment installation (~one arc minute of tilt). This requires a camera with a detector at least 20 mm across. The camera must have a readout rate that is sufficient to be used for closed loop telescope guiding.

The PFC mounting structure must position the camera at the telescope prime focus, and it must have sufficient adjustment travel under remote control to accommodate telescope fabrication tolerances plus the effects of thermal expansion and structural deflections due to gravity (tens of millimeters).

The conceptual design of the PFC is a bare 2k x 2k pixel scientific camera mounted on an X,Y,Z stage. It will be attached to a tripod structure that suspends it at a point behind the location of the secondary mirror, as shown schematically in **Figure 8-41**.

The design of the PFC will be routine; no significant development will be required.

Most of the components of the PFC are commercial-off-the-shelf. The final design and fabrication of the mounting structure will be completed by the contractor responsible for the telescope structure.

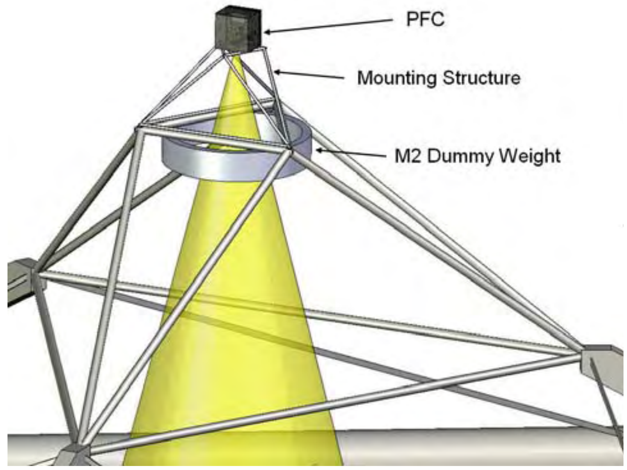


**Fig 8-41: Mounting configuration for the PFC. Note the M2 dummy weight, which must have an aperture to allow the light from the central 120 segments to reach the PFC.**

#### 8.3.6.4 Alignment and Phasing System

**Overview**

The Alignment and Phasing System (APS) is responsible for the alignment of M1, M2 and M3. Here, the word "alignment" in general encompasses the determination as well as the correction of both rigid body and surface figure degrees of freedom. APS will use starlight to measure the wavefront errors and then will determine the appropriate commands to send to align the optics. Once the optics are aligned, the various control systems will record the set points for later use. In particular APS will measure and correct or align:

- M1 segments in piston, tip and tilt
- M1 segment surface figure
- M2 five degrees of rigid body motion (piston, tip, tilt, and x- and y-decenter)
- M2 surface figure
- M3 surface figure
- M3 two degrees of rigid body motion (tip and tilt)

APS will align the telescope at various elevation angles and then from the set points for the M1, M2 and M3 control systems, lookup tables will be generated to correct for gravity-induced deformations. In a similar fashion, data will be collected at various temperatures over time and lookup tables will be built as a function of temperature as well.

APS will have an acquisition camera with a 1 to 2 arcminute field of view, which can be used for pointing, acquisition, and tracking tests. APS will also provide a port where an On-Board Instrument WaveFront Sensor (OIWFS) can be placed in order to test its performance and validate the active optics control algorithms against APS.

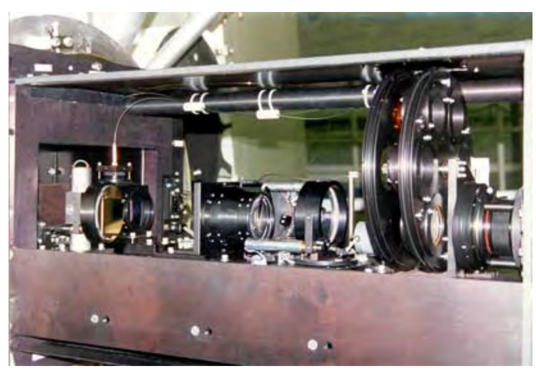

**Fig 8-42: Keck 2 phasing camera system installed at the left bent Cassegrain focus.**

APS is based upon the successful Keck Observatory Phasing Camera Systems (PCS) [1], and will play a similar, though somewhat expanded role. Each of the two Keck telescopes is equipped with a PCS, shown in **Fig. 8-42**. Together the two PCS systems have almost 25 years of on-sky experience and have successfully aligned the Keck telescopes a total of over 600 times. On the basis of this experience, we can confidently make quantitative predictions about how well we will be able to align many, though not all, of the optical degrees of freedom of TMT [2]. There are, however, some significant differences between PCS and APS. These include the following:

1. TMT has an order of magnitude more segments than Keck, which substantially increases the "source confusion" problems in the Shack-Hartmann wavefront sensor software. At the same time, the sheer

number of Shack-Hartmann subimages, as many as 20,000 in some APS functions, will mandate a very high degree of automation and afford almost no opportunity for manual operator intervention.

2. Keck is almost never used without all 36 segments installed. However, the TMT primary mirror will be built up sequentially, and as a result there will be long periods when it may often be used without all 492 segments installed (or at least controlled). APS will have to implement a robust incomplete mirror capability that can handle missing or uncontrolled segments.

3. APS will automatically control the warping harness on the M1 segments. At Keck, PCS made segment figure measurements, but the corresponding warping harness commands were then computed offline and the harnesses were adjusted manually.

4. APS will align the mirror shapes of M2 and M3 (these are static at Keck). This will require that APS make off-axis measurements to decompose the measured wavefront errors into the individual contributions from M1, M2 and M3.

**Conceptual Design Description and Options**

**Fig. 8-43** shows the conceptual design for the APS. The light from the telescope reflects off the first fold mirror and then encounters a beam splitter just after the telescope focus. The majority of the light (~95%) will pass through the beam splitter to the Shack-Hartmann camera, ~5% of the light will be reflected off to the imaging channel. Calibration sources are located on another side of the beam splitter and provide artificial stars with which to test and calibrate the cameras.

In the Shack-Hartmann camera after the light leaves the beam splitter, the pupil is de-rotated using a K-mirror. Lick Observatory has performed an initial design of this mirror [3]. After the K-mirror the light is collimated using a refractive design by Optical Research Associates (ORA) [4]. ORA has looked at several designs to determine how best to re-image the pupil over the required wavelength range of 600-900nm with the required pupil image quality. We believe the final design will likely be transmissive (as is shown in **Fig. 8-43**) with a pupil demagnification of ~400 or a 75mm pupil and a FoV of ~12 arcseconds. After the collimator there is a tilt plate for fine transverse control of the pupil location, a filter wheel, and at the telescope re-imaged pupil will be a wheel with multiple Shack-Hartmann masks/lenslets as described below. After the pupil the light will be re-imaged onto a 4Kx4K CCD.

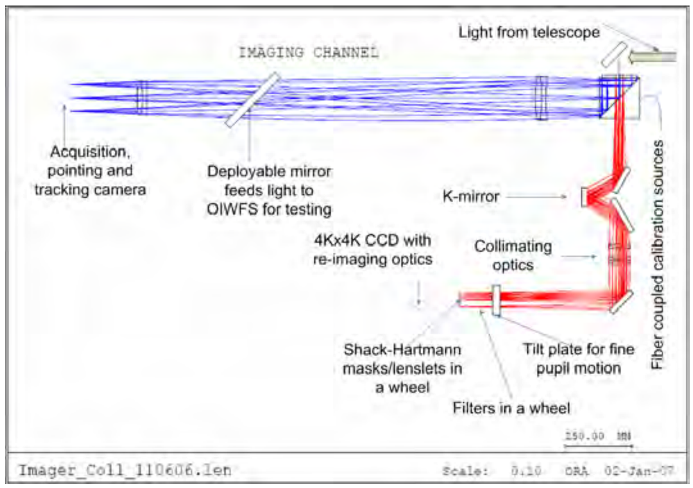


**Fig 8-43: Conceptual design and layout of the APS.**

In the imaging channel a 1 to 2 arcmin FOV will be imaged onto a CCD (currently 1Kx1K pixels). This camera will be used by APS for acquisition and tracking to keep the star centered on the Shack-Hartmann camera during exposures. It will also be used by TMT for more general acquisition, pointing and tracking tests. There will also be a deployable mirror in the imaging camera, which will pick off a portion of the field and feed it to, for example, an OIWFS for testing of the planned instrument active optics loops.

In the remainder of this section we describe the main APS alignment procedures. See the APS software requirements document [5] for a more complete list and description of the various procedures.

**M1 Segment Phasing**

APS will utilize the same general phasing techniques that were developed at and have been used extensively at the Keck telescopes. The coarse or broadband algorithm [6] is used primarily to capture segments in the piston degree of freedom; the fine or narrowband algorithm [7] determines the ultimate accuracy with which the segments are phased. Both algorithms are wave optics generalizations of the usual (geometrical optics) Shack-Hartmann technique. In the narrowband algorithm, the details of the diffraction pattern formed by a circular subaperture at an intersegment edge provide the phasing signal. [By contrast, in the traditional Shack-Hartmann test, the signal is simply the centroid of the corresponding subimage.] In the broadband algorithm, the signal is essentially the coherence of the same subimage. The broadband algorithm is analogous to the narrowband algorithm except that the scale over which it operates is the coherence length of the wavelength filter used to define the beam; in the narrowband algorithm the scale is set by the (much smaller) central wavelength.

We anticipate that the APS will utilize two or three subapertures per intersegment edge, as opposed to the single subaperture per edge used at Keck. The additional subapertures will increase the accuracy of the technique and can also be used to provide independent information on the segment tip/tilts. We have shown elsewhere [8] how this additional information can be used to smooth the overall figure of the TMT primary mirror.

**On-Axis Alignment of M1 and M2**

M1 segments will be captured in tip/tilt using a Shack-Hartmann procedure with a single subaperture per segment. Higher order information on segment figures will be obtained using a Shack-Hartmann array with 37 subapertures per segment, or about 20,000 subapertures overall. This is in contrast to Keck, where the segment figure information was obtained by zooming in to individual segment locations and making the corresponding measurements one segment at a time; an approach which is clearly not practical at TMT. The mean segment aberrations (averaged over the entire array of segments) will be used, as they are at Keck, to position M2 in piston, tip, and tilt. A significant difference for TMT is that the calculations for this latter step will be done via a semi-analytic raytrace code that is imbedded in the APS software; at Keck these calculations were done purely analytically. The latter approach has several drawbacks, including the fact that it involves unevaluated approximations, and the difficulty of identifying all terms of a given order of approximation.

The APS measurements will be used on-line to correct the segment figures via warping harnesses via a control matrix that works using the influence functions of the warping harnesses directly. At Keck, the control is done through an intermediate step that utilizes Zernike representations. The latter are not optimal for this purpose and there is an attendant loss of information.

**M2/M3 Surface Figures**

In order for APS to determine surface figures for M2 and M3 it will make measurements over the entire telescope field of view. This is necessitated by the small footprint of the optical beam on M3, but it is also required in order to provide sufficient information to disentangle M1, M2, and M3 aberrations, which exhibit a high degree of degeneracy on-axis. The bulk of the APS instrument will remain fixed; it will steer to various points in the field of view by means of coordinated motion of M3 and a steering mirror at the front end of the APS optics. A preliminary analysis of how the APS can effectively cover the field in this way has been completed by Optical Research Associates [4].

We have begun a mathematical analysis of the disentangling problem by means of the same semi-analytic raytrace code that will ultimately be used for positioning M2 in piston, tip, and tilt (see discussion of On-Axis Alignment of M1 and M2 above). The results to date (so far restricted to M1 and M2) show that the difficulty of the disentangling decreases as the azimuthal order of the aberrations increases; that is, the azimuthally symmetric aberrations (e.g. focus and spherical aberration on M1 and M2) are the most difficult to disentangle. We have a high level of confidence that if the aberrations are large enough to have optical consequences for the various instruments, then APS should be able to measure and correct them.

**Capabilities**

In many, if not most, cases, the APS alignment capabilities are limited by atmospheric turbulence, even for the long (~300 second) integrations that we anticipate for most modes.

We have developed a simple model to characterize this residual atmospheric turbulence based on the last six years of Keck alignment data. **Fig. 8-44** shows the results of the measurements vs. the best-fit model (the fit involves a single parameter, essentially the effective coherence diameter $r_0$). This model can be readily extrapolated to an aperture diameter of 30 meters and this provides a quantitative basis for our estimates of the atmospheric limitations to APS performance.
The model also provides an effective means to separate atmospheric effects from non-fundamental limits. Thus we have argued elsewhere [2] that the discrepant point in **Fig. 8-44** is due to contamination by noise from the Keck Active Control System.

**Table 8-10** shows the measurement uncertainties for various telescope misalignments and segment aberrations for a ~300 second exposure as measured at Keck and predicted for TMT. The values are for the average seeing at Keck ($r_0$=0.1m @ 500nm). The PCS systematic errors have been measured by inserting a fiber coupled reference source at the nominal telescope focus within PCS. In all cases the TMT predicted systematic errors are significantly smaller then the atmospheric errors.

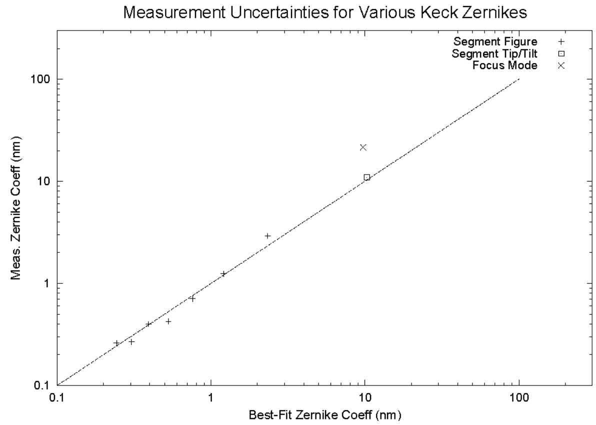


**Fig 8-44: Keck misalignment uncertainties expressed as Zernike coefficients on scales from a segment to the full 10 meter aperture.**

**Table 8-10: Aberration/Misalignment uncertainties from atmospheric and systematic errors (reference beams). All numbers refer to surface, not wavefront errors.**

| Aberration/Misalignment | | Keck Atmos. | Keck Ref. Beam | TMT Atmos. | TMT Ref. Beam |
|---|---|---|---|---|---|
| Segment Piston | (nm) | 6.0 | < 2.0 | 6.8 | n/a |
| | | | | | |
| Segment Tip/Tilt | (nm) | 10.3 | 4.0 | 8.5 | 0.9 |
| Segment 2$^{nd}$ Order | | 2.92 | 0.3 | 1.92 | n/a |
| Segment 3$^{rd}$ Order | | 1.24 | n/a | 0.99 | n/a |
| Segment 4$^{th}$ Order | | 0.71 | n/a | 0.63 | n/a |
| Segment 5$^{th}$ Order | | 0.42 | n/a | 0.44 | n/a |
| Segment 6$^{th}$ Order | | 0.40 | n/a | 0.32 | n/a |
| Segment 7$^{th}$ Order | | 0.27 | n/a | 0.25 | n/a |
| Segment 8$^{th}$ Order | | 0.26 | n/a | 0.20 | n/a |
| | | | | | |
| M1 Focus Mode | (nm) | 9.7 | 10 [est.] | 24 | 8.3 [est.] |
| | | | | | |
| M2 Piston | ($\mu$m) | 3.6 | 1.4 | 3.0 | 0.5 |
| M2 Tip/Tilt | (arcsec) | 2.6 | 2 [est.] | 0.8 | 0.3 [est.] |

**Key Development Tasks**

In this section we discuss the key development tasks for the APS and the plans for the associated risk mitigation.

1. The requirement to align the surface shapes of M1, M2 and M3 is unique to TMT. As discussed in the above section (M2/M3 Surface Figures) we have already started the analysis of this problem via a

semi-analytic raytrace code, and this work will continue until we have a working algorithm. Eventually this code will be incorporated into the APS software.

2. The warping harnesses at Keck perform significantly worse than the theoretical predictions. Much work has gone into understanding the errors at Keck, including experiments conducted at the Keck telescope, and while some significant progress has been made, the performance is on average a factor of 3 worse than the predictions. There is evidence that part of the problem is due to human error associated with the man-in-the-loop nature of the Keck procedure, but this same problem makes it difficult to perform definitive controlled experiments. TMT is relying on the warping harnesses performing at or near their theoretical limits in order to meet the stringent wavefront specifications imposed by adaptive optics systems. The warping harnesses at TMT will be motorized, which should allow for iterations of the control loop - something which is not feasible with the manual Keck system. TMT is also working on detailed modeling as well as investigating experiments with the ESO ELT effort and additional experiments at Keck.

3. As described above, the phasing function of APS utilizes details of the subimage diffraction patterns (and not simply their centroids) in order to determine the segment piston or phase errors. This places stringent requirements on the optical quality of the micro-optics used to form these subimages. At Keck, micro-prisms were used for this purpose. These are ideal as they can be built with extremely high optical quality; however, micro-prisms are not practical for TMT because the very large number of subimages implies unreasonably small prisms, probably a factor of 3 smaller (in each dimension) than the 2 mm by 3 mm prisms used in the Keck PCS. We will procure a prototype lenslet array with similar specifications to those needed for APS and test the optical quality in order to better understand whether this will be a problem for APS.

4. We have learned from our experiences with PCS that the algorithms, procedures, and even requirements continue to evolve during development, delivery and for years after delivery of the subsystem. As a result we believe it is essential to have a flexible software framework in place for procedure development and execution that allows the Optical Engineer to focus on solving the scientific/engineering problems without having to focus on software related issues. We have a potential solution and we will develop a test version of this system well before Preliminary Design Review (PDR) in order to insure that it will meet our requirements.

5. APS has a requirement on pupil stability of one part in 3000 or (0.03%) over 120 seconds. This is set by the phasing function of APS. This stability sets a requirement both on the telescope itself (principally M3) and on the internal K-mirror that APS utilizes to de-rotate the pupil. An initial analysis of the design of a K-mirror has been completed by Lick Observatory and shows that this level of accuracy will be difficult to maintain. The telescope system engineering group is currently analyzing if the telescope can met the needed requirements. A fall-back position is to add another camera to APS that will re-image the pupil after the K-mirror and provide fast (~1 second) measurements of the pupil and image position. The pupil position can then be corrected using optics internal to APS, while the image position would be corrected by means of adjustments to the telescope pointing.

6. APS will be the first “instrument” at TMT and as such it will be the first to work with many of the major telescope subsystems (M1CS, M2CS, M3CS, TCS, and the observatory database). During the early stages of integration and operations, it is inevitable that not all subsystems will be working properly and it can be particularly challenging to determine whether a given problem is internal or external to the APS. To deal with this issue effectively will require an extensive suite of tests and diagnostics internal to APS.

**Work Plan**

The principal investigator (PI) for the successful Keck PCS systems will likely be the PI for APS [1]. Because of the increased scale and complexity of APS, it makes sense to team with an industrial partner or a national lab that has experience delivering systems of similar scope. Collaboration has already started with the Jet Propulsion Lab, where there is also a significant existing knowledge base with Keck and the PCS. The PCS software lead is currently serving as a consultant to the APS team and will likely eventually become the APS software lead. We are leveraging as much as possible on the Keck experience in order to deliver a successful and cost effective solution for alignment and phasing of the TMT.

As mentioned above APS is a critical element in building TMT and in reaching first light. APS will likely be the first subsystem to use and test the telescope as a complete system. Thus it is essential that APS arrive at the telescope completely tested and working. The APS is being carefully integrated into the TMT project schedule. APS has scheduled a conceptual design review in August of 2007. Before APS ships to the telescope, we will execute a comprehensive test plan, which will include testing all APS procedures using internal light sources, testing with the telescope software interfaces, and thoroughly characterizing the systematic and random errors intrinsic to APS.

At the start of AIV, APS will be located on the telescope elevation axis, but it can be moved off the elevation axis at a later point if necessary. During AIV with the telescope, we plan to initially use APS for 14 nights once the first 120 segments are installed. We will start with pointing, acquisition and tracking tests, and then proceed to align the telescope on-axis. On-axis alignment includes M1 segment, tip, tilt and piston, M2 tip, tilt and piston, as well as M1 segment shape control. After the initial commissioning APS will be used after every additional 100 segments are installed to continue to align the telescope optics. Once all 492 segments are installed, we will complete the commissioning of the APS on-axis alignment functionality. The next and last step will be to test and commission the figuring of M2 and M3 shapes via off-axis measurements.

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#### 8.3.6.5 Global Metrology System

**Overview**

The GMS is a system based on permanently mounted surveying instruments (total stations) that can be used to automatically measure the relative positions of M1, M2, M3, and instrument, during operation of the telescope. At any time during the night, the telescope operator can pause between exposures and measure these positions to an accuracy of 50 microns in each axis, in a time period of about one minute. The GMS will be used to locate the M2 and M3 in their intended positions when they are initially installed, which will place them within the capture range of the APS.

**Requirements**

Each target must be viewable by at least one total station, preferably by at least two. The total stations must have a clear view of each other to establish the base reference frame. The total stations must have a distance range of 40 meters, and when used as a system must be able to measure the position of targets anywhere in that range with an accuracy of ±50 microns in X, Y and Z. The total stations must be cooled to minimize heat dissipation into the observatory environment. The GMS may not emit light during use of the telescope for science. The GMS must be controllable by the telescope operator, following prepared measurement programs. The full set of measurements shall be completed in one minute or less.

**Conceptual design description**

The GMS will consist of three total stations mounted in the upper telescope structure at locations where they can see: several fixed reference points around the perimeter of the M1, three points attached to the M2, three points attached to the M3, and three points around the entrance window of the instrument in use. The targets will be corner cubes or other similar retro-reflectors. Each total station will be kept continually warmed up, so each will be mounted in an enclosure that can open to allow use, and close to provide thermal isolation and active cooling. **Fig. 8-45** illustrates the GMS working geometry.

**Development Tasks**
The key components of the GMS are currently available commercially. No significant development is required.

**Work plan**
The total stations and targets will be commercial-off-the-shelf components. TMT will design the mounting hardware and enclosures for the total stations, and the mounting hardware for the targets. A subcontractor will provide the custom software for determining the target positions from the three sets of measurements. Controls Group engineers will develop the software that links the GMS to the Telescope Control System.

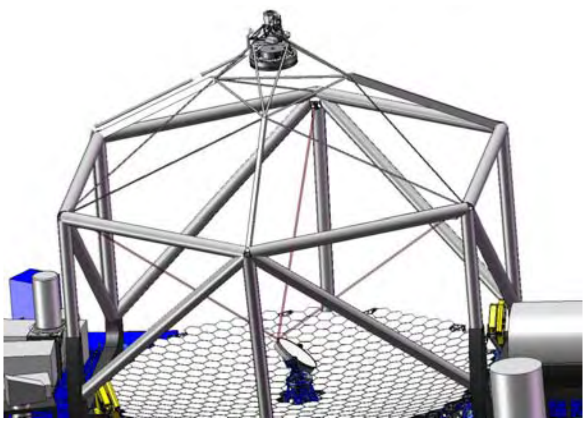

**Fig 8-45: The configuration of the GMS. The three surveying instruments are permanently mounted in small enclosures near the top of the telescope.**

### 8.3.7 Optics Installation and Maintenance Equipment

#### 8.3.7.1 Overview

The telescope optics will need special installation and maintenance equipment, including lifting, handling and storage equipment for the mirrors and their cells, coating equipment, and in-situ mirror cleaning equipment. These items of special equipment will be designed and fabricated as part of the construction project.

**Installation**
The installation process for M1 segments will be similar to that used with the Keck telescopes. The M1 Subcells will be installed on the mirror cell with the Segment Handling Cranes (SHCs). The subcells will be aligned using the surveying equipment and procedures outlined in **Section 8.3.6.**

Each Primary-mirror Segment Assembly (PSA) will be lifted into place with the SHC, which will be equipped with a hoist and a talon-type lifting mechanism. The lifting mechanism will be similar to that used at Keck. The SHC will place the PSA onto the segment jack attached to the M1 Subcell. The lifting mechanism will be disengaged and the PSA will then be lowered into place and aligned against registration features on the Subcell. Procedures for removal of the segment assembly are in reverse order, except the M1 Subcell remains in place on the mirror cell.

Installation of the Secondary Mirror (M2) Assembly will be with the telescope at horizon pointing. The enclosure-mounted crane will be used to lift the M2 Positioner and place it on the telescope structure interface mounts. The same crane will be used to lift the M2 Cell Assembly off the M2/M3 handling cart and place it on the Positioner interface mounts. Enclosure-mounted platforms will be used for personnel access while installing the M2 Positioner, mirror and cell. The procedure is reversed to remove the M2 Cell Assembly from the telescope for maintenance and re-coating.

The M3 Positioner will be installed using a mobile articulated boom crane, prior to installing the M3 Cell Assembly. The baseline approach for installing and removing the M3 Cell Assembly also uses the same articulated boom crane. The telescope will be elevated to 45 degrees and the Positioner rotated such that the mounting surface for the M3 Cell Assembly is horizontal. The articulated boom crane will pick up the M3 Cell Assembly and place it on the interface pads for the M3 Positioner. For maintenance and recoating, the M3 Cell Assembly will be removed from the telescope and transported on the M2/M3 handling cart to the coating area for stripping and re-coating.

**Servicing and Maintenance**
Servicing and maintenance of the optics includes in-situ cleaning and re-coating. In–situ service access for checking/replacing electrical and mechanical components is discussed in **Section 7.2.5.**

In-situ cleaning includes $CO_2$ snow cleaning and water/detergent washing. $CO_2$ snow cleaning of M1 and M3 will be performed semi-automatically using $CO_2$ snow cleaning nozzles attached to the SHCs. The M2 will be manually snow cleaned using a snow cannon controlled by a person on the enclosure-mounted service platform. The M2 will be manually washed by personnel on the enclosure-mounted platform. The M3 will be manually washed from a person-basket suspended from the mobile articulated boom crane. Catchment trays will be installed on the M2 and M3 Cells to contain the liquid and prevent it from getting on other optics and/or other equipment. These procedures are still at the conceptual stage and may change following preliminary design studies.

The mirrors will be coated in a 5-meter diameter coating chamber equipped for sputtering of multiple materials. The mirrors will be coated face down, which requires fixtures for turning the mirrors and for holding them in the upper part of the chamber. Four segments will be coated at one time; the M2 and M3 will each be coated separately. Old reflective coatings will be chemically stripped with the mirrors sitting face-up on corrosion-resistant handling carts. The mirrors will then be thoroughly washed and will be dried by large air knives before recoating.

#### 8.3.7.2 Requirements

The baseline coating recipe is the Gemini protected silver coating [1]. It has been shown to last 2 to 3 years in an observatory environment, with frequent cleaning. Other coating recipes are being investigated to improve durability and increase reflectance in the ultraviolet. Reflectance requirements and goals are summarized in **Table 6-2**. The lifetime requirement for the new coating is 3 to 4 years, with a goal of > 5 years under conditions that include frequent $CO_2$ snow cleaning and washing.

It is anticipated that the M1 segments and M3 will require weekly cleaning with $CO_2$ snow, because they face upward and will collect more dust. Because the M2 faces down and collects less dust, it will only need cleaning monthly.

The required M1 Segment coating rate is 4 segments every two days. Two days are allocated for coating the M2 and M3, each. Any attached mirror support components that go into the coating chamber must be vacuum compatible and not contaminate the chamber or the coating.

Requirements on the handling equipment relate to people and equipment safety, efficiency and effect on performance. Interface requirements for the installation and maintenance equipment are being developed.

#### 8.3.7.3 Conceptual Design Description and Options

**Figure 8-46** illustrates the current concept for the SHCs. Two SHCs will be mounted to the telescope elevation structure as shown. Each is a modified version of a commercial knuckle-boom crane that can be stowed compactly out of the optical path when not in use.

The TMT lifting mechanism will be patterned after the Keck design, which is shown in **Figure 8-47.**

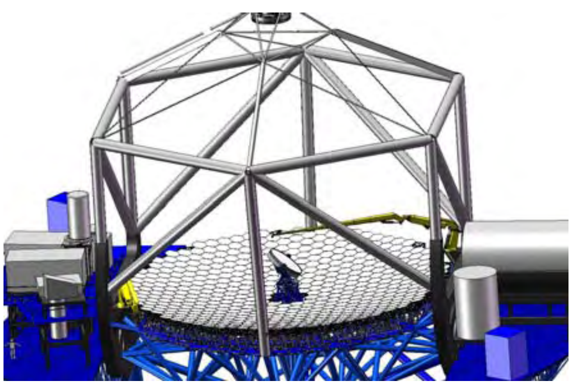

**Fig 8-46: The segment handling cranes, one shown in stowed position and the other extended.**

**Fig 8-47: The Keck segment lifting mechanism.**

**Figure 8-48** shows an example of a commercial-off-the-shelf (COTS) handling fixture [3] that can be modified to serve as the segment handling carts, similar to those used at Keck (see **Figure 8-47**). **Figure 8-49** shows a COTS shelving unit [4] of a type that can serve as the segment storage units. Each storage unit will store three PSAs and will use less floor space than storing each segment on a handling cart, as is done at Keck.

**Fig 8-48: A COTS handling fixture that can be modified to serve as the segment handling carts.**

**Fig 8-49: A COTS heavy-duty shelving unit with roll-out 1.2-meter shelves. TMT will purchase larger, modified, enclosed versions of this type of unit to serve as the segment storage units.**

**Figure 8-50** illustrates the installation or removal of the M2 Cell Assembly using the enclosure-mounted crane and deployable enclosure-mounted service platform, with the telescope horizon-pointing.

The installation or removal of the M3 Cell Assembly is illustrated in **Figure 8-51**. A mobile crane will be used to lift the M3 Cell Assembly with the telescope elevated to 45 degrees and the M3 rotated to be upward-facing.

The coating chamber will be similar in concept to the chambers used by the Gemini Observatory to coat their 8m primary mirrors, except the TMT mirrors will be coated face down.

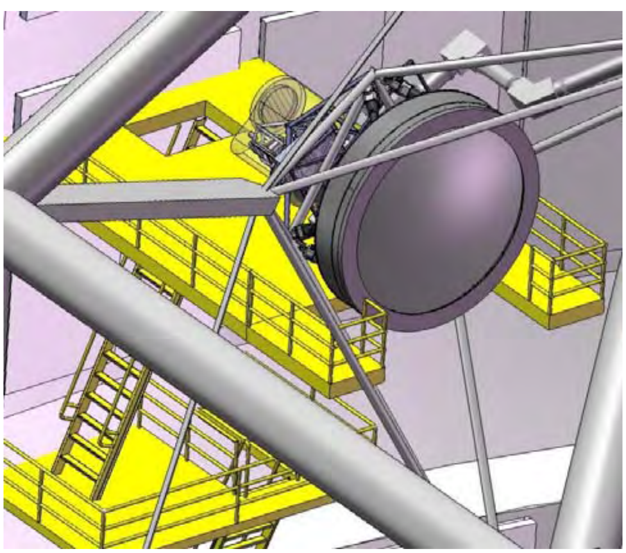

**Fig 8-50: The configuration for removal of the M2 and its mirror cell, with telescope horizon pointing and the enclosure-mounted service platform deployed.**

#### *8.3.7.4* Development Tasks

Further design studies are required to develop the details of the installation and removal of the mirrors in the telescope with the smaller dome design and knuckle-boom concept for the SHC.

TMT currently has a development contract with Pacific Northwest Labs (Battelle) to develop a durable coating that meets the reflectance requirements. Samples provided from this study will be tested at UCSC. Additional studies are anticipated. TMT will commission a preliminary design study to develop the process and coating chamber design appropriate for the coating being developed.

#### 8.3.7.5 Work Plan

Some of the equipment designs are modifications of COTS equipment, e.g. the Segment Handling Cranes, Segment Handling Carts and Segment Storage Units. The Segment Lifting Mechanism will be designed by the same contractor who is designing the segment support. The lifting fixtures for the M2 Mirror and the M2 Cell will be designed and fabricated by the contractor who designs the M2 Cell Assembly. Similarly, the lifting fixtures for the M3 Mirror and the M3 Cell will be designed and fabricated by the contractor who designs the M3 Cell Assembly. Mirror cleaning equipment will be designed by a contractor experienced in the design of $CO_2$ snow cleaning equipment. Most of the rest of the specialized mirror handling equipment and mirror stripping and washing equipment will be designed by project engineering staff.

The coating chamber will be designed and built by a contractor. The performance of the coating chamber will be tested before it is shipped to the site.

All of the installation and maintenance equipment and procedures will be tested with dummy loads before being used with the real mirrors.

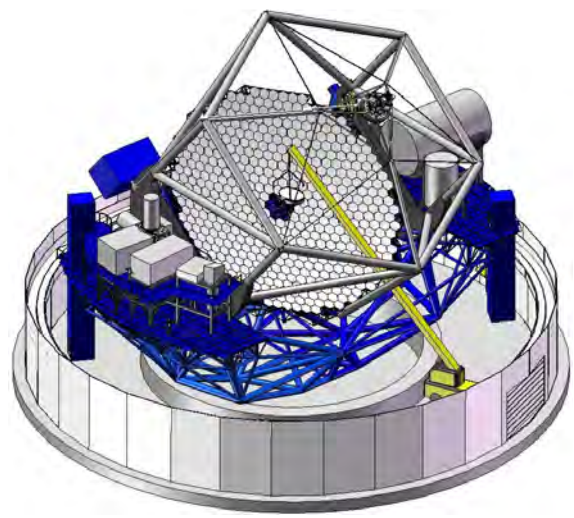

**Fig 8-51: Removal of the M3 and its mirror cell using the mobile crane, with the telescope pointing 45 degrees from the zenith.**

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## *8.4 Observatory software*

### 8.4.1 Overview

Observatory software covers a collection of design and implementation activities that include:

- High-level software system architecture
- A common TMT software development framework for all software subsystems
- Communications architecture and software (middleware) for system integration
- Critical software subsystems for observatory control, data management and queue observing

Level-1 software requirements for TMT can be found in the Observatory Requirements Document [1]. The Observatory Architecture Document [2] contains a summary of the Level-1 software architecture.

### 8.4.2 Requirements

Observatory software has the following top-level functional requirements:

- Enable efficient user command, control, and monitoring of all observatory functions.
- Enable target acquisition and observation initiation in no more than five (5) minutes (10 minutes if an instrument change is involved).
- Enable all the baseline science operations services discussed in **Section 5.2**.
- Enable the later implementation of all the enhanced science operations services discussed in **Section 5.2**.
- Enable telemetry capture for the purposes of performance analysis and monitoring.
- Capture and store observatory data streams (science, engineering, and adaptive optics) at mean rate of 0.02 Gbit/s (estimated peak rates: 0.10 Gbit/s). At least 100 TB of storage must be available.

All TMT software subsystems have the following additional top-level technical requirements:

- Use common communications (middleware) infrastructure
- Use common user interface look-and-feel design paradigms
- Use common software development framework
- Plan for extensibility and maintainability

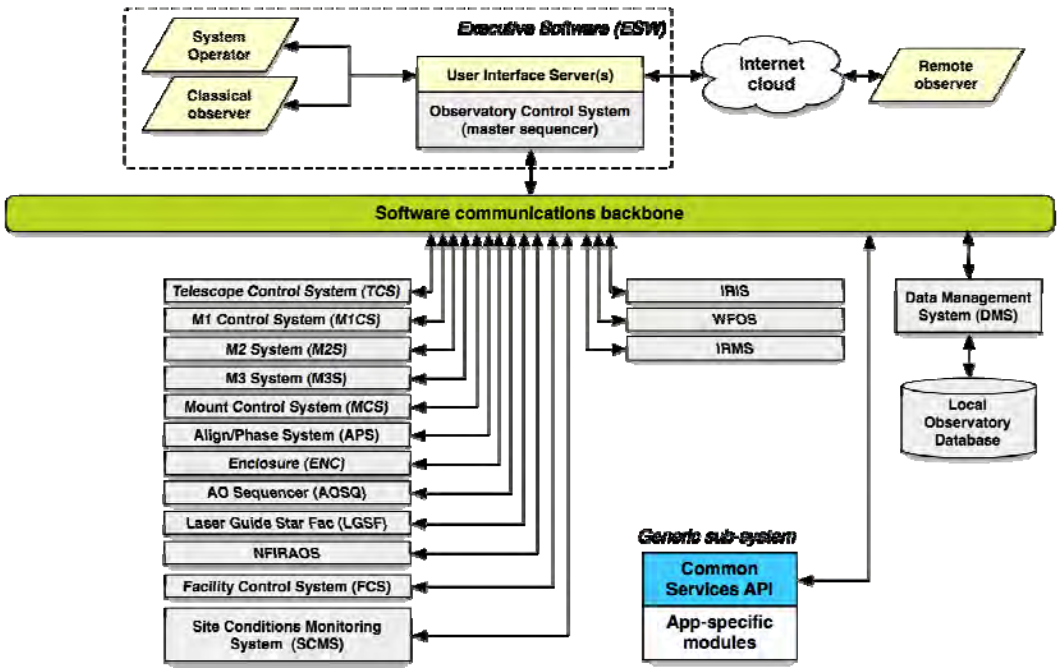



**Fig 8-52: OES integration architecture.**

### 8.4.3 Conceptual design

At the functional core of the TMT software system is an observation execution system (OES). Actual observations (and other system-wide observatory actions) are initiated and coordinated using the dynamical command-and-control architecture discussed in Section 7.3.2 and shown in Figure 7-10. From a communications and integration perspective, the OES is a distributed system; that is, it consists of a set of applications interacting with each other through a communications (middleware) layer. A local observatory

**Table 8-11: Common services definition.**

| Service | Task |
|---|---|
| Location/connection | Manage inter-process communications connections |
| User single sign on | Manage user authentication/access control |
| Event | Manage event publishing/subscription |
| Health | Manage health check signals |
| Logging | Capture/store log information |
| Bulk data store | Capture/store bulk data (e.g. science data) |
| Telemetry store | Capture/store telemetry |
| ODB access | Middle-tier for database access |
| Time | Standard GPS-based Network Time Protocol (NTP) service |

database will provide persistent storage as necessary. User interfaces shall act as client-side applications interacting with the system as a whole. A high-level view of the OES integration and communications architecture is shown in **Figure 8-52**.The middleware layer shown in **Figure 8-53** can be decomposed into the services listed in **Table 8-11**.

The communications (middleware) backbone shown in **Figure 8-53** can be decomposed into the services listed in Table 8-12.

Each of these services will have an Application Programming Interface (API) that is service implementation neutral, i.e. it should be possible to change how a service is implemented without needing to make code modifications to the subsystems using that service.

It may be desirable to build these services on top of available middleware toolkits such as RTI Data Distribution Service (formerly NDDS), Ice, CORBA, EPICS, the Internet2 middleware initiative, FioranoMQ, etc. Various such solutions shall be evaluated during the design phase.

**Table 8-12: Communications protocol stack.**

| **Layer** | **Possible solutions** |
|---|---|
| *TMT-specific standards and content* | |
| Service-specific data structure content | TBD (TMT-specific) |
| Service-specific data structure syntax | TBD (TMT-specific) |
| *Industry standards* | |
| Data structure standard | HTML, XML, FITS |
| Application (inter-process communication, IPC) | HTTP, SMTP, Java RMI |
| Transport | TCP |
| Network | IP |
| Data Link | ATM, PPP |
| Physical | Ethernet, CAN, ISDN, WiFi |

These services will be built on top of generic protocol stack described in **Table 8-12**.

User interfaces with command and monitor functionality must be developed for classical observers (on-site or remote), systems operators, and technical staff responsible for monitoring performance. These interfaces will be graphical and have a common look-and-feel. Each user interface is essentially a thin-client interacting with the rest of the system as if it were a server. Care will be taken to allow for using such interfaces in monitor-only mode from remote locations.

Observation execution is central to a larger program execution workflow common to all general-purpose observatories (see **Figure 8-53**). To support that workflow, a program execution system (PES) has been designed. Due to resource limitations, the PES will be implemented incrementally. Hence, the PES architecture and subsystem design must take that limitation into account.

### 8.4.4 Development tasks

Two tasks are important foundations for design and implementation of all TMT software subsystems.

First, specifications and initial design for the software communications backbone services (including the API for each service) must be completed. After that, middleware solution evaluation can begin in earnest. If existing solutions are found to be insufficient, in-house design and implementation work should begin.

In parallel, a cross-system software development framework must be defined and will include (but is not necessarily limited to):

- Common services APIs and libraries
- GUI builders
- Data structure editors

- Build tools and build process specification
- Centralized configuration control server
- Centralized and automatic build, integrate, and test process
- Standards for:
    - Sequencing engines
    - Data and meta-data structures
    - User interfaces
    - Development languages
- Specifications for:
    - Development environment (OS, hardware, compilers…)
    - Deployment environment (OS, hardware)
- Associated documentation

Once this foundation work is completed, attention can turn to completing the specifications and initial design work for such OES subsystems as:

- OCS: Observatory Control System (master sequencer)
- DMS: Data Management System
- HSCM: High-level System Control & Monitoring (operator & observer user interfaces)
- ICS-Generic: Instrument Control System (Generic)
- ODB: Observatory Database

As necessary, specifications and initial design work should be completed on various PES subsystems to make sure they use interfaces, data structures, and inter-process communication solutions that are compatible with the core OES architecture.

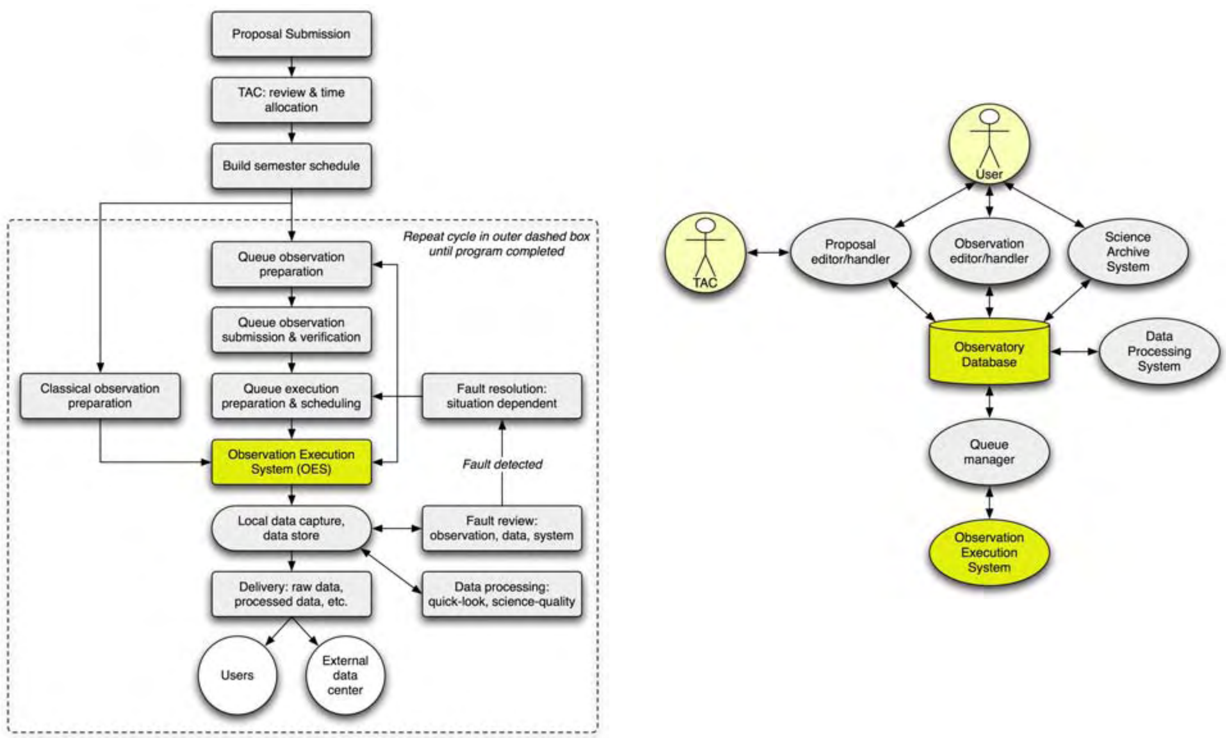



**Fig 8-53: PES workflow and architecture.**

### 8.4.5 Work plan

During the DDP phase, all the development tasks described above will be completed by a small in-house software architecture and system engineering team.

Construction phase activity falls roughly into two categories: subsystem implementation and system engineering.

The first category (subsystem implementation) contains all the work necessary to implement the various subsystems shown in Figures **8-52** and **8-53** above. Work related to telescope, adaptive optics, and science instrument subsystems will be completed by external contractors as part of larger delivery packages. Work related to observatory sequencing, facility control, site monitoring, and information management is planned for an in-house team but is structured so that outsourcing is possible.

The second category (software system engineering) contains all the work necessary to integrate and test the entire TMT software system. Incremental lab integration is foreseen so that software system delivered to the site has already been extensively tested. This work will be done by an in-house team. That team will also provide support to subsystem developers using the TMT common software development framework.

### *References*

[1] Observatory Requirements Document (ORD), TMT.SEN.DRD.05.001

[2] Observatory Architecture Document (OAD), TMT.SEN.DRD.05.002

## *8.5 Early Light Adaptive Optics*

### 8.5.1 System Architecture

#### 8.5.1.1 Overview

Adaptive optics (AO), including laser guide star (LGS) adaptive optics, has already proven its importance and popularity on the current generation of 8-10 meter class ground-based astronomical telescopes. Because the benefits of AO grow dramatically with telescope aperture (the so-called "$D^4$ scaling"), the anticipated use and significance of AO for future ELTs is even greater. According to our SRD [1], at least 40 percent of TMT observing time will utilize AO from the very beginning of science operations, a percentage that will only increase as the telescope and its instrumentation mature. The range of potentially interesting AO concepts and science applications that have been proposed to address this opportunity is much too large to be outlined here; the challenge is not only to identify a plausible AO architecture for TMT, but to select the configuration which will maximize scientific return as soon as possible following telescope first light at acceptable cost, complexity, and risk.

The initial AO architecture for TMT has been defined to provide near-diffraction-limited wavefront quality and high sky coverage in the near infra-red (IR) for the early light science instruments IRIS and IRMS. It is an LGS multi-conjugate AO (MCAO) architecture consisting of three major systems: (i) the facility Narrow Field IR AO System (NFIRAOS), which is located on the TMT Nasmyth platform and relays light from the telescope to three science instrument ports after sensing and correcting for wavefront aberrations introduced by atmospheric turbulence and the observatory itself; (ii) the Laser Guide Star Facility (LGSF), which generates multiple LGS in the mesospheric sodium layer with the brightness, beam quality, and asterism geometry required by the NFIRAOS wavefront sensors (WFSs); and (iii) the Adaptive Optics Sequencer (AOSQ), which automatically coordinates the operations of NFIRAOS and the LGSF with the remainder of the observatory for safe and efficient observations.

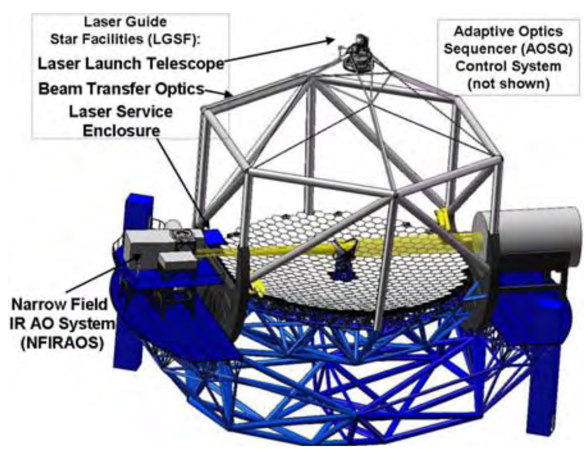



**Fig 8-54: Early Light AO Facility.**

This top-level decomposition of the early light AO facility is completely analogous with current and near-term facility LGS AO systems on many existing 3-10 meter astronomical telescopes. In fact, much of the overall design philosophy (and many important subsystem design concepts) for NFIRAOS and the LGSF has also been derived from these existing AO systems, and the use of MCAO to widen the corrected field of view has recently been demonstrated on the sky at the VLT. Although the order of wavefront correction required for a 30 meter telescope will be at least a full factor of ten greater than today's facility AO systems, recent and ongoing advances in critical component technologies will enable the use of scaled and/or re-engineered versions of many existing designs (for instance, deformable mirrors and sodium guidestar lasers), supplemented by several more innovative concepts which are already under development (wavefront sensing detectors and real time control processors).

Finally, we have developed a detailed work plan and schedule that are consistent with commissioning NFIRAOS and the LGSF immediately following telescope commissioning. Our cost estimate has been derived from this work plan, and is supported by credible quotes from component and subsystem suppliers.

#### 8.5.1.2 Top-Level and Derived Architectural Requirements

The top-level requirements for the early light AO facility are described in Sections 3.3.15 and 3.3.18 of the TMT ORD [2]. These requirements have been defined to provide diffraction-limited atmospheric turbulence compensation for the IRIS, IRMS, and NIRES instruments. In general terms, these requirements include:

- High throughput in the J, H, and K, and (as a strong goal) I, spectral bands with very low emissivity;
- Diffraction-limited near IR image quality over a "narrow" field-of-view of 10-30 arc seconds, which is still significantly larger than the isoplanatic patch size;
- 50% sky coverage at the galactic pole;
- Excellent photometric and astrometric accuracy; and finally
- High observing efficiency, with a minimum of downtime and night-time calibration.

Further, more quantitative, discussion of these requirements is given in the following subsections, but the above considerations already define many basic features of the early light AO facility.

High sky coverage can only be achieved using LGS AO for higher-order wavefront correction. Furthermore, the requirement for diffraction-limited wavefront compensation and the large TMT aperture diameter imply a requirement for multiple LGS and tomographic wavefront reconstruction to defeat the cone effect, which would result in an unacceptably large wavefront error with only a single LGS. Additionally, the diameter of the science field and the requirements on photometric and astrometric accuracy imply a need for MCAO, which provides atmospheric turbulence compensation over an extended field by using multiple deformable mirrors (DMs) conjugate to several different ranges in the atmosphere.

Next, the TMT aperture diameter and the SRD specifications for diffraction-limited image quality combine to yield requirements for very high order wavefront sensing and correction, as well as very high control bandwidths. These requirements in turn imply a need for bright laser guide stars and computationally efficient wavefront control. Schedule risk should be minimized to be ready for first light, so all of these devices must be based upon existing or near-term AO component technology wherever possible.

The demanding SRD specifications for sky coverage also place important requirements upon the approach to natural guide star (NGS) tip/tilt wavefront sensing.[20] IR tip/tilt sensing will be necessary, both because of the higher density of "red" (K and M class) guide stars and the fact that "sharpening" (AO compensation) of the IR images permits the use of dimmer guide stars. Even so, a large tip/tilt WFS patrol field will still be needed to maximize the probability of detecting a sufficiently bright guide star. Because the tip/tilt measurements obtained from a single off-axis NGS are corrupted by tilt anisoplanatism, multiple tip/tilt guide stars must be utilized to estimate tip/tilt in the direction of the science object via a process of interpolation. Finally, the SRD specification to minimize emissivity requires a cooled AO optical path.

#### 8.5.1.3 Architecture Design Description

For this subsection, we will define the "design" of the early light AO facility to include the decisions made regarding key component technologies, high-level design options, and the values of the fundamental AO parameters (e.g. control bandwidth) that determine the performance of the AO control loop. These values then become requirements imposed upon NFIRAOS, the LGSF, and their components, as will be described in the following subsections.

[20] Laser guide stars cannot currently be used for tip/tilt sensing, since their precise location on the sky is unknown due to a combination of laser jitter, telescope jitter, and atmospheric turbulence.

**Table 8-13** summarizes the choices made regarding critical component technologies for the early light AO facility. As described further below, the options selected for lasers, laser beam transport, and deformable mirrors represent relatively modest extrapolations to existing devices, which may be incorporated into practical subsystem designs with minimal risk and acceptable cost. On the other hand, the technologies selected for the NGS WFS detectors and the real time controller (RTC) are more ambitious choices which are mandated by the challenging SRD sky coverage specifications and sheer size of the wavefront control problem for TMT. Finally, we have selected the “polar coordinate” CCD array concept (now under development by the Adaptive Optics Development Program, or AODP) for LGS wave front sensing because it will minimize the impact of the guide star elongation induced by the use of continuous wave (CW) guidestar lasers.

**Table 8-13: Technologies Selected for Critical AO Components.**

| Component | Technology |
|---|---|
| Sodium guide star lasers | Solid state, continuous wave (CW), sum frequency |
| Laser beam transport | Conventional optics (not fibers) |
| Deformable mirrors | Piezostack actuators |
| LGS WFS detectors | “Polar coordinate” CCD array |
| NGS WFS detectors | High-speed, low-noise IR detector arrays |
| Real Time Controller (RTC) | DSP and FPGA hardware<br>Preconditioned conjugate gradients (PCG) algorithm |

**Table 8-14** summarizes some of the high-level design choices imposed upon the NFIRAOS and LGSF design teams. Laser beams will be projected from behind the TMT secondary mirror to minimize the magnitude of LGS elongation, which would be approximately twice as large if the beams were launched from the edge of M1. The lasers themselves must be mounted on the telescope center section (moving with the primary mirror), since it currently appears difficult to transport laser beams from the Nasmyth platform onto the telescope without using optical fibers at unrealistically high power levels.[21]

Turning to the design of NFIRAOS, we have decided to transfer the requirements for field de-rotation and tip/tilt wavefront sensing onto the NFIRAOS science instruments, since this will help reduce both the number of “warm” optical surfaces and the un-sensed tip/tilt biases between the tip/tilt wavefront sensors and the scientific focal plane. Additionally, one of the NFIRAOS deformable mirrors will be mounted on a tip/tilt platform to further reduce the number of optical surfaces.

**Table 8-14: High-Level Design Choices.**

| Design Choice | Decision |
|---|---|
| Laser Launch Telescope location | Behind TMT secondary mirror |
| Laser location | Enclosure mounted on telescope elevation journals |
| Tip/tilt NGS WFS location | Within science instruments (not within NFIRAOS) |
| Field de-rotation | Rotation bearing at NFIRAOS-Instrument interface |
| Tip/tilt control architecture | “Woofer-tweeter” control, with a DM mounted upon a tip/tilt platform |

Finally, **Table 8-15** lists the first-order AO design parameters for NFIRAOS and the LGSF that determine the potential performance of the control loop. Derived and validated using detailed modeling codes, these design parameters yield a delivered, on-axis RMS wavefront error of about 187 nm (including implementation error sources) for the early light TMT AO system. Further details of the error budget are presented in **Section 8.5.2** below.

[21] This decision will be reviewed at the beginning of the TMT construction phase based upon performance achieved by optical fibers at that time.

**Table 8-15: Fundamental AO Design Parameters.**

| Parameter | Value |
|---|---|
| Laser power per guide star, W | 25[22] |
| LGSF optical throughput | 0.75 |
| Launch telescope aperture diameter, m | 0.5 |
| LGSF delivered Strehl | 0.85 due to high spatial frequency errors<br>0.70 due to low frequency (quadratic) errors |
| Order of wavefront sensing and correction | 60x60 subapertures |
| Control loop update rate, Hz | 800 |
| DM conjugate ranges, km | 0 and 12 |
| LGS asterism | 1 on-axis guide star<br>5 guide stars in ring with a 35 arc sec radius |
| LGS WFS pixel size and read noise electrons | 0.5 arc sec, 5 electrons/pixel/read |
| Tip/tilt NGS WFS pixel size and read noise electrons | 1/128$^{th}$ arc sec, 10 electrons/pixel/read |

#### 8.5.1.4 Key Development Tasks

The key development tasks for each individual early light AO subsystem and its components are described in the following subsections. At the architectural level, the most important additional “development task” is the systems engineering needed to correctly allocate and update performance and interface requirements for these subsystems and components. Accurate and consistent requirements flow-down depends upon both (i) rigorous modeling and error budgeting tools, and (ii) good communication between all subsystems design teams and the TMT systems engineering group to insure that these tools are exercised upon proper input assumptions and that the results obtained are well understood.

We are now in the process of upgrading our AO modeling codes to support the above systems engineering tasks. Sample questions that can be addressed using completed or ongoing upgrades include the compensation of telescope aberrations by the early light AO system and the introduction of focus and other wavefront aberrations due to the variability of the sodium layer. We will anchor these models against actual LGS AO results obtained at Keck Observatory.

#### 8.5.1.5 Work Plan

Once again, the detailed work plan for each AO subsystem or component is described in the corresponding subsection below.

In general terms, the overall work plan for the complete early light AO system is based upon extensive coordination and collaboration between the AO group at the TMT Project Office and the independent development teams for NFIRAOS and LGSF subsystems. The TMT Project Office will take responsibility for the procurement of the critical AO components (including deformable mirrors, WFS detectors, the Real-Time Controller, and guide star lasers), and deliver them to the NFIRAOS and LGSF development teams for integration into these subsystems. The Project Office will continue to provide simulation and analysis support to evaluate and optimize the predicted overall performance of the early light AO system. Finally, the TMT AO group staff will participate fully in the AIV and commissioning of NFIRAOS and the LGSF, both at their development facilities and later at the TMT site. This will provide additional support and specialized expertise for the subsystem development teams, and will also aid in transitioning these subsystems into Early Operations at TMT.

Additional important characteristics of the overall AO work plan are (i) coordinated development of the telescope, early light AO systems, and early light instruments from the very beginning of the TMT Design and Development phase, and (ii) comprehensive testing of all major AO systems at their development facilities before they are delivered to the Observatory. For example, NFIRAOS will be integrated and tested with IRIS, and LGSF testing will include high power testing with one of the deliverable 50 W guide star laser systems. This emphasis upon early design coordination and system-level testing reduces schedule and performance risk

[22] 17 W yields acceptable performance during seasons of at least average sodium column density.

for the early light TMT AO system, thereby maximizing the prospects for scientific observations with instruments like IRIS and IRMS immediately following TMT first light.

### 8.5.2 Early light AO systems

#### 8.5.2.1 NFIRAOS

The early light AO system on TMT will be a facility on the Nasmyth platform capable of feeding up to three live astronomical instruments. This Narrow Field IR AO System (NFIRAOS), which senses and corrects wavefront aberrations induced by the atmosphere and the observatory, will provide diffraction-limited resolution and high Strehls over a 10-30 arc second science field of view. It uses two deformable mirrors conjugate to ranges of 0 and 12 km to extend the AO-compensated field-of-view beyond the isoplanatic patch size, and also to improve sky coverage by sharpening near-IR natural guide stars over a 2 arcminute diameter “technical” field. This larger field will also be used by the IRMS instrument, taking advantage of the significantly improved image quality out to the edge of the field (Strehl ratio >3%.)

**NFIRAOS Requirements**

The following **Table 8-16** shows the key specifications for NFIRAOS taken from the TMT Observatory Requirements Document [2].

**NFIRAOS Design Summary**

Our complete design [3], of both opto-mechanics and controls, meets all of the requirements in the table immediately above. **Fig. 8-55** below shows a side view of the opto-mechanics within NFIRAOS. These optics, which have 85% throughput, will be housed in a cooled (-35 C) enclosure to achieve the background emissivity specification. NFIRAOS will have a mass of 17 tonnes and dimensions of L x W x H of 8 x 3.8 x 5.5 m. This size is a direct consequence of correcting the f/15 telescope beam with an order 63x63 deformable mirror with a clear aperture diameter of 300 mm.

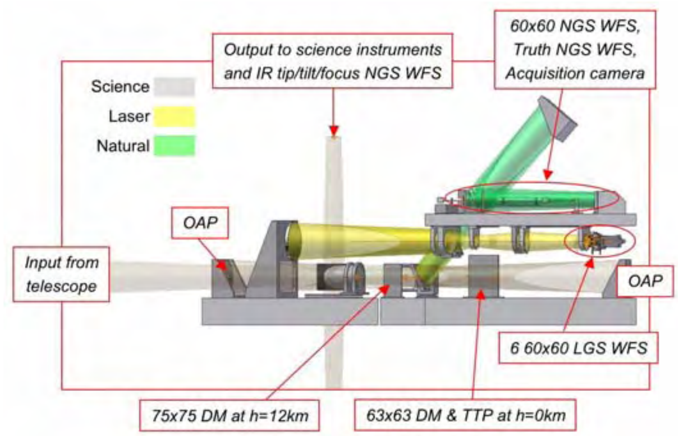



**Fig 8-55: Optics paths within NFIRAOS.**

During the conceptual design phase, the TMT project office and the Herzberg Institute of Astrophysics worked together to conduct trade studies on the number and location of laser guide stars, and the optimum altitude to conjugate each of two DMs. The resulting design has one deformable mirror, DM0, conjugate to the telescope pupil (mounted on a Tip-Tilt Platform), and a second, DM12, conjugate to 12 km. Other principal component parameters for NFIRAOS are listed in the table of Fundamental AO Design Parameters in **Section 8.5.1.3**.

In **Fig. 8-55**, the input beam from the telescope enters from the left via a shuttered, double-paned evacuated window (not shown). NFIRAOS accepts the telescope beam, corrects it and passes it to three identical instrument mounting ports – two with vertical axes and one horizontal, with 1 m back focal distance in each case. There is an airtight seal to each instrument’s window.

Light from the telescope is collimated by an off-axis parabola (OAP, shown to the lower right in the figure), reflects off the high altitude, and then the ground conjugated, DMs, passes through a beamsplitter, before being reimaged by a matching OAP. Finally an instrument selection mirror diverts the corrected light to one of three ports.

After the DMs, a beamsplitter sends visible light to the middle level where the artificial laser light is again split off to the laser zoom optics that refocuses the sodium layer while accurately imaging DM0 onto the six 60x60 LGS WFSs lenslet arrays. These zoom optics must also correct aberrations arising from imaging artificial laser guide stars off-axis and as close as 90 km by means of a telescope and science path optics, which are designed for objects at infinity.

The natural visible light continues to the upper level in **Fig. 8-55**. Here, a Truth WFS monitors a natural star for long term drifts in image quality during operation, and updates offsets within the real time computer. For operation without lasers, there is also a visible wavelength natural guide star (NGS) wavefront sensor, which can control the DMs via a bright natural source.

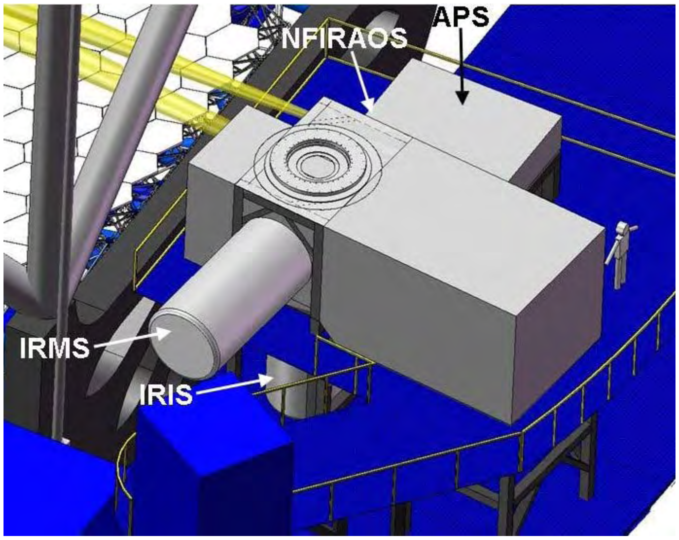



**Fig 8-56: NFIRAOS on Nasmyth Platform.**

At the start of each observation, a near-IR acquisition camera, internal to NFIRAOS and fed by a fourth position of the instrument selection steering mirror, will measure the location of three stars accurately enough to position NFIRAOS' Truth WFS and the two Tip-Tilt sensors and the single Tip-Tilt focus sensor within client instruments. These provide fast guiding, calibrate focus biases in the LGS WFSs induced by variations in the structure and range of the sodium layer, and also detect quadratic modes of tip/tilt anisoplanatism. Thus, typical operation will use LGS WFSs within NFIRAOS blended with measurements from NGS IR wavefront sensors within instruments.

NFIRAOS also includes remotely-deployable simulated NGS and LGS sources, which will be used to characterize and calibrate system performance, especially non-common path aberrations between the wavefront sensing and science optical paths.

**Table 8-16: Specifications for NFIRAOS.**

| **Requirement** | **Specifications** | **Comments** |
|---|---|---|
| Concept | Facility Laser Guide Star AO system | |
| Purpose | Correct atmospheric turbulence and feed three near infrared instruments | |
| Wavelength range | 1.0 – 2.5 $\mu$m | (goal 0.6 – 2.5 $\mu$m) |
| Corrected science field of view | 10-30 arc seconds | |
| High Order wavefront error | 187 nm rms over science field of view (at early light) | 207 nm rms over a 30 arc second field (at early light) |
| Upgradeability | 133 nm rms high order wavefront error over 30" science field of view | With order 120 x 120 wavefront correction |
| Tip/Tilt Jitter | 0.002 arc seconds rms at early light | for 50% sky coverage (goal <0.1 $\lambda$/D ) |
| Sky Coverage | 50% | at galactic pole |
| Throughput | >85% | (goal >90%) |
| Background | <15% increase | vs. (K-band inter-OH sky + telescope background) |
| Operating Efficiency | Switch instruments with <10 minutes closed shutter time | |
| Versatility | Natural guide star operation also required | |
| Schedule | Ready for commissioning at TMT first light | with low risk, reasonable cost |

**NFIRAOS Performance Summary**

We have developed a comprehensive error budget with most terms supported by detailed simulations. The expected 187 nm RMS wavefront error compares favorably with performance of existing AO systems on 8- to 10-m class telescopes (240 - 380 nm RMS).

In the **Table 8-17** Wavefront error budget, the line "Ideal AO" encompasses these fundamental AO errors: WFS noise and spatial aliasing; control loop servo lag; tomographic reconstruction errors, errors projecting turbulence onto the DM planes; and DM fitting errors. "AO implementation" includes DM hysteresis; actuator calibration; DM influence function imperfections; entrance pupil, DM, and WFS optical mis-registration; LGS WFS gain estimation; sodium layer focus tracking; non-common-path calibration; obscuration from the telescope secondary mirror supports; real-time controller numerical accuracy; and uncorrectable NFIRAOS optics errors. Next, the uncorrectable telescope error item is an allocation from the top-level TMT observatory error budget. Similarly, the uncorrectable instrument error is an allocation imposing a requirement on client instruments.

For the tip-tilt error budget, we used a Monte Carlo simulation of the NFIRAOS tip/tilt control loop with multiple natural guide stars. This code evaluates the overall tip/tilt error associated with each randomly generated NGS asterism accounting for anisoplanatism, servo lag, WFS noise, windshake and partial sharpening of NGS images by NFIRAOS.

This error budget is based upon detailed analysis of the numerous terms summarized in the above paragraphs. The expected total wavefront error of 187 nm RMS on-axis, and 191 nm RMS averaged over a 10" field, is superior to AO systems on the largest telescopes today.

Three to four items that have particularly concerned us include M1 figure aberrations, LGS elongation effects, telescope windshake jitter, and the fact that LGS MCAO has not yet been demonstrated on the sky. M1 figure errors must be amenable to AO correction i.e. without appreciable high spatial frequency aberrations and edge discontinuities, in order for NFIRAOS to attenuate them to the allocated level in the observatory error budget. The edge of the TMT pupil is much further from the laser launch telescope than for any existing AO system, so the thickness of the sodium layer and its variability have a larger potential impact on NFIRAOS as described below in **Section 8.5.3.2**. Image jitter is very important for NFIRAOS, since the diffraction limit of TMT is small, yet NFIRAOS relies on a state-of-the-art, 20 Hz tip tilt platform with a large 30 cm clear aperture. Observatory windshake modeling is still ongoing, but we have developed a robust woofer-tweeter control scheme to meet our error budget even under conservative assumptions. Finally, while theory, modeling and NGS MCAO field tests all indicate that LGS MCAO should work, it remains a subject for further testing and development.

**Table 8-17: Wavefront error budget.**

| Error Budget Element | On-axis RMS nm | Average over 10" RMS nm |
|---|---|---|
| Ideal AO | 130 | 136 |
| AO implementation | 89 | 89 |
| Telescope | 45 | 45 |
| Instrument | 30 | 30 |
| RSS higher-order total | 166 | 170 |
| Two-axis Tip/tilt | 85 | 86 |
| RSS total | 187 | 191 |

**Key Development Tasks**

**Table 8-18** is a summary of our approach to the NIFIRAOS risk mitigation plan. An astronomical AO system which operates substantially cooler than ambient is a new concept. However, during initial testing, and later during servicing at TMT, NFIRAOS must also function at ambient temperature. To ensure success, careful opto-mechanical design and prototyping has already begun during the DDP phase. Similarly, algorithm development and atmospheric turbulence and sodium measurement campaigns are underway. Finally, the integration and testing work at both NRC/HIA and at the observatory will be thorough and comprehensive.

Component development tasks (DMs, TTP, Polar Coordinate CCD, IR detectors, RTC) are described later in the components section.

**Table 8-18: NFIRAOS Risks and Mitigations.**

| Risk | Mitigation |
|---|---|
| Operation at ambient and -35 C | - Good athermalization design practices<br>- DM prototype testing<br>- Purging and cooling system design<br>- Evacuated double-pane entrance window<br>- Subsystem tests in cold chamber |
| Challenging LGS & turbulence simulator (TG) optics (zoom, lenslets, TG space envelope) | - Early emphasis on optical design effort<br>- Trade studies in conjunction with vendors |
| Static and dynamic telescope aberrations may be higher than expected | - High bandwidth TTP specified and prototyped<br>- Conservative DM actuator stroke specified and prototyped<br>- Conservative WFS subaperture field of view (many pixels) |
| WFS aliasing of sodium layer and high spatial frequency aberrations | - Truth WFS, with very high order sampling of pupil and detector |
| Sodium layer variability may be larger and faster than expected | - Develop background RTC algorithms to update WFS gains and biases<br>- Implement a second truth WFS with moderate order and high bandwidth<br>- High frame rate sodium layer characterization with 6.5 m telescope |
| Challenging schedule | - Early design coordination with LGSF, AOSQ, telescope, instrument and system engineering teams<br>- NFIRAOS Preliminary design review during DDP phase<br>- NFIRAOS will be integrated and tested with IRIS at NRC/HIA |

**Work Plan**

NRC/HIA is the prime contractor for NFIRAOS, and will develop the design. Performance modeling work is done by the TMT project office, in collaboration with NRC/HIA for specific items. The Preliminary Design of NFIRAOS is included in the Design and Development Phase (DDP) of TMT; the Final Design and later phases will be funded from the construction budget.

NRC/HIA will design and procure the NFIRAOS components except for the DMs, RTC, and Polar Coordinate CCDs, which are managed directly by TMT. HIA will integrate the components at its facilities, and test NFIRAOS as a system together with the IRIS instrument. Working together with the TMT staff, NRC/HIA will Assemble, Integrate and Verify (AIV) NFIRAOS at the observatory.

#### 8.5.2.2 Laser Guide Star Facility System (LGSF)

**LGSF Requirements**

As described above, the early light AO facility for the TMT includes a Laser Guide Star Facility (LGSF) to generate artificial guide stars in the mesospheric sodium layer with the brightness, beam quality and asterism geometries required by both the NFIRAOS early light AO system and later AO instruments. **Table 8-19** lists the main LGSF requirements, including the top-level technology requirements and design choices that have already been introduced.

**Table 8-19: LGSF Requirements.**

| Parameter | Requirement |
|---|---|
| Asterism | - NFIRAOS asterism: 1 LGS on-axis and 5 LGS equally spaced at a 35 arcsec radius<br>- Support additional asterisms for other AO modes with up to 9 LGS and radii varying from 5 arcsec to 510 arcsec<br>- Rapid switching from one asterism to another (in 2 minutes) |
| LGS Power | - 25 W per beacon (17 W minimum) generated using 589.3nm solid state, continuous wave, sum-frequency lasers<br>- 150 W total laser power required for NFIRAOS |
| LGS Image Quality | Far field $1/e^2$ diameter 0.6 arcsec |
| LGS Tip Tilt Jitter | 50 mas 1-axis, 1-sigma |
| LGS Polarization | 98% circularly polarized |
| Beam Transfer Optics | Use conventional optics (not fibers) |
| Laser enclosure location | Mounted on the elevation journals of the telescope |
| Laser Launch Telescope | - Located behind the secondary mirror<br>- Diameter: 0.5m |
| LGSF Optical Throughput | 0.75 from the laser system to the Laser Launch Telescope |
| LGSF Operation | - Downtime < 0.5% (0.26% allocated for the lasers)<br>- Multiple lasers for contingency<br>- Necessary control and diagnostics systems |
| LGSF Safety | Class 4 laser safety requirements with respect to damage to personnel, observatory, illumination of aircraft or satellites, and interference with neighboring telescopes |
| LGSF General | - Mass, volume, power consumption, heat dissipation similar or superior to existing 50W class laser designs<br>- Maintainability and reliability<br>- Hardware and software interfaces with the rest of the observatory |
| Potential LGSF Upgrades | - Pulsed lasers for range gating of Rayleigh backscatter and/or dynamic refocusing<br>- Increased laser power by up to a factor 4 to 5 (materials and coating specifications)<br>- Up Link AO correction |

**LGSF Design**

An LGSF conceptual design has been developed that satisfies all of the above requirements [4],[5]. This design utilizes heritage from other LGS systems that are already in operation or under construction, including the Gemini North and Gemini South LGSF systems. The design relies upon currently available laser and beam transport technologies. The main subsystems of the LGSF are (i) the laser and its enclosure (LSE), (ii) the beam transfer optics, laser launch telescope, and associated control systems and (iii) the LGSF safety system. **Figure 8-57** is a functional block diagram of the LGSF system.

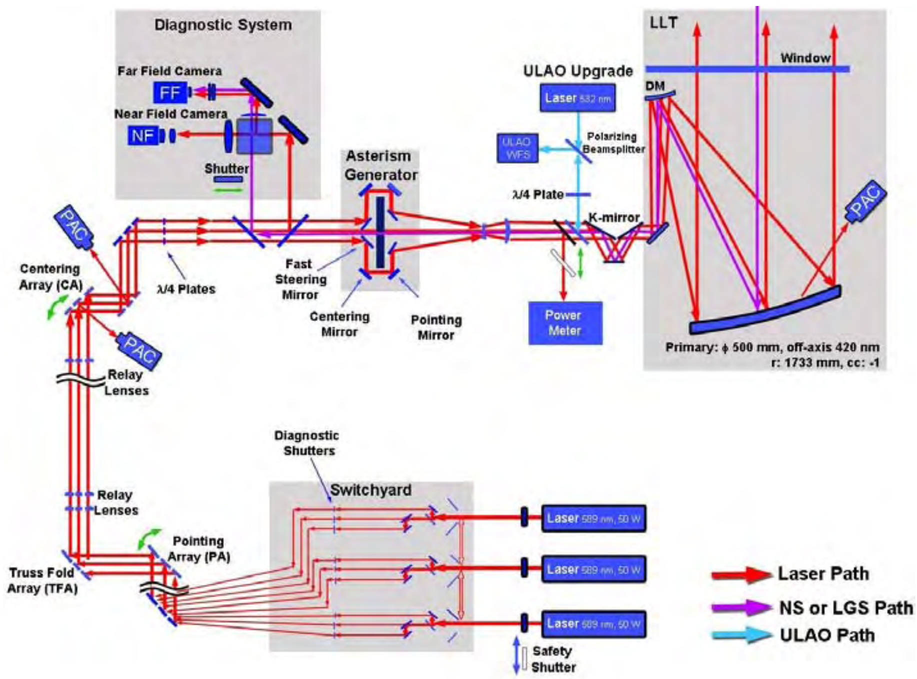



**Fig 8-57: Functional block diagram of the LGSF. For clarity only three of the nine beams are shown after the output of the laser switchyard.**

**Lasers and enclosure**

The baseline LGSF uses three 50 W, CW sodium lasers to achieve the total power requirement of 150 W and address the reliability requirements described above. The laser switchyard accepts the input beams from 1-3 operating laser systems and generates the requested number of beams at the desired power level using beam splitters and mirrors. The lasers and the laser switchyard are located in a single, clean, temperature-controlled room attached to the elevation journals of the telescope.

**Beam transfer and launch optics**

At the output of the switchyard, the beams are formatted in a compact 3x3 configuration for transport up the telescope structure to the Beam Transfer Optics Optical Bench, which is located behind the TMT secondary mirror. Each beamline consists of a total of five mirrors and three lenses (note that one to two additional mirrors may be required now that the location of the laser room has moved to the telescope elevation journals). Two mirrors in each beamline are controlled in tip/tilt at a low bandwidth to maintain the centering and pointing of the beams at all telescope elevations. Finally, each beamline includes a quarter-wave plate to produce circularly polarized output beam that will maximize the photon return from the sodium layer.

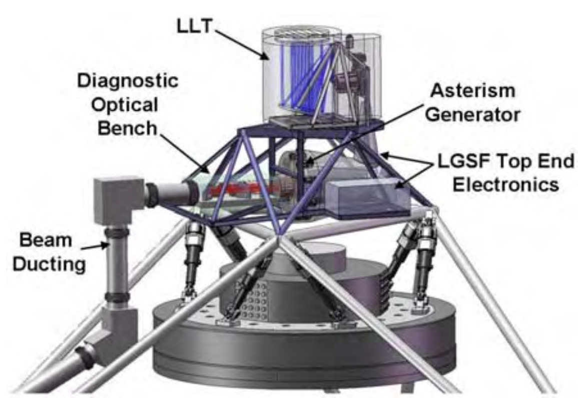



**Fig 8-58: Beam Transfer Optics Optical Bench.**

The Beam Transfer Optics Optical Bench is itself composed of several assemblies: (i) the diagnostics bench, (ii) the asterism generator, and (iii) the Laser Launch Telescope (LLT) and its associated bench. The conceptual design of this subsystem is illustrated in **Figure 8-58**. The diagnostics system samples 0.5% of each laser beam through a beam-splitter into two cameras for near- and far-field measurements. These cameras are used to measure the intensity profile and quality of each beam, and provide the alignment error signals used to drive the pointing and centering mirror arrays in closed loop.

The asterism generator transforms the square pattern of up to 9 beams into the requested asterism. It is composed of a series of four fixed and moving mirrors for each beam. For each beam, two of the mirrors are controllable in tip and tilt at low bandwidth to maintain the centering of the beams on the LLT pupil as well as the pointing of the beacons on the sky. This feature compensates for flexure within the optical bench and pointing errors of the LLT due to telescope flexure with zenith angle. The asterism generator also includes one fast steering mirror per beam, which is used to compensate LGS pointing jitter as measured by the associated LGS wavefront sensor in an AO system.

The LLT then expands the beams generated by the asterism generator from their 5 mm to 300 mm diameter and projects the asterism onto the sky. The LLT consists of an off-axis R-C telescope preceded by two lenses acting as a collimator. It is protected from the outside environment by a window. A K mirror located before the LLT serves as an image rotator to maintain the fixed orientation of the LGS asterism in the focal plane of each LGS AO system. Both the LLT and the diagnostic systems are designed to observe a natural guide star during commissioning and major maintenance periods in order to align the pointing of the LGS asterisms with respect to the optical axis of TMT.

Finally, the beam transfer optics optical bench includes a beam dump mirror, which may be used to divert the beams into a power meter. This feature can be used to shutter the beams at the top end of the beam transport, for example when the telescope is slewing to another target.

The current design of the Beam Transfer Optics and LLT System includes a total of ~180 actuators and sensors. Because the motors and sensors are spread across the telescope structure up to the secondary, the control architecture is highly distributed and will use commercially available Ethernet based motion controllers. This will reduce the complexity of the software by having smaller and local subsystems in charge of a small set of actuators and sensors.

**Safety System**
The TMT Laser Safety System will be modeled on the Gemini Laser Safety System, and is composed of three main subsystems:

- An Aircraft Detection system, which itself consists of two subsystems:
  - The All Sky CAMera system (ASCAM), consisting of four cameras working in the visible with a 180 degree field of view, which is dedicated to the detection of aircraft moving toward the laser beams. This system acts as a warning system before aircraft interference occurs.
  - The BOresighted CAMera system (BOCAM), consisting of an infrared camera mounted on the telescope with a narrow field of view co-aligned with the LLT. The purpose of this camera is to detect aircraft approaching very close to the laser beams using their thermal infrared emission. It serves as a backup to the ASCAM.
- A Laser Traffic Control System dedicated to the prevention of beam collisions with neighboring telescopes or with an aircraft detected by the all sky cameras.
- A Laser Interlock System dedicated to shuttering the laser beams and automatically opening AO control loops in response to events received from the Aircraft Detection system, the Laser Traffic Control System, and other AO subsystems. The LGSF is equipped with both high-speed and high-power shutters, which provide a means to rapidly block the laser beams in emergencies to protect personnel, equipment, and aircraft detected by the boresighted camera.

Predictive avoidance of earth-orbiting satellite will utilize the same approach implemented by existing US LGS AO systems.

In addition to meeting the early light requirements, the LGSF has been designed to include several upgrade paths, as described further in **Section 8.7**.

**Key development tasks and critical components**
The critical components of the LGSF are the lasers, the LLT, and the beam transfer optics, all of which contribute to the brightness and beam quality of the LGS finally projected onto the sky. The lasers will be discussed in **Section 8.5.3.5** below. Even though the LLT alignment and fabrication tolerances are tight, we are confident that the required specifications can be achieved based on the experience at Gemini Observatory, which has recently implemented a similar off-axis LLT with a 0.45 m primary mirror.

Finally, we have demonstrated that the complexity of the beam transfer optics is manageable with the proposed distributed control architecture. The specifications on beam quality and optical throughput can be achieved using high-quality laser optics and an enclosed optical path. Of course, the use of hollow-core fibers to transport the laser beams could dramatically simplify the beam transfer optics system and even permit the laser room to be located off the elevation journals of the telescope. This approach has been adopted for several 10 W class CW lasers on 8 meter telescopes. However, the TMT requirements are significantly more stressing in terms of peak power and optical path length than these existing and planned systems. For these reasons, fiber transport is not considered as the baseline for the early light LGSF system, but developments in this area will be closely followed and the current design approach will be reviewed at the beginning of the next design phase.

The main development risks of the LGSF and the corresponding risk mitigation strategies have been identified and are summarized here:

- The risk that the LGS power is not met is mitigated by the fact that (i) the laser power requirement includes some margin except during seasons of low sodium column density, (ii) the laser power requirement can be achieved by existing laser designs and (iii) an additional laser could be added in an enlarged Laser Room.
- The risk that the Beam Transfer Optics and Laser Launch Telescope optical transmittance requirements are not met is mitigated by the fact that (i) again the laser power requirement includes some margin and (ii) the BTO and LLT will be integrated in the LGSF Vendor facility with one of the three 50W lasers, allowing thorough integrated high power tests of the Beam Transfer Optics and Laser Launch telescope.
- Schedule risk (in particular the laser schedule) is mitigated by (i) a close coordination with both the LGSF Vendor and the Laser Vendor, and (ii) the fact that both the laser and the Beam Transfer Optics design utilize existing technologies. In addition, the current LGSF schedule contains roughly 6 to 12 months of contingency before final integration with the telescope at the TMT site.

**LGSF Work Plan**

The TMT AO group plans to sub-contract the LGSF work, with the contract starting at the beginning of the construction phase. Laser development will be sub-contracted separately from the LGSF and managed directly by the TMT AO group. The LGSF Vendor will be responsible for the design, construction and test of the LGSF, which includes the laser room and associated support structure, a laser sequencer (the software layer used to sequence the 3 lasers), the beam transfer optics, the LLT and the safety systems. The Vendor will also be responsible for the LGSF integration at the TMT site, with the support of the TMT AO group. The LGSF schedule includes the integration of one laser with the rest of the LGSF at the LGSF Vendor facility, and contains roughly 6 to 12 months of contingency before final integration at the TMT site.

#### 8.5.2.3 Adaptive Optics Sequencer

A highly automated AO Sequencer is required due to the complexity of the interactions between the AO systems and the TMT requirement for high observing efficiency. This software system will be critical to achieving successful AO-assisted observations. Indeed, each TMT science-observing program will result in complex sequences involving the telescope, the AO facilities and an instrument. The Observatory Control System (OCS) will manage all aspects of the science-observing program and act as the main sequencer (see **Section 8.4**). The OCS will delegate sequencing tasks to three software systems:

- The Telescope Control System (see **Section 8.3.5**) will sequence the actions of the telescope subsystems (The mount, M1, M2, M3 and the enclosure)
- The AO sequencer will sequence the actions of the AO subsystems (LGSF, NFIRAOS, tip/tilt sensors within the NFIRAOS instruments, etc.) and act as the main public interface between the AO system and the remainder of the observatory.
- The instrument sequencer will configure and control the instrument

In more detail, the top-level requirements of the AO sequencer include:

- Sequencing and coordinating the actions of the AO systems and instruments (LGSF, NFIRAOS, Tip Tilt Focus Wavefront Sensors with instruments, etc.). These sequences are split in 3 categories:
  - AO configuration sequences, including for example (i) “the LGSF configuration sequence” to project the required asterism for the selected AO system, and (ii) “the NFIRAOS configuration sequence” to select the AO mode and instrument port, position the wavefront sensors mechanisms, and configure the NFIRAOS Real Time Controller (RTC).
  - AO calibration sequences, which include day and night time calibration of the LGSF, NFIRAOS, and instrument Tip Tilt Focus Wavefront Sensors.
  - AO operation sequences, which include the management of the AO closed loop in either NGS or LGS mode.
- Offloading DM corrections for low-order, persistent wavefront aberrations to the telescope subsystems including M1 and M2.

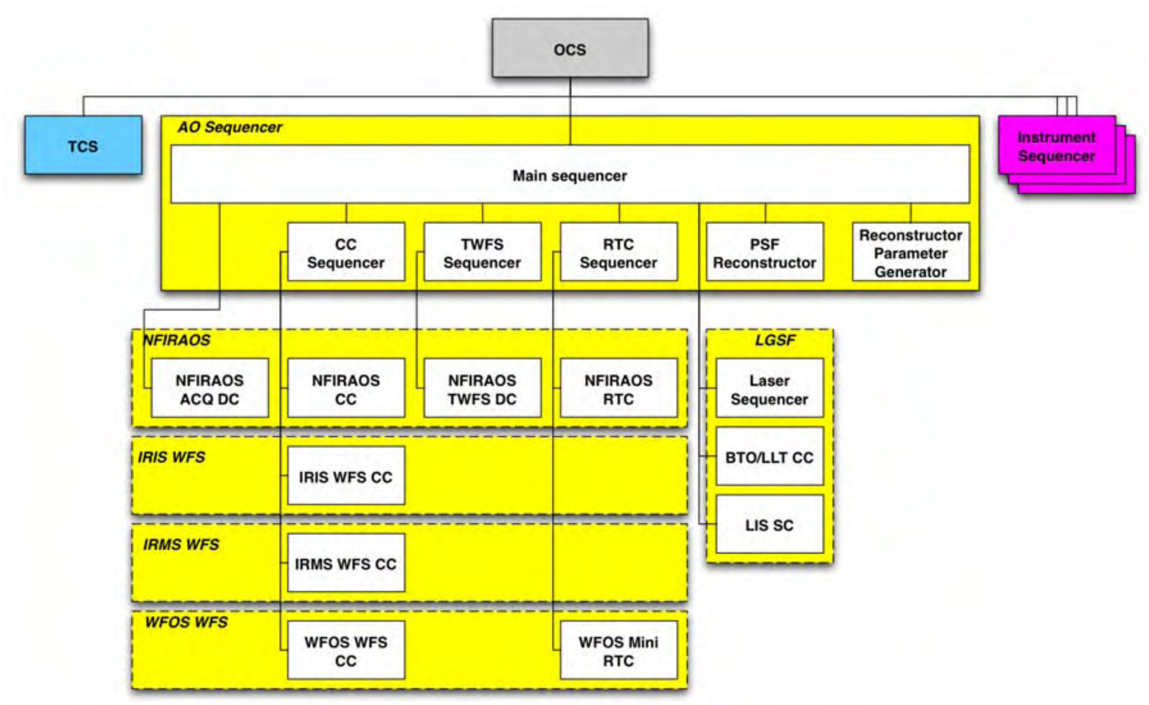



**Fig 8-59: Adaptive Optics Sequencer Functional Block Diagram (early light version).**

- Providing AO reconstruction parameters to the RTC for each AO system. These include the initial parameters for the wavefront sensor gradient estimation algorithm, and the matrices for the wavefront reconstruction algorithm updated at a slow rate.
- Post-processing science PSFs using wavefront structure functions computed in real time by the RTC of each AO system
- Finally, extensibility and maintainability are also major requirements.

The Adaptive Optics Sequencer will be a modular and extensible system as illustrated in **Fig. 8-59**. Only the early light AO systems and their associated science instruments have been represented in this figure. The AOSQ will interface primarily with the OCS to receive commands for implementing sequences and configurations, and to report the status of these commands. It will interface with the Telescope Control System to transfer the telescope modes computed by the RTC (offload router module). It will also interface with the Data Management System to transfer the Point Spread Function (PSF) estimates for each AO observation (PSF module), and to download AO engineering telemetry.

The most critical components of the AO Sequencer are the Reconstructor Parameter Generator and the PSF Reconstructor modules, both of which will implement challenging algorithms that are not yet fully defined. Possible approaches have been defined [6], however, and will be studied in detail before the start of the construction phase.

The TMT AO group plans to sub-contract the development of the AO Sequencer. Work is scheduled to start at the beginning of the construction phase. The Reconstructor Parameter Generator module and the PSF Reconstructor module will be designed and developed jointly with the TMT AO group. Two AOSQ systems will be integrated, and will be sent to the LGSF Vendor and HIA for tests with the LGSF and with NFIRAOS and IRIS, respectively.

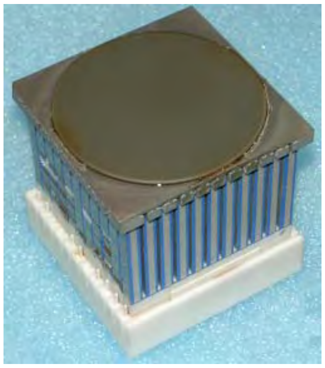


**Fig 8-60: CILAS Subscale 9x9 DM.**

### 8.5.3 Early Light AO Components

#### 8.5.3.1 Deformable mirrors

Piezostack DMs will be used in NFIRAOS on account of their superior level of technical maturity in comparison with other concepts for very high order wavefront correction, including MEMS, spatial light modulators, bimorph mirrors, and electrostatic membranes. Although Piezostack DMs have already been used very successfully in numerous AO systems, the requirements for NFIRAOS will be exceptional in terms of the order of correction, actuator stroke, operating temperature, and implementation of one DM on a large tip/tilt platform (TTP).

**Table 8-20** quantifies these requirements and compares them against the DMs utilized in existing and near-term AO systems. Good progress is already underway towards meeting the most stressing requirements as a result of design and prototyping work supported by TMT at Compagnie Industrielle des Lasers (CILAS) and their subcontractor, the Observatoire de Paris-Meudon.

**Table 8-20: NFIRAOS DM requirements vs. Current AO Systems.**

| Parameter (innovative requirements in **bold**) | NFIRAOS Requirement | Existing and Near-Term AO Systems |
|---|---|---|
| **DM Order** | 63x63 (DM0) and 75x75 (DM12) | 41x41 Spectro-Polarimetric High-contrast Exoplanets Research (SPHERE) |
| Inter-actuator spacing, mm | 5 | 5-7 |
| **Maximum stroke, μm** | 8-10 | 4-7 |
| Inter-actuator stroke, μm | 2-3 | 2-3 |
| Surface flatness, RMS nm | 20 (goal 10) | 10-20 |
| Hysteresis, per cent | 5 | 5 |
| **Operating temperature, C** | -35 | 0 to -10 |
| **Integration with tip/tilt platform** | Yes, 20 Hz tip/tilt bandwidth | Yes, for small bimorph mirrors at higher bandwidths |

**Figure 8-60** illustrates the 9x9 subscale prototype DM fabricated and tested by CILAS during their feasibility demonstration in 2005-06. This mirror demonstrated an actuator stroke of 11 μm, surface flatness of 13 nm RMS, and hysteresis of 5-6%, all at an operating temperature of -35 degrees Celsius as will be required for TMT.

**Figure 8-61** illustrates the conceptual designs developed by CILAS and Observatoire de Paris-Meudon for the full-scale DM and its tip/tilt platform. The conceptual design for the DM is based closely upon the designs of mirrors with 41x41 and 25x25 actuators for the ESO SPHERE instrument (now in fabrication) and the Gemini-South MCAO system (successfully fabricated and tested). This includes the fabrication of actuators in linear strips (or "combs"), which are then assembled into a 2-dimensional array. Finally, the tip/tilt platform is a flex-pivot gimbal design that is also traceable to existing systems, although the design for NFIRAOS involves control of a larger, heavier mass at a lower control bandwidth.

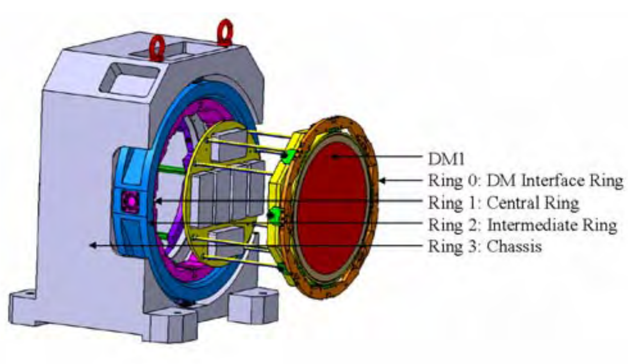



**Fig 8-61: NFIRAOS DM and Tip/Tilt Platform.**

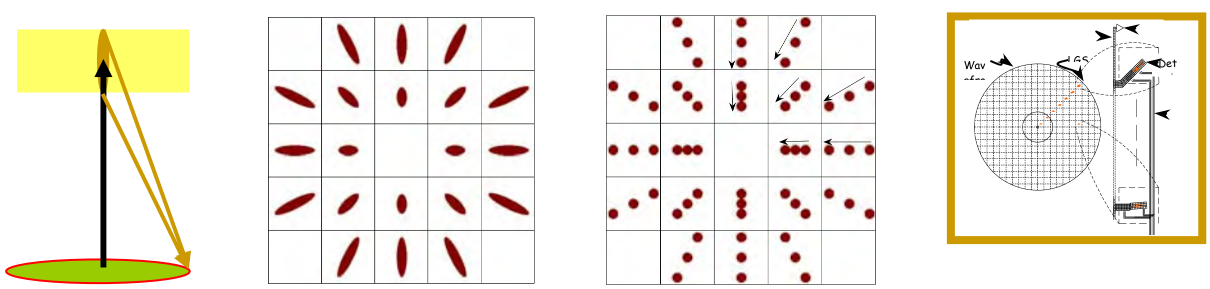
The next stage of the DM development plan is to design, fabricate, and test a full-scale prototype of the tip/tilt platform and confirm that the 20 Hz bandwidth can be achieved for the NFIRAOS DM design parameters. Two other important issues are (i) achieving the required facesheet surface flatness at -35 degrees Celsius without using up a significant fraction of the mirror's stroke, and (ii) fabricating a DM of this size with very few (ideally no) detached or frozen actuators. The former issue will be addressed by further finite element analysis during the detailed design phase. CILAS will gain valuable experience on the latter issue with the 41x41 actuator DM for SPHERE.[23]

The TMT AO group will continue to manage the development of the deformable mirrors for NFIRAOS. The contract for the TTP prototype demonstration is already underway and will be completed by the end of the TMT Design and Development Phase. The TTP prototype will then be shipped to NRC/HIA, where it will be subject to additional testing and characterization to support the development of NFIRAOS. Fixed price contracts for the pair of NFIRAOS DMs (denoted as DM0 and DM12) will be placed with CILAS at the beginning of the construction phase. The TTP prototype will be returned to CILAS for refurbishment, upgrading, and integration with DM0. The DMs will then be delivered to HIA for integration into the NFIRAOS optical system.

Finally, it should be noted that there are no cost or performance issues associated with the high voltage drive electronics for these DMs. The drive electronics will be procured by the NFIRAOS developer under a separate contract.

#### 8.5.3.2 LGS WFS detectors

The (roughly) 10 km thickness of the mesospheric sodium layer represents a significant challenge for LGS wavefront sensing for any extremely large telescope such as TMT. As illustrated in **Figure 8-62** (a), this thickness is perceptible in each wavefront sensing subaperture, resulting in radial elongation of the Shack-Hartmann "spots" as indicated in **Figure 8-62** (b). For TMT, this elongation reaches a value of approximately 4 arc sec at the edge of the telescope aperture, which is large enough to significantly increase the LGS WFS measurement error due to noise. Short (~3 μsec) laser pulses have been proposed as a possible means of eliminating this effect; such a pulse would instantaneously illuminate only a ~1 km depth of the sodium layer, resulting in much smaller, nearly symmetrical "spots" which would sweep radially across the Shack-Hartmann detector array (**Figure 8-62** (c)).



(a) Guidestar elongation

(b) Shack-Hartmann spots, CW laser

(c) Shack-Hartmann spots, pulsed laser

(d) Polar coordinate CCD array concept

**Fig 8-62: Sodium guidestar elongation and its impact on LGS wavefront sensing.**

With or without a pulsed laser, a "polar coordinate" CCD array containing separate patches of pixels for each WFS subaperture (**Figure 8-62** (d)) provides significant advantages in comparison with more conventional detectors. For elongated guidestar images, the polar coordinate geometry greatly reduces the total number of pixels which must be read out, thereby reducing pixel read rates and detector read noise. With short laser pulses, synchronized charge shifting can be used to compensate for the radial motion of the Shack-Hartmann spots as the laser pulse transits the sodium layer, eliminating all or most of the guidestar elongation and reducing the wavefront sensing measurement error due to noise.

**Table 8-21** summarizes the top-level requirements for the polar coordinate CCD. The fundamental parameters for the number of subapertures and frame rate are derived directly from the design of NFIRAOS. The

[23] CILAS has already demonstrated that detached actuators can be successfully repaired with the 25x25 DM for the Gemini-South MCAO system.

specifications for quantum efficiency and detector read noise have been derived to meet the RMS wavefront error due to noise which is budgeted for NFIRAOS (36 nm), given the expected values for end-to-end optical throughput, laser power and beam quality, and the depth and density of the sodium layer. The remaining physical parameters for the array are matched to the optical design of the NFIRAOS LGS wavefront sensor; the exact number of pixels per subaperture remains to be determined pending further analysis of the required wavefront sensor dynamic range.

A prototype polar coordinate CCD array is already under development as part of an AODP project at MIT Lincoln Laboratory. The objective of this project is to fabricate and test one quadrant of an array (with $30^2$ subapertures) meeting the requirements given in **Table 8-21** below. The array will also demonstrate charge shifting to enable its use with a pulsed guidestar laser at a future date. The critical development tasks are to develop a layout for the CCD array which includes shift registers configured to support charge shifting, and to obtain 3 read noise electrons at an effective frame rate of 2 KHz with a practical number of output amplifiers.[24] The first round of AODP test results are expected to be obtained by early 2008.

TMT will continue to closely monitor this AODP project. During the construction phase, the Project Office will support an iteration of the design for the actual production arrays to be used in NFIRAOS and future TMT LGS AO systems. These arrays will then be fabricated in a dedicated foundry run (to reduce the risk of schedule delays), tested, and provided to the NFIRAOS development team for integration into their system.

**Table 8-21: Polar coordinate CCD array requirements.**

| Performance parameters | | Design constraints | |
|---|---|---|---|
| Number of subapertures | $60^2$ | Array size, mm | 30 |
| Readout time, μsec | 500 | Pixel size, μm | 12.5-25.0 |
| Quantum efficiency | >0.9 | Pixels per subaperture (edge of pupil) | 12x4 to 16x6 |
| Read noise electrons | <5 (goal 3) | | |

### 8.5.3.3 NIR NGS WFS detectors

The sky coverage specifications for the NFIRAOS LGS AO system can only be met if low-noise, high-speed, IR detector arrays are used for natural guide star (NGS) tip/tilt wavefront sensing. Tip/tilt sensing in the Near IR (NIR) improves sky coverage due to the propensity of “red” (L and M class) guidestars, and also because NFIRAOS will “sharpen” guidestar images at these wavelengths. These NGS tip/tilt sensors will actually be located in the science instruments fed by NFIRAOS; this approach reduces the magnitude of unsensed optical alignment errors and also permits each instrument to utilize the spectral or spatial NGS “pickoff” method best matched to their requirements. Each instrument will employ 3 NGS sensors, since anisoplanatism would be a significant tip/tilt error source if only a single, off-axis NGS was utilized. At least one of these sensors will also measure the focus errors (using a 2x2 Shack-Hartmann array) that are induced in the NFIRAOS LGS AO system by unknown variations in the range to the sodium layer.

Top-level specifications for these IR detectors have been developed via detailed sky coverage simulations. **Table 8-22** summarizes these requirements, and compares them against the objectives of a current IR detector development program supported by a consortium of Gemini Observatory, ESO, and New Mexico Technical University (NMT). Many of these values represent a significant advance over the current state-of-the-art. Relatively large arrays are required, since the pixel angular subtense must be matched to the guide star blur diameter (8.6 milli arc sec at $\lambda$=1.25 μm), while the total field-of-view of the array should be at least 1 or 2 arc sec for efficient and reliable guide star acquisition. Relatively high frame rates are required to minimize the tip/tilt error on (relatively) bright guide stars, while detector read noise must be very low to accommodate dim stars. Wavefront sensing in the J+H bands is required for acceptable sky coverage, and including the K band would also enable the observation of certain science targets in obscured fields. The remaining requirements on these arrays (fill factor, crosstalk, linearity, dead pixels, read noise with TE cooling…) are consistent with existing science-grade devices and have been omitted from **Table 8-22**.

Achieving a read noise level of 5-10 electrons is the most challenging of the above requirements. Several vendors have proposed approaches to achieving this requirement with the specified array size and frame rate, using (for example) APD arrays of HgCdTe detectors with CMOS read-out electronics. The Gemini/ESO/NMT

[24] This AODP project has already demonstrated a JFET output amplifier yielding 1 read noise electron at lower pixel rates, but the number of output amplifiers that would be needed to duplicate this result for the NFIRAOS LGS WFS would be prohibitive.

consortium has released RFPs to develop devices with performance specifications given in the last column of **Table 8-22** and hopes to fund a development contract later this year. We intend to monitor this development activity very closely, and the TMT construction budget contains a contingency in case further R & D is needed to meet our requirements. The final production arrays for the NFIRAOS science instruments will then be procured by the TMT project office, and then delivered to the IRIS and IRMS development teams for integration into these instruments.

**Table 8-22: IR detector array requirements for NGS tip/tilt wavefront sensing.**

| Parameter | Requirement | Goal | Gemini/ESO/NMT Objective |
|---|---|---|---|
| Array size, pixels | $128^2$ | $256^2$ | $256^2$ |
| Pixel size, μm | 18-40 | 18[25] | 18-40 |
| Frame rate, Hz | 500 | 800 | 625 |
| Spectral bandwidth, μm | 1.0-1.7 | 1.0-2.5 | 1.0-2.5 |
| Quantum efficiency | 0.7 | 0.8 | 0.7 |
| Read noise electrons | 10 | 5 | 5 |

#### 8.5.3.4 Real Time Controller

One of the most critical and challenging early light AO components is the NFIRAOS RTC. The NFIRAOS RTC will provide all of the control functions for NFIRAOS that are required for calibration, test, and real-time atmospheric turbulence compensation. It will operate under the control of the AO Sequencer to execute instructions provided either by users or by the AO Sequencer itself. It will accept and process input from a suite of wavefront sensors, including six 60x60 order LGS Shack Hartmann wavefront sensors, three tip tilt focus Shack Hartmann wavefront sensors per NFIRAOS instrument, and one 60x60 order NGS Shack Hartmann wavefront sensor. It will compute and apply the commands to two high order DMs (with total of ~7500 actuators) and one Tip Tilt Platform on the basis of these WFS measurements. It will interface with additional telescope and AO subsystems as necessary for real-time atmospheric turbulence compensation, including the Telescope Control System, the LGS facility and the AO- and instrument Component Controllers. It will update and optimize the control algorithms used for the above purposes in real time as observing parameters and atmospheric conditions change. Finally, it will compute LGS WFS wavefront structure functions in real time for each observation. These structure functions will be used by the AO Sequencer to estimate the AO PSF for each observation as a post-processing task. A complete block diagram of the NFIRAOS RTC is given in **Fig. 8-63**.

The RTC requirements are at least two orders of magnitude greater than the advanced 8-meter class systems such as the Gemini South MCAO RTC currently under development, and will require advanced wavefront reconstruction algorithms and new hardware approaches. The most stressing computational task is the tomographic estimation of the three-dimensional turbulence profile from a combination of multiple NGS and LGS wavefront sensor measurements. The Optical Science Company (tOSC) has studied the hardware implementation of possible algorithms for this task in collaboration with the TMT AO group. At present, the Fourier Domain Preconditioned Conjugate Gradient (FD PCG) algorithm appears to have the greatest potential for a high-speed, parallel implementation, and also meets the TMT AO wavefront error budget requirement. It is also less demanding in its requirement for fast internal memory.

tOSC has devised a hardware architecture for this algorithm that is based upon existing processor technology, such as the TigerSHARC Digital Signal Processor (DSP) and the Xilinx Virtex-4 Field Programmable Gate Arrays (FPGA). **Fig. 8-64** illustrates the proposed architecture. A group of 13 embedded processing boards provides the real time functionality of the RTC. Twelve boards are comprised of either 8 DSPs and one FPGA (used to compute gradients from the NGS and LGS WFS intensities), or eight FPGAs and one DSP (used for tomographic reconstruction and the final DM command computation). The final board provides a dual core Pentium processor that is dedicated to computing the LGS WFS wavefront structure functions.

These 13 boards reside in a single chassis that is controlled by a Pentium-D-based processor system. Archival storage of the AO telemetry data is provided by a disk array. tOSC has estimated that this architecture can provide the complete reconstruction in ~900 μs.

[25] 18 μm corresponds to the desired angular subtense of 8.6 milli arc sec at the NFIRAOS output focal ratio of f/15, with no requirement for additional relay optics.

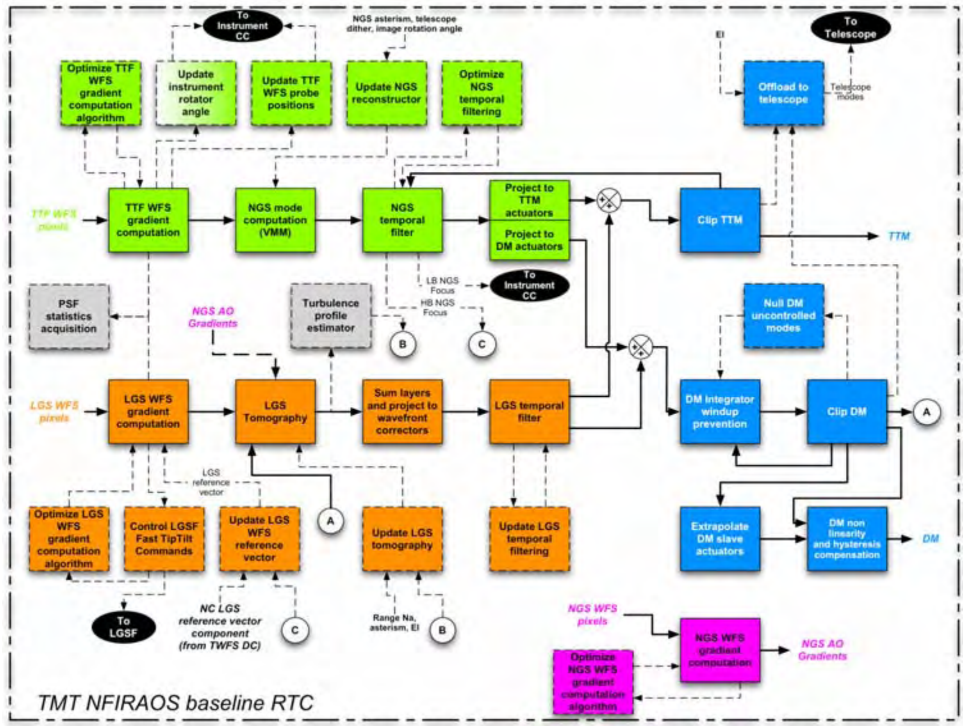


Fig 8-63: NFIRAOS RTC functional block diagram.

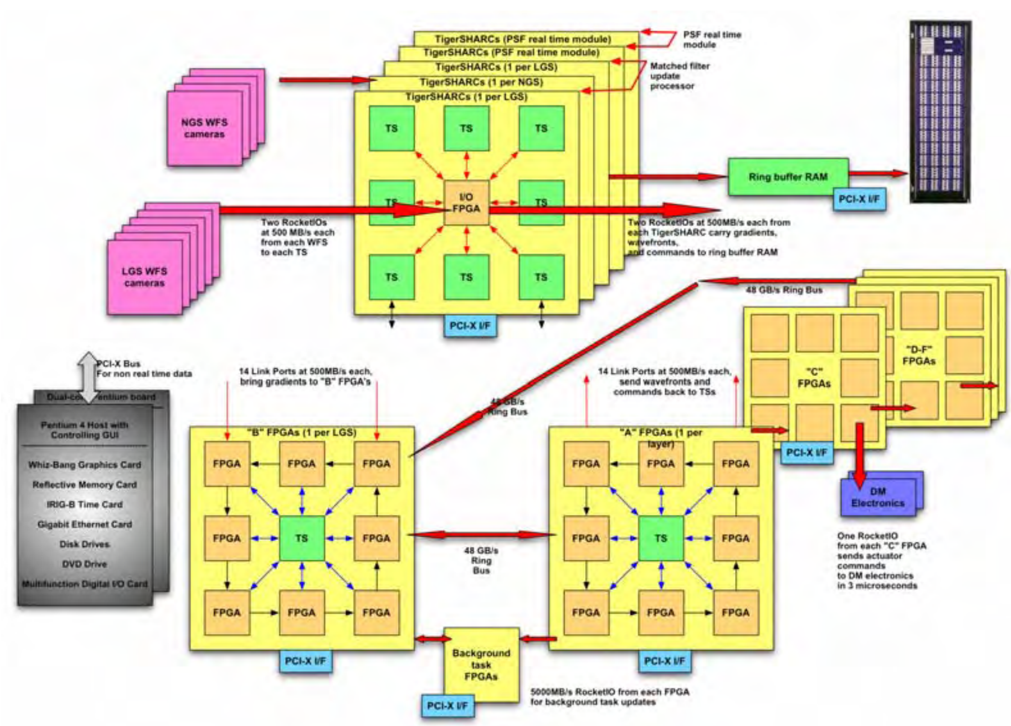


Fig 8-64: NFIRAOS RTC proposed architecture.

The Real Time Controller remains a critical and challenging system is spite of the encouraging results from the tOSC feasibility study. The immediate key task is to determine the correct reconstruction algorithm in terms of both AO performance and implementation requirements (computations, latency, and memory). This activity has already started, and will be completed before the end of the TMT DDP phase. Full-fidelity versions of FD-PCG and other promising wavefront reconstruction algorithms are now being exercised in full-scale simulations of NFIRAOS as part of this effort.

The TMT AO group plans to sub-contract the development of the RTC, with work beginning at the start of the construction phase. A two-stage delivery is envisaged to allow smooth integration of NFIRAOS at NRC/HIA. The functionality of the first version of the RTC will be limited to (i) control and readout of the WFSs and (ii) control of the DMs. These features will be used to align these components with respect to the NFIRAOS optics and validate their interfaces with the RTC. The final version of the RTC will provide full wavefront reconstruction. The final integration and test of the RTC will be performed at HIA in close coordination with NFIRAOS closed loop testing.

#### 8.5.3.5 Guidestar lasers

TMT will utilize multiple, bright, artificial guidestars in the mesospheric sodium layer for both the early light NFIRAOS LGS MCAO system, and also additional LGS AO systems that may be implemented for the MIRES, WFOS, HROS, and IRMOS instruments at later dates. The top-level requirements for producing these guidestars are already met by the current generation of solid state, continuous wave (CW), sum-frequency-generation (SFG) guidestar lasers, even though guidestar elongation becomes a very significant issue for a 30-meter telescope and the required guidestar brightness increases by about a factor of 2.5 in comparison with 8-10m telescopes. Additional engineering will still be needed to improve the reliability and maintainability of these existing lasers, and also to meet a new requirement for operation with a changing gravity vector that varies with telescope elevation angle. We have reviewed these new requirements with laser suppliers, and have factored their cost and schedule estimates into our LGSF development plan for the construction phase.

**Table 8-23** summarizes the performance and design requirements for the early light guidestar lasers for TMT. Our approach to generating these requirements has been to begin with the performance characteristics of existing laser systems, and then confirm that the NFIRAOS LGS asterism can be generated by a modest number of such lasers which can be packaged into a practical design for the TMT LGSF. More specifically, the NFIRAOS wavefront error budget includes an allocation of 36 nm RMS for the LGS WFS measurement error due to noise, which is achieved with an LGS signal level of about 1500 photo-detection events per 0.25m$^2$ subaperture at a the WFS sampling rate of 800 Hz.[26] This signal level is achieved with 25 W of laser power per LGS, given reasonable specifications for end-to-end optical throughput and sodium column density. The NFIRAOS asterism of 6 LGS can therefore be generated using 3 50-W lasers, with a total mass and volume which is consistent with mounting the Laser Service Enclosure (LSE) to the telescope elevation journals as described in **Section 8.5.2.2** above.

**Table 8-23: Early light guidestar laser requirements.**

| Performance parameters | | Design limits | |
|---|---|---|---|
| Laser power, W | >50 | Laser volume (HxWxD), m | <2.4x3.7x1.2 |
| Polarization | Circular | Electronics volume, m | <2.4x1.3x1.0 |
| Pulse format | CW or mode-locked CW | Total mass, kg | <2400 |
| Line width, GHz | <1.5 (goal 0.050) | Electrical power | <60A @ 208V |
| Beam quality, xDL | <1.1 (goal 1.0) | Other | Variable gravity vector |

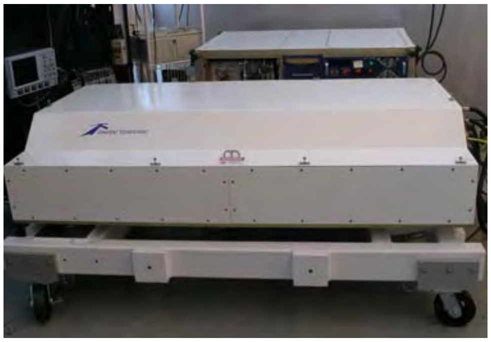
[26] This requirement has been derived based upon current estimates for the thickness of the sodium layer (~10 km) and relatively conservative design parameters for the polar coordinate CCD array (5 noise electrons per pixel per read and a pixel width of 0.5 arc seconds on the sky).

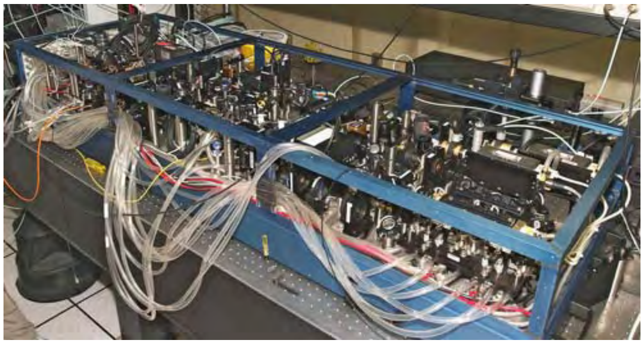
The requirements given in **Table 8-23** match (with one exception) the design specifications for the Gemini-South MCAO laser system, currently under development at Lockheed-Martin Coherent Technologies (LMCT) with an expected delivery date to Gemini in September 2007. In fact, the USAF Research Laboratory has already demonstrated the above levels of performance with a significantly smaller and lighter laser system (**Figure 8-65 (b)**), but we have not baselined this design because it is not yet available from a commercial company.

Both of the above laser systems can best be described as robust prototypes, and additional work is needed to develop fully engineered designs, which are highly reliable, require a minimum of alignment and maintenance, and support fully automated operation within the observatory software environment at TMT. Further improvements to the lasers' passive and active alignment control systems will also be required to enable operation with a variable gravity vector. These issues have been discussed with LMCT and have been factored into our cost and schedule estimates for the TMT construction phase.

Additionally, we will continue to monitor ongoing laser R & D projects funded by AODP, ESO, and other sponsors. These projects are working to demonstrate pulsed guidestar lasers and hollow-core optical fibers at power levels of interest to TMT. We will update our LGSF baseline design if sufficient technical progress is made in one or both of these areas.

The TMT Project Office will have the responsibility for developing and procuring the guidestar laser systems for the LGSF. Work will begin with competitive Conceptual Design Studies at the start of the construction phase. We will use the results of these studies to finalize our choices of laser and beam transport technologies and define a baseline laser system design. The second and final step will be a fixed price contract (presumably with industry) to deliver 3 50W lasers to TMT. The first of these lasers will be delivered to the LGSF developer for high-power testing with the BTO, LLT, and the LGSF software and safety systems. The remaining two lasers will be delivered to the TMT site for integration into the LGSF, followed by testing and commissioning with the NFIRAOS LGS MCAO system.





**a) LMCT laser for Gemini North** **b) USAF Research Laboratory**

**Fig 8-65: Current generation guidestar laser systems.**

### *References*


[1] Science-Based Requirements Document, TMT.PSC.DRD.05.001.

[2] Observatory Requirements Document, TMT.SEN.DRD.05.001.

[3] NFIRAOS Conceptual Design Report, TMT.AOS.CDD.06.010.

[4] Laser Guide Star Facility Conceptual Design Report, TMT.AOS.CDD.06.035.

[5] Laser Guide Star Facility Conceptual Design Report Appendices, TMT.AOS.CDD.06.034.

[6] PSF Reconstruction Implementation for the TMT NFIRAOS LGS MCAO System, TMT.AOS.PRE.06.106.

**Additional references:**

B. Ellerbroek and al., "A conceptual design for the Thirty Meter Telescope Adaptive Optics system", SPIE Proc. 6269, 2006, TMT.AOS.JOU.06.14.

G. Herriot and al. "NFIRAOS: TMT narrow-field near infrared facility adaptive optics", SPIE Proc. 6269, 2006, TMT.AOS.JOU.06.013.

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Pierre Gigan et al., Tip Tilt Stage Conceptual Design Report, (Observatoire de Paris-Meudon), TMT.AOS.CDD.06.037.

Stephen Browne et al., tOSC RTC Feasibility Study Report, (tOSC), TMT.AOS.CDD.06.041.

## *8.6 Early Light Science Instruments*

### 8.6.1 Introduction

As discussed in **Section 3** and the Science Requirement Document (SRD, [1]), the TMT SAC requested a comprehensive suite of eight instruments required to tackle the science that they envisage for the first decade of operation of TMT. A summary that provides an overview of the desired instrument capabilities is given in **Table 8-24**. The proposed instruments stretch the TMT discovery space in wavelength **(**$\lambda$**)**, spatial/spectral resolution (R) and field-of-view/slit length (FOV/SL). They also stretch a number of important TMT subsystem parameters such as the maximum instrument physical size and weight that the observatory will need to accommodate.

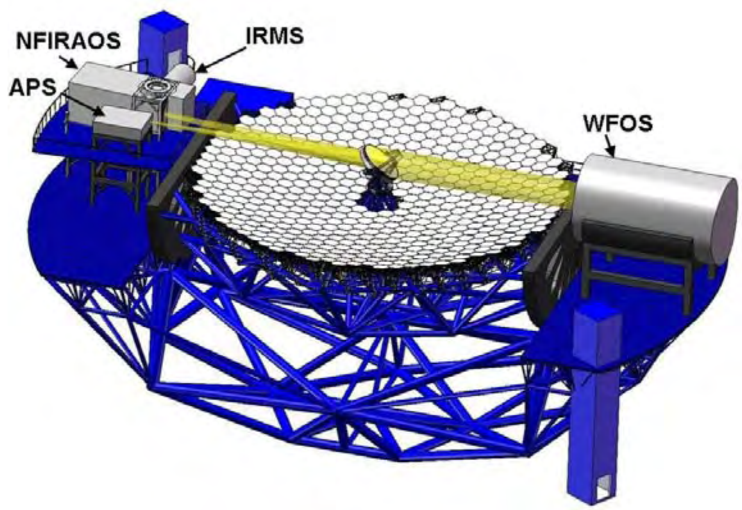


**Fig 8-66: The early light instruments on the TMT Nasmyth platforms. APS is at the on-axis position on the –x platform, and NFIRAOS is at +5° off-axis. IRIS is mounted on the upward-looking port of NFIRAOS, and WFOS is the large cylinder on the +x platform. The Nasmyth platforms are located 7 meters below the optical axis of the telescope [2] to minimize M1 airflow blockage by the instruments themselves. Electronics and other instrument support systems will be located on this level.**

Six of the instruments use built-in AO systems or use NFIRAOS to exploit the diffraction-limited capability of TMT, and the other two (WFOS and HROS) are seeing-limited but could utilize Ground-layer AO (GLAO) or Laser Tomography AO (LTAO) to improve their observing efficiency. The instruments also exploit the entire wavelength range of TMT, from 340 nm to 28 microns; they include a high contrast instrument; and instruments with a variety of field sizes, up to 20 arcmin in diameter. Thus the instrument suite is representative and suitable for defining general instrument requirements that should provide enough flexibility to accommodate future instruments.

Feasibility studies of all of the above instruments were carried out in 2005-2006. Nearly two hundred scientists and engineers at forty-six US, Canadian and French institutions were involved in these studies, which were reviewed by panels of international experts. Most importantly, perhaps, these studies demonstrate that the instruments are feasible for a 30m telescope, albeit challenging in some aspects. The science cases and operational concept documents of these studies highlight and document the tremendous scientific potential of TMT.

**Table 8-24: The SRD science instrument suite and its main characteristics.**

| INSTRUMENT | λ (μm) | FOV / SL | R | SCIENCE CASE |
|---|---|---|---|---|
| Near-IR diffraction-limited (DL) spectrometer and imager (IRIS) | 0.8 – 2.5 | 10″×10″ (imaging) 0″.7,1″.6 or 4″.5 (IFU) | 4000 | • Assembly of galaxies at high z<br>• Black holes/AGNs/Galactic Center<br>• Resolved stellar populations in crowded fields |
| Wide-Field Optical Spectrometer (WFOS) | 0.34 – 1.0 | 92.4 $arcmin^2$/ 1300″ | 150 – 7500 | • IGM structure and composition at 2 < z < 6<br>• Stellar populations, chemistry and energetics of z > 1.5 galaxies |
| Deployable multi-IFU, near-DL, near-IR Spectrometer (IRMOS) | 0.8 – 2.5 | 5′ patrol field 2″ per IFU | 2000 - 10000 | • Early Light<br>• Epoch of Peak Galaxy Building<br>• JWST follow-ups |
| Mid-IR Echelle Spectrometer and Imager (MIRES) | 4.5 - 25 | 3″ | 5000 – 100000 | • Origin of Stellar Masses<br>• Accretion and outflows around protostars<br>• Evolution of gas in protoplanetary disks |
| Planet Formation Imager (PFI) | 1.1-2.4 | 2″.2 × 2″.2 | 70 – 500 | • Direct detection and spectroscopic characterization of exoplanets |
| High-Resolution Optical Spectrometer (HROS) | 0.34 – 1.0 | 20″ | 30000 – 100000 | • Doppler searches for exoplanets<br>• Stellar abundance studies in Local Group<br>• ISM abundances/kinematics<br>• IGM characterization to z~6 |
| MCAO Imager (WIRC) | 0.8 - 5 | 30'' x 30'' | 5 - 100 | • Precision astrometry (e.g. Galactic Center)<br>• Resolved stellar populations out to 10 Mpc |
| Near-IR, DL Echelle (NIRES) | 1 – 5 | 2″ | 5000 – 30000 | • IGM z > 7, Gamma-ray bursts<br>• Local group abundances<br>• Abundances, chemistry and kinematics of stars and planet-forming disks<br>• Doppler detection of terrestrial planets around low-mass stars |

The instrument suite has been divided by the TMT SAC in December 2006 [3] into "early light" and "first decade" instruments for a variety of pragmatic reasons: funding constraints, commissioning practicalities, and technological readiness. The early light suite consists of IRIS (behind NFIRAOS), WFOS ("two-barrel" configuration), and IRMS (a clone of the Keck MOSFIRE, also to be used behind NFIRAOS). These are discussed in the following sections, and the remaining instruments, including their AO components are discussed in **Section 8.7**. While bringing the early light instruments on-line is clearly the top priority of the TMT instrumentation program, it should be emphasized that the ultimate goal of this program is to bring the full SRD suite into operation over the first decade of TMT operations. Many design decisions and choices were therefore made with this ultimate goal in mind.

The very ambitious WFOS requested in the SRD has been scaled back to reduce cost, risk and commissioning complexity and make it suitable for early light. Likewise, the early light IRIS configuration has also been kept as simple as possible yet still retaining the ability to meet its key science objectives.

### 8.6.2 Wide-Field Optical Spectrograph (WFOS)

#### 8.6.2.1 WFOS overview

A number of key TMT science programs will be best conducted with a powerful survey instrument operating at optical wavelengths. These programs include the determination of the baryonic power spectrum, the tomography of the intergalactic medium, the determination of the dynamical states of stellar populations in nearby galaxies, the dark matter distribution in elliptical galaxies, and the star formation history in local galaxies. A high multiplexing capability (several hundreds of spectra) over a relatively large (∅~ 15′-20′) field-of-view is required to sample large cosmological volumes with sufficient target density to probe the range of desired physical scales. The spectrograph should also provide good image quality and moderate spectral resolutions.

The main WFOS requirements listed in the TMT Observatory Requirement Document (ORD, [4]) are:

- Multi-object spectroscopy over as much of a 20' field as possible
- Wavelength range: 0.34-1.1µm (0.31-1.6µm goal); atmospheric dispersion correction required
- Field of view: 40.5 arcmin$^2$; may not be contiguous
- Total slit length ≥ 500 arcsec
- Image quality: ≤ 0.2 arcsec full width at half maximum (FWHM) over any 0.1µm wavelength interval (including contributions from the telescope and the ADC at z = 60°)
- Spatial sampling: ≤ 0.15 arcsec per pixel, goal ≤ 0.10 arcsec
- Spectral resolution: R=500-5000 for 0".75 slit; goal: 150-7500
- Throughput: ≥ 30% from 0.34 – 1.0 µm
- Sensitivity: Photon-noise limited spectra for all exposure times > 60 sec; background subtraction systematics must be negligible compared to photon noise for total exposure times as long as 100 kiloseconds; nod and shuffle capability in the detectors may be desirable.
- Wavelength stability: flexure < 0.15 arcsec at detector
- GLAO-based image quality improvement a possibility

#### 8.6.2.2 WFOS feasibility

The Wide-Field Optical Spectrograph [5, 6,7] concept is the work of an ACURA/NRC/HIA team with Roberto Abraham (U. Toronto) as Principal Investigator. Although the original WFOS concept consisted of four individual spectrograph barrels, the early light configuration adopted by the TMT SAC in December 2006 will be a two-barrel one. The WFOS concept was reviewed by an independent expert panel in March 2006 [8].

Each WFOS barrel feeds blue and red camera arms for increased simultaneous wavelength coverage. The field-of-view of each barrel is 4′.5 × 5′.4. It will be possible to put as many as 750 slitlets on a single mask for science applications (e.g. point sources) that need relatively short slitlets. The physical size of a mask will be 590mm × 708mm, and the mask holder in each barrel will allow up to 18 masks to be loaded at once. A combination of Volume-Phase Holographic (VPH) gratings and traditional ruled reflective gratings will be used to achieve high performance at resolutions of R=300-7500.

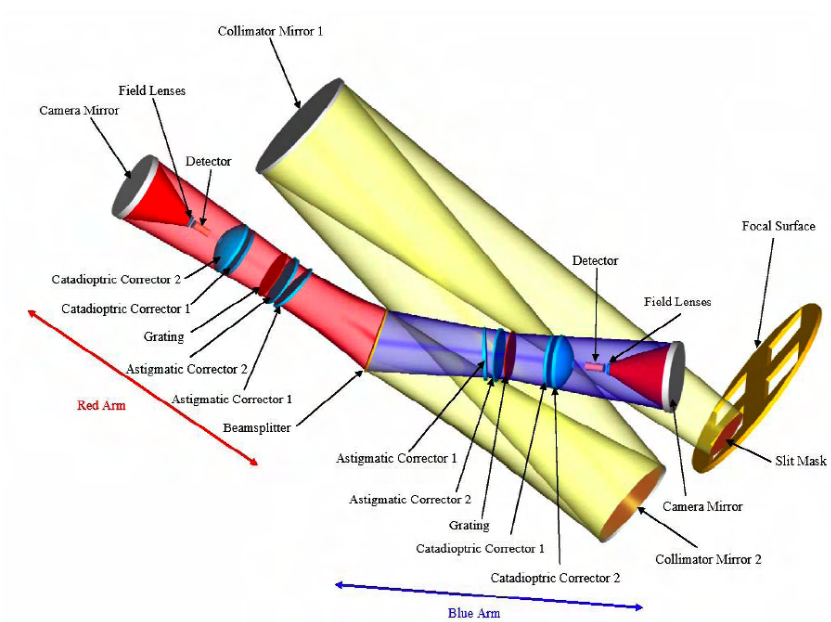


**Fig 8-67: Opto-mechanical layout of a single WFOS barrel.**

The first elements in the optical path of WFOS (see **Figure 8-67**) are separate Atmospheric Dispersion Compensators (ADCs) deployed in front of each barrel. The size of the barrels/fields is ultimately set by the reasonable diameter (≤ 1m) of glass in the ADCs. The collimator will use two spherical mirrors, and residual astigmatism will be corrected using a two-element refractive corrector system near the gratings. The collimator pupil at the grating will have a diameter of 570mm. VPH gratings will yield very high efficiency at the higher spectral resolutions. The reflective collimator design corrects the field curvature from the Ritchey-Chrétien telescope, resulting in good image quality over the WFOS field, satisfying the WFOS science goals. Refractive collimator designs were ruled out as they could not deliver the required pupil size due to limitations on the available sizes of CaF2 elements and their inability to compensate the telescope field curvature. After the light passes through the collimator, a beamsplitter will direct it down the blue and red arms. The split will nominally occur at 560.0 nm, but daytime beamsplitter changes will be possible to accommodate science cases with different wavelength splits. The camera is an f/1.5 catadioptric design with a spherical mirror. The two-element corrector near the pupil and a three-element refractive system in front of the detector provide good image corrections for a flat science focal plane on the detector.

A striking characteristic of WFOS (or of any other seeing-limited instrument on an ELT for that matter) is its sheer physical size. The two-barrel WFOS will be nearly six meters in diameter. This unprecedented (but not unexpected) size for an optical spectrograph is a direct consequence of the scientific requirement for a large field-of-view. Keeping in mind that size does not necessarily imply increased (and unmanageable) complexity, the scientific return from WFOS will have to be balanced against technical/scheduling risks as well as against the special requirements that large instruments place on TMT facilities (e.g. Nasmyth platform size). An interesting outcome of the WFOS feasibility study is that a horizontal orientation is now part of the baseline concept. It initially appeared that a vertical orientation would be favored because it keeps the instrument under a fixed gravity vector as the instrument rotates to compensate for the field rotation of TMT. However, this vertical orientation required a large and expensive fold mirror, and detailed finite-element analysis showed that the expected flexure for a horizontal orientation would fit within the opto-mechanical tolerances of the current design. More details are given in Pazder et al. [9]

#### 8.6.2.3 Development tasks and work plan

There are three main WFOS development tasks:

**Collimator re-design**
The optical prescription of TMT was changed from an aplanatic Gregorian to a Ritchey-Chrétien configuration as part of a project re-scope in Fall 2006. The net effect for the instruments is a change in the sign of the focal plane curvature, and preliminary designs (see **figure 8-68**) demonstrate that, as expected, the RC design yields improved performance for WFOS.

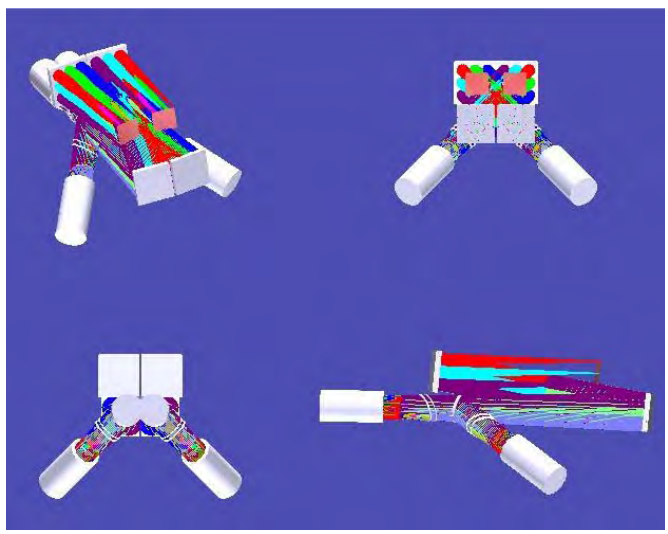

**Fig 8-68: Two-barrel Ritchey-Chrétien WFOS design.**

**Re-scope from four to two barrels**
The WFOS feasibility study focused on a concept that met the SRD requirement for large field-of-view. This requirement and the limitation on the largest piece of glass that can be manufactured for the ADCs led to the original four-barrel WFOS concept. In December 2006, the TMT SAC decided to adopt a two-barrel version of “WFOS-SRD” as the early light configuration. The main impact of this decision will be to re-design the WFOS superstructure to optimally accommodate two barrels instead of four.

**VPH grating risk retirement**
The technology for the production of VPH mosaic gratings is advancing, and there are two companies that appear to have the ability to at least attempt the fabrication of the WFOS grating. We will continue to work with vendors to identify fabrication processes and establish/refine cost estimates for grating fabrication. Chris Clemens’ group at the University of North Carolina – Chapel Hill is already working on technologies related to multiplex, mosaiced and very wide bandwidth gratings in collaboration with the TMT instrumentation program.

A full conceptual design study will be initiated for WFOS in 2007. The schedule estimates for the much more complex four barrel version that was developed in the feasibility study indicate that the new two barrel RC instrument can be delivered in time for TMT first light. There are several groups within the TMT partnership who have the relevant experience and expertise to contribute to this development. While future TMT instruments will likely be designed and built as much as possible through a competitive process, the plan for the early light instruments is to have them built by partner institutions. There will be a lead institution with 2-3 other partner institutions responsible for various WFOS subsystems. Design will be done at these partner institutions with industries being given targeted technological developments. The WFOS feasibility has already highlighted some key technologies (e.g. VPH grating) that may be well suited to industrial partnerships. Industrial involvement will grow in later stages of the WFOS projects as system and component designs become better defined and thus easier to outsource for further design or fabrication.

There will be a project manager and a system engineer devoted solely to the WFOS project. Both will be located at the WFOS integration site (and lead institution). WFOS will be tested at this site before shipping to the TMT site for re-assembly and commissioning. Some WFOS testing will require the actual telescope beam. Fortunately, these on-sky tests will be possible even if all TMT primary mirror segments have not yet been installed and we expect to conduct some of them prior to official first light at TMT.

### 8.6.3 InfraRed Imaging Spectrograph (IRIS)

#### 8.6.3.1 IRIS overview

Prime science drivers for IRIS are the first luminous objects in the Universe, supermassive black holes at the cores of distant galaxies, relativistic effects at the Galactic center, resolved stellar populations in the crowded fields of galaxies out to the Virgo galaxy cluster and high-resolution imaging and spectroscopy of planets and satellites in the Solar System. IRIS will occupy one of the ports on NFIRAOS, and it will be able to conduct diffraction-limited imaging and integral field spectroscopy (IFS) observations in parallel. The TMT SAC has consistently ranked IRIS as the top instrument priority for TMT.

IRIS is envisioned as an integral field spectrograph and imager working at the TMT diffraction limit fed by NFIRAOS. The main IRIS requirements listed in the TMT Observatory Requirement Document [4] are:

- Wavelength range: 0.8-2.5µm
- Image quality: 35nm RMS (end-to-end wavefront error) must fit within the current NFIRAOS budget of 187 nm rms wavefront error on axis.
- Field of view: < 2'' for IFU, up to 30'' x 30'' for imaging mode
- Spatial (detector) sampling:
  - 0.004 arcsec per pixel (Nyquist sampled ($\lambda$/2D)) over 4096 pixels for IFU)
  - Nyquist sampled (0.004 arcsec/pixel) over 10x10 arcsec for imaging
  - Plate scale adjustable to 0.004, 0.009, 0.022, 0.050 arcsec/pixel
  - 128x128 spatial pixels for a small ($\Delta\lambda/\lambda \leq 0.05$) wavelength coverage
- Spectral resolution
  - R=4000 over entire J, H, K bands, one band at a time
  - R=2-50 for imaging mode
- Throughput: Should be equal to or exceed comparable instruments on 8-10m telescopes
- Thermal background: Should not increase (inter-OH lines) background by more than 5% over that emitted through NFIRAOS
- Detector: Dark current and read-noise should not increase effective background by more than 5% for an integration time of 2000 seconds
- Parallel imaging: goal

#### 8.6.3.2 IRIS feasibility

The IRIS feasibility study [10,11 12] was conducted at UCLA and Caltech with James Larkin as the Principal Investigator. It builds upon the heritage of the OH-Suppressing Infrared Imaging Spectograph (OSIRIS) [13] at Keck. The IRIS concept was reviewed by an independent expert panel in March 2006 [14].

The design of the IRIS imaging channel is built around a Rockwell 4k×4k infrared array with a 10μm pitch. This pixel sampling corresponds to 4.6 milliarcsec in the f/15 focal plane. The imager is a 1:1 Offner relay with three spherical mirrors that provides excellent image quality over 15″, a well-formed intermediate cold pupil and a location for the filters. The mirrors will be made of ULE or Zerodur to keep the wavefront errors introduced by each reflection quite small (< 7 nm per optical surface). The total wavefront error for the IRIS imager must fit within the current NFIRAOS budget of 187 nm rms wavefront error on axis. Given that the imager optics will be offset on one side of the original beam, it will in principle be possible to easily combine multiple imaging modules in a common focal plane. However, the baseline requirement is to have one such imager. IRIS will have its own set of 3 NGS wavefront sensors: 2 tip-tilt (TT) + one tip/tilt/focus (TTF). NFIRAOS requires that TTF measurements be made in the science focal plane in the J-band, where AO corrections can make it possible to use fainter reference stars (J < 22) for increased sky coverage. The three sensors will patrol the 2′ corrected field produced by NFIRAOS.

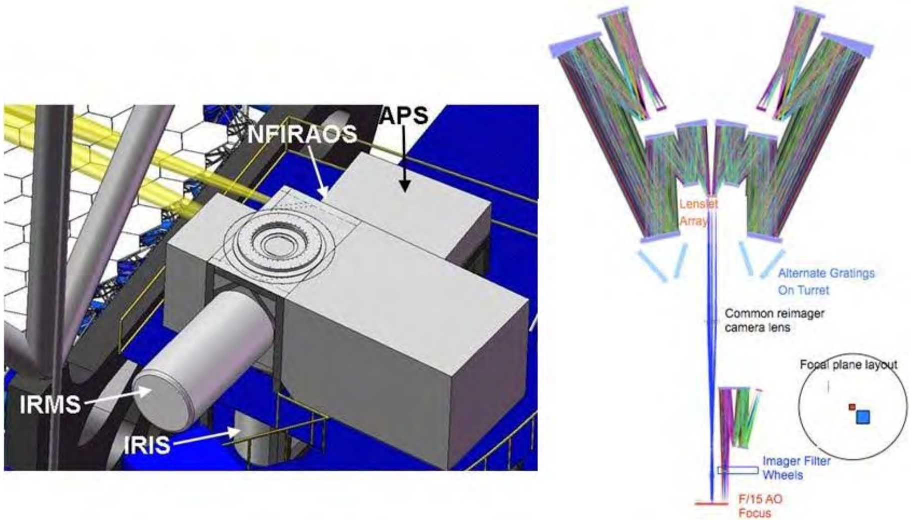


**Fig 8-69: Views of IRIS mounted on NFIRAOS (left) and of the basic IRIS design concept (right). The focal plane layout shows the imaging and IFU fields in blue and red respectively.**

For the integral field spectroscopy (IFS) channel of IRIS, both lenslet and slicer designs have been carried through the current concept. Other similar instruments such as NIFS on Gemini and SINFONI on VLT are usually based on a slicer design. OSIRIS on Keck is the only near-IR IFU based on a lenslet array. The key advantage of the slicer design is that it makes far better use of science detector pixels with a more efficient packing of the spectra. Reduction of slicer-based IFU data is also simpler because the spectra run parallel to the rows of the detector. However, a slicer may introduce wavefront errors that are unacceptable. The IRIS science team has indicated a strong preference for a larger field-of-view rather than spectral coverage (they advocated only a 5% bandpass at R=4000) and a need for three different spatial scales (4, 9 and 25 milliarcsec per lenslet). A spectrograph design was adopted that uses a "4K" detector array with 18 micron pixels (e.g. 2×2 array of 2k×2k Hawaii-2RG detectors) and will be fed by a 128×128 lenslet array. The spectrograph optics consists of a pair of three mirror anastigmats to serve as the collimator and camera system. Re-imaging optics needed for the different spatial scales will use two simple biconvex lenses made of Barium Fluoride ($BaF_2$). These lenses will be singlets to minimize the number of re-imaging surfaces and their associated wavefront errors. Three gratings operating in first order in each module will cover the J, H and K bands, and the Y-band will be covered with the K-band grating in second order.

#### 8.6.3.3 Development tasks and work plan

The development tasks for IRIS are:

**Image slicer versus lenslet array**
The IRIS feasibility study carried both image slicer and lenslet array concepts through to the end but did not settle on the preferred option. Lenslet arrays have traditionally been known to deliver better wavefront errors. However, further trade studies must be performed as part of the IRIS conceptual study, especially in the light of recent advances in slicer mirror manufacturing that produce higher quality surfaces, to determine whether an image slicer or a lenslet array will best meet all IRIS requirements.

**Spatial versus spectral coverage**
By their very nature, IFU-based spectrographs feature an inherent trade-off between field of view and spectral coverage. The IRIS science team indicated a strong preference for a limited spectral coverage of 5% ($\Delta\lambda/\lambda \leq 0.05$) in favor of a larger field of view. However, the TMT SAC later re-affirmed that the IRIS spectral coverage

should be closer to 20%. For example, a larger spectral coverage enables studies of a larger combination of emission-line diagnostics. More detailed trade studies of IRIS science will be needed to settle this issue.

**Non-common path errors**
The expert panel that reviewed the IRIS concept judged that the requirement for 30 nm rms residual wavefront error (uncorrected by NFIRAOS, Table 8-17) was too severe [14] especially in the light of a potential on axis 187 nm rms wavefront error from NFIRAOS and the existence of a dedicated instrument for high contrast applications (PFI). The panel recommended that a total wavefront error budget for the entire system be formulated and then apportioned to subsystems in a logical manner. The fact that PFI is not part of the early light instrument suite should bear on the final amount of NCP error that can be tolerated especially if early coronagraphic observations are to be conducted with IRIS.

**Number of imaging modules**
The early light IRIS configuration adopted by the TMT SAC features a single imaging module. However, the IRIS study also proposed a configuration with four imaging modules that would have a field of view equivalent to WIRC. This option would thus fold WIRC into IRIS albeit at a higher cost. Further design and cost estimating efforts as well as overall project funding will determine whether this option may be pursued in the end.

**Atmospheric Dispersion Compensators (ADCs)**
The expert panel that reviewed the IRIS concept was concerned that the ADCs could involve substantial operational complexity. The ADCs were not studied in the feasibility phase. The panel encouraged further mechanical engineering studies that would include space requirements of the tip-tilt focus sensors, ADCs, imagers and spectrographs within the available space envelope, and explore crowding near the focal plane.

A conceptual design for IRIS will be initiated in 2007, and it is planned to complete the IRIS instrument in time for integration and pre-commissioning with NFIRAOS.

As for WFOS, IRIS will also be designed and built at partner institutions with a level of industrial involvement during each phase of the project that will be dictated by how the required expertise and resources will be best acquired. There will be a project manager and a system engineer devoted solely to the IRIS project. Both will be located at the IRIS integration site (and lead institution).

IRIS will actually undergo three integration/testing phases. IRIS will be first integrated and tested by itself at the lead institution. Following the successful completion of these tests, IRIS will then be shipped to the NFIRAOS site for mating and testing with NFIRAOS. The Project has identified the testing of the NFIRAOS+IRIS system as a whole in a controlled laboratory environment before shipment to the TMT observatory site as a highly desirable goal to minimize such critical work (and related costs) in a relatively hostile site such as a remote mountain summit. IRIS is actually required to completely test NFIRAOS. The IRIS schedule is therefore tightly linked to the NFIRAOS schedule. Current schedule work indicates that both schedules are indeed compatible with achieving this goal. Once the NFIRAOS+IRIS system has been thoroughly tested in a controlled environment, it will be disassembled and shipped to the TMT site for final re-integration and on-sky commissioning leading to science operations.

### 8.6.4 InfraRed Multi-slit Spectrometer (IRMS)

#### 8.6.4.1 IRMS overview

The TMT SAC has consistently stated that some form of multi-object NIR spectroscopy is an essential capability for early light. Understanding the so-called “First Light” objects in the Universe, the origin and evolution of galaxies and other objects detected by JWST and ALMA will require spectra of many extremely faint objects in the NIR, and multiplexing will thus be essential. Unfortunately, IRMOS with its deployable IFU system, was judged to be too risky and expensive for an early light instrument. In December 2006, SAC agreed to adopt a clone of the MOSFIRE multislit instrument, currently being built for Keck, as an acceptable interim capability [3]. Although MOSFIRE will be a seeing-limited instrument for Keck, it can fortuitously be easily adapted for use in a quasi diffraction-limited mode with NFIRAOS, providing an exceedingly powerful capability for TMT at low risk and modest cost.

#### 8.6.4.2 IRMS feasibility

IRMS is intended to strictly be a clone of MOSFIRE [15] in order to reduce risk and save cost. MOSFIRE is a multi-slit instrument designed for the f/15 Cassegrain focus on the Keck 1 telescope. This is the same f/ratio as the Nasmyth foci envisioned for TMT and, without change to the existing instrument, it would naturally take in the entirety of the NFIRAOS field of regard of 2’ diameter. A summary of the MOSFIRE parameters and their corresponding numbers at f/15 on a 30m telescope is given in **Table 8-25** The parameters listed in the table are not optimized in any way, but are simply what would result if the as-designed instrument were placed behind TMT+NFIRAOS.

**Table 8-25: Specifications for MOSFIRE-like instrument at f/15 on a 30m telescope.**

| | |
|---|---|
| Field of View | 2.27' diameter imaged onto 2.05' sq. detector (2k x 2k 18 micron pitch); Entire field of view is useable for spectroscopy |
| Pixel scale | 0.06"/pix imaging; 0.08"/pixel in dispersion direction |
| Multiplex factor | 46 movable cryogenic masking bars, each 2.43" long on sky (slits can be any multiple of 2.5" in length); continuously variable slit widths, all remotely configurable. |
| Spectral Resolution | R=3270 with 3 pixel slit (0.24" wide)<br>R=4660 with 2 pixel slit (0.16" wide) |
| Spectral Coverage | All of Y, J, H, or K for slits placed over most of the available field of view (fixed reflection grating used in order 6,5,4,3). |
| Imaging | Images entire NFIRAOS field of regard with 60 milliarcsec sampling |

The spatial pixel scale is reasonably well-matched to the sampling scale (50 milliarcsec) requested in the SRD for IRMOS and the length of individual slitlets (made by masking bars in MOSFIRE) is similar to the recommended scale for IRMOS. The requirements for spectral resolution (R>3000) would be satisfied for slit widths smaller than about 0.3 arc seconds (but slit widths smaller than 160 milliarcsec would be spectrally under-sampled, i.e. less than 2 pix/resolution element) and the desired spectral coverage of 1 atmospheric band at a time for Y, J, H, and K bands would be met over much of the NFIRAOS field of regard. For multiplexing, the individual bars can be configured in up to 46 slitlets over the entire NFIRAOS field; in practice, some of the slitlets would be made into contiguous slits of lengths that are multiples of 2.5". The width of slits and their placement within the field are remotely configurable in real time.

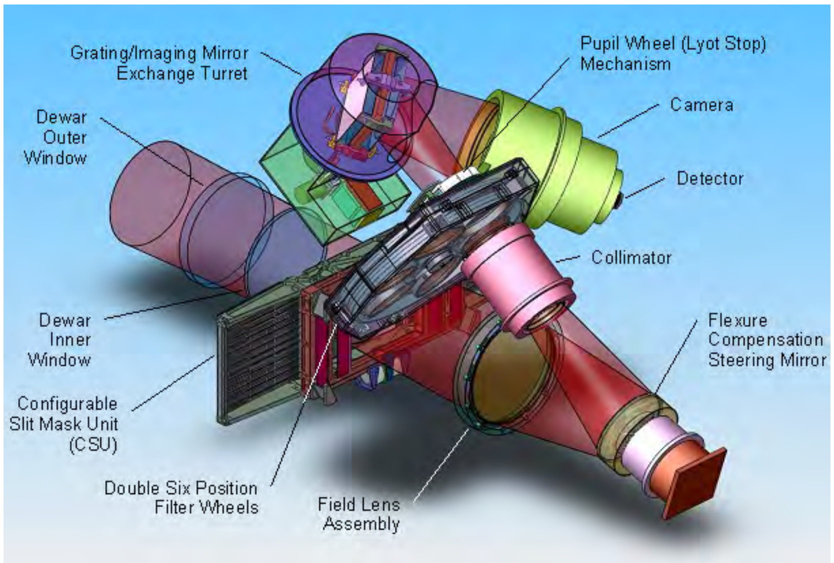


**Fig 8-70: MOSFIRE basic design concept** [15].

As a bonus, the instrument can be configured (remotely, in ~30 seconds) as an imager that would cover the entire NFIRAOS field of regard, albeit with spatial sampling of only 60 milliarcsec (roughly 4 times larger than the diffraction limit at 2 microns). MOSFIRE successfully passed DDR in April 2007, and it is expected to be complete by December 2009.

Preliminary results from studies of the optical and mechanical interfaces between NFIRAOS and IRMS under way at the time of writing are quite encouraging (Powell, Atwood & Byrnes, NRC/HIA – private communication). MOSFIRE on Keck is designed for a curved focal plane with a radius of 2100mm, and the pupil is located near the secondary mirror at a distance of 20m from the focal plane. On the other hand, NFIRAOS delivers a flat focal plane with a pupil at a distance of 0.5 km.

In order to minimize background, MOSFIRE must image the pupil on a cold Lyot stop, and the two basic questions for the NFIRAOS-IRMS optical interface are thus: can the exit pupil of NFIRAOS be imaged onto the Lyot stop and what will the different focal plane geometry do to the IRMS image quality? Decreasing the power of the field lens to force the pupil image to coincide with the same location as found with the Keck telescope and optimizing its shape and location to yield maximum performance results in a plano-convex element of the same size as the original, but with a spherical surface with a radius of curvature of 518mm. This modification must also be accompanied by a longitudinal displacement of the entire MOSFIRE assembly of 20mm from the NFIRAOS focal plane. In terms of image quality, **Figures 8-71** and **8-72** show J, H, and K encircled energy curves based on simulations of the NFIRAOS wide field performance optimized over two different field-of-view diameters. Significant gains over the seeing-limited (SL) case are obtained in both sets of simulations for the minimum (Nyquist-sampled) IRMS slit width of 160 milliarsec.

In summary, MOSFIRE on TMT/NFIRAOS would provide most of the basic capabilities requested in the SRD for IRMOS. It will **not** provide the multi-object integral field (2D) spectroscopic capability that is ultimately desired for TMT, but it is recognized that such a system is both too expensive and too technologically risky for first light.

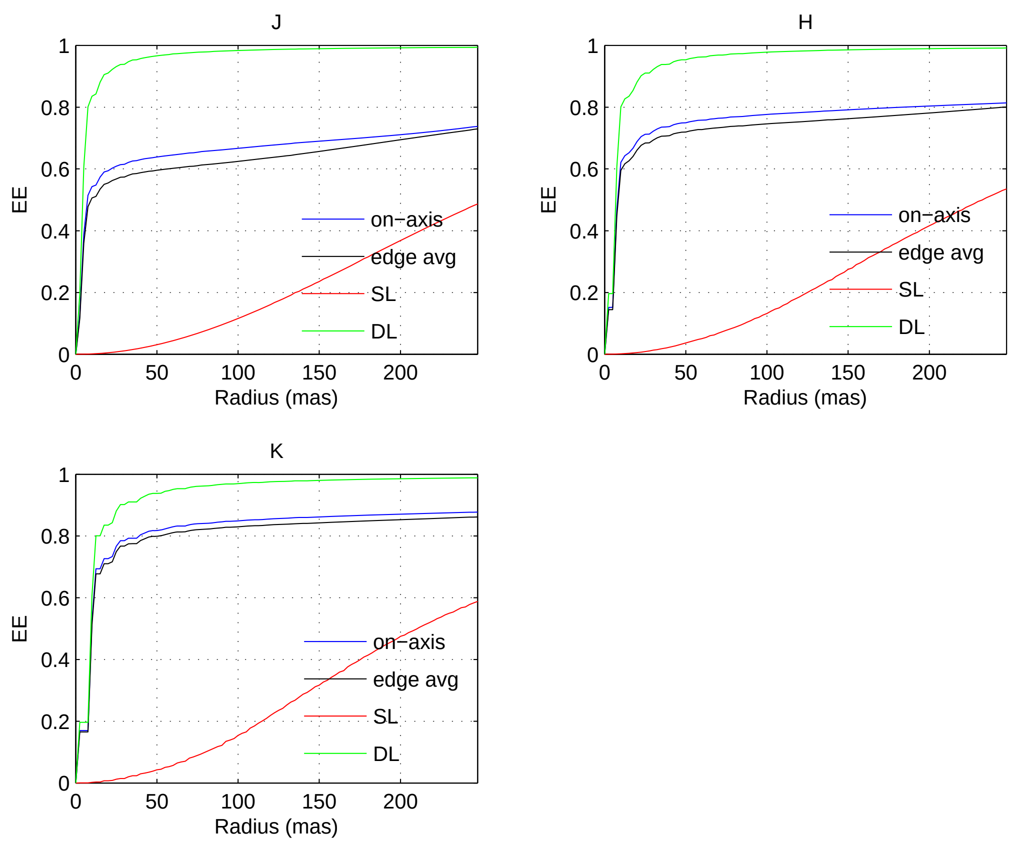


**Fig 8-71: Encircled energy curves showing the NFIRAOS wide field performance in J, H and K with tomographic reconstructor parameters tuned to optimize image quality over a 30'' diameter field [16]. The minimum (Nyquist-sampled) IRMS slit width is 160 mas, and it thus encloses light within a radius of 80 mas.**

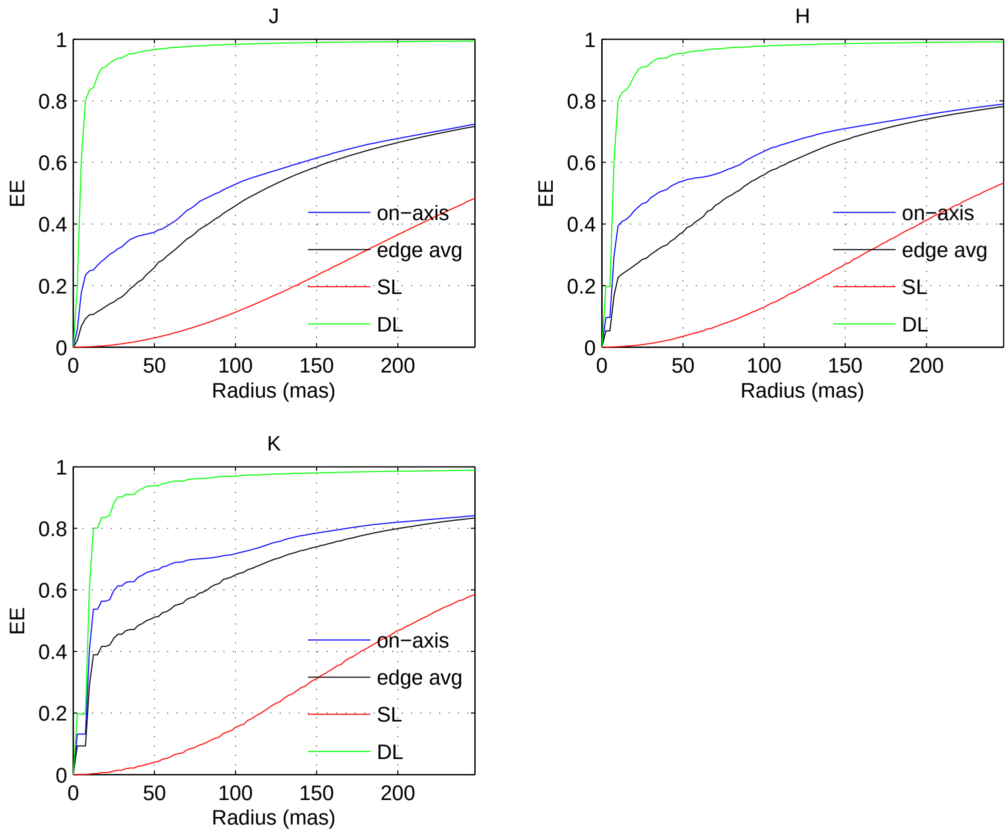


**Fig 8-72: Encircled energy curves showing the NFIRAOS wide field performance in J, H and K with tomographic reconstructor parameters tuned to optimize image quality over the full 2' diameter field [16]. The IRMS slit width is 60 mas.**

#### 8.6.4.3 Development tasks and work plan

Although IRMS is meant to be clone of MOSFIRE, there are a number of important development tasks that will still need to be undertaken. The fundamental difference between MOSFIRE and IRMS is that IRMS will operate at the back-end of an AO system (NFIRAOS). Already, our preliminary analyses demonstrate that the mechanical interface will not be too difficult and that a simple change of the field lens will be sufficient to adapt the location of the exit pupil of NFIRAOS to the location of the Lyot stop.

The performance of IRMS behind NFIRAOS is also being investigated with respect to main themes found in the IRMOS science case: first light objects, metal-free star formation, epoch of peak galaxy assembly, resolved stellar populations out to Virgo cluster, embedded star-forming regions.

The work plan for IRMS will naturally be dominated by the MOSFIRE schedule and progress. MOSFIRE passed its Preliminary Design Review in April 2006, and its critical design review in April 2007. It is scheduled for delivery at Keck in mid-2009. The MOSFIRE development work will allow us to move directly into a Preliminary Design phase for IRMS. This phase will include all modifications needed based on actual MOSFIRE experience at Keck. The UCLA/Caltech/UCSC MOSFIRE consortium is the obvious choice for the IRMS lead institution.

### *References*

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[2] Nasmyth Platform Structural Design Concept, TMT.STR.TEC.06.043.

[3] TMT SAC Meeting Minutes 2006-12, TMT.PSC.MGT.06.016.

[4] TMT Observatory Requirements Document, TMT.SEN.DRD.05.001.

[5] WFOS Feasibility Study Report, TMT.INS.FDD.06.003.

[6] WFOS Operational Concepts Definition Document, TMT.INS.DRD.05.002.

[7] WFOS Functional Requirements Definition Document, TMT.INS.DRD.05.001.

[8] Review Committee Report on the WFOS Design Review for TMT, TMT.INS.COR.06.008.

[9] Pazder et al. 2006, "WFOS: A Wide Field Optical Spectrograph for the Thirty Meter Telescope", Proc SPIE 6269-70, TMT.IAO.TEC.06.012.

[10] IRIS Feasibility Report, TMT.IAO.FDD.06.001.

[11] IRIS Initial Operational Concept Document, TMT.INS.DRD.06.002.

[12] IRIS Functional Requirements Document, TMT.IAO.DRD.06.001.

[13] OH-Suppressing Infrared Imaging Spectrograph (Keck OSIRIS web page).

[14] Review Committee Report on the Feasibility Study for IRIS, TMT.IAO.TEC.06.011.

[15] Multi-Object Spectrometer for Infra-Red Exploration (UCLA web page).

[16] NFIRAOS Wide Field Performance, TMT.IAO.TEC.07.011.

## 8.7 Instrumentation Development Plans

### 8.7.1 Introduction

Several of the remaining instruments described in the SRD will include sophisticated AO systems, and some will require advances in technologies. The TMT SAC's specific recommendation for the next generation of instruments is: "We recommend that MIRES, NIRES-B and IRMOS be implemented as soon as possible after the early light suite. We hope that the first two of these can be implemented within 3 years of first light. IRMOS is also high priority and should be implemented soon as technically feasible. PFI is a very exciting, highly-focused instrument, which we hope can be funded. There is also strong support for HROS, and we hope that it can be brought on line within the first decade of operations. The SAC reaffirms the importance of high-quality wide-field diffraction-limited imaging [WIRC]." [1]. It is anticipated that SAC will review the priorities and capabilities of the instruments on an annual basis so that details of the following instruments may change. However, as mentioned earlier, the observatory is being designed to accommodate the requirements of the entire instrument suite, not just the early light instruments.

The development of these instruments (and future ones) will be an on-going activity that will require careful and judicious planning and management. To ensure that these instruments begin arriving as required, some of them will have to be initiated early in the construction phase, even though they will *not* be funded from construction funds. The instrumentation plan will have to be able to adapt to changing budgetary scenarios, technological advances, and opportunities. For these reasons, a separate Instrument Development Office (described in **Section 8.7.4**) is planned that will guide instruments all the way from pre-concept studies through to successful commissioning with the goal of enabling forefront science as quickly and as efficiently as possible. One of the first activities of this team will be to initiate development of the first decade instruments in the SRD. A brief description of these instruments follows.

### 8.7.2 First Decade Science Instruments

#### 8.7.2.1 Planet Formation Instrument (PFI)

**Overview**

SAC recognized that the Planet Formation Instrument (PFI) is a unique instrument with high scientific merit but also felt that it addresses a rather specialized scientific niche. It is focused on one primary goal: the direct detection of extrasolar planets. PFI is also unique in that it places significant requirements on the telescope optics (primary pupil shape, secondary support structure, segment edge and reflectivity) and vibrational environment, and these requirements have been factored in the telescope design.

PFI will build very strongly on the heritage being gained by the "planet finder" instruments that are currently being designed for Gemini ("GPI", [2]) and the VLT ("SPHERE", [3]) It is not yet at a sufficient level of technological readiness to include it in the early light suite.

The main PFI requirements listed in the TMT Observatory Requirement Document [4] are:

- Wavelength range: 1-2.5µm (one band at a time), goal 1-4µm
- Field of view 0.7 arcsec radius. Goal 2 arcsec radius (applies to all requirements for PFI)
- Planet detection contrast:
  - $10^{-8}$ @ 50 milliarcsec, goal of $10^{-9}$ @ 100 milliarcsec (parent star magnitude I < 8, 5$\sigma$ detection in two hour integration)
  - $10^{-6}$ @ 30 milliarcsec, goal of $2 \times 10^{-7}$ @ 30 milliarcsec (parent star magnitude H < 10, 5$\sigma$ detection in two hour integration)
- Critically sampled at H-band, goal is at J-band
- Spectral resolution, full FOV, IFU: R = 50, goal 100
- Spectral resolution, partial FOV, IFU: R = 500, goal 1000
- Polarization: simultaneous dual channel.

**Feasibility**

High-contrast imaging is an important capability that places stringent requirements on the full optical path of TMT. The Planet Formation Instrument concept [5, 6, 7, 8] results from a collaboration involving Lawrence Livermore National Laboratory, Jet Propulsion Laboratory, Université de Montréal and University of California, Berkeley. The PFI Principal Investigator is Bruce MacIntosh (Lawrence Livermore National Laboratory (LLNL)). A block diagram of the PFI system is shown in **Figure 8-73**. Current AO systems achieve imaging contrasts of $10^5$ at an angular separation of ~ 1 arcsecond. The goal of PFI is to achieve an extremely high contrast of $10^8$ down to an inner working angle of 50 milliarcsec on a $I$ < 8 parent star. The PFI concept was reviewed by an independent expert panel in March 2006 [9].

The first stage in the PFI system is a high-speed, visible-light, front-end AO system. It will operate at very high update rates (2-4 kHz) to minimize dynamic atmospheric errors. At the heart of this AO system will be a pyramid wavefront sensor running in quasi-interferometric mode. Errors from these wavefront measurements should be factor of 2-4 smaller than those obtained with a conventional Shack-Hartmann sensor. The pyramid sensor will be combined with a high-order (~$128^2$) Micro-Electric-Mechanical Systems (MEMS) deformable mirror (DM) to deliver expected H-band Strehl ratios above 0.9 on bright stars and 0.84 down to $I$ = 9 mag.

The second stage of PFI is a diffraction suppression system (DSS) that will control the light scattered by diffraction from the telescope pupil. The DSS will be a dual-stage shearing nulling interferometer that will combine four offset and phase-shifted copies of the telescope pupil to remove the uniform component of the EM field that causes diffraction. This "nuller" architecture offers two significant advantages: (1) very small inner working angles (~ 3 $\lambda$/D) needed to detect planets in reflected starlight, and (2) robustness against pupil obscuration. However, one disadvantage of this nuller is its low throughput (~10-20%). Downstream from the DSS is a dedicated, interferometric infrared wavefront sensor. This "back wavefront sensor" will be a Mach-Zehnder interferometer that will combine the bright and dark outputs from the DSS. It will control a second MEMS inside the DSS to remove subnanometer internal static optical errors.

The final stage of PFI is the science instrument itself. It will be an integral field spectrograph (IFS) capable of disentangling the exoplanet signal from the chromatic changes in residual artifact speckles. Such a speckle suppression system is expected to boost image contrast by an order of magnitude. The IFS will provide spectral resolutions up to 700 for follow-up studies of detected planets as well as a dual-channel imaging polarimetry mode to discriminate planets against the disks in which they may be embedded.

**Development tasks and work plan**

The most important issue is by far technical readiness. PFI includes AO technologies that are still very much in development (**Table 8-26**). These include very high order MEMS, higher speed, low noise, visible and near IR wavefront sensing detectors, and novel wavefront sensor concepts designed for maximum photon sensitivity and measurement precision with a very large number of subapertures. In general, the requirements for all of these components and subsystems represent one or more stages of further improvement beyond the devices now under development for ExAO and visible light AO on 5-10m class telescopes. We will continue communicating with these projects, and intend to review our schedule and design concepts for PFI in 2009-10 as these projects approach their commissioning tests.

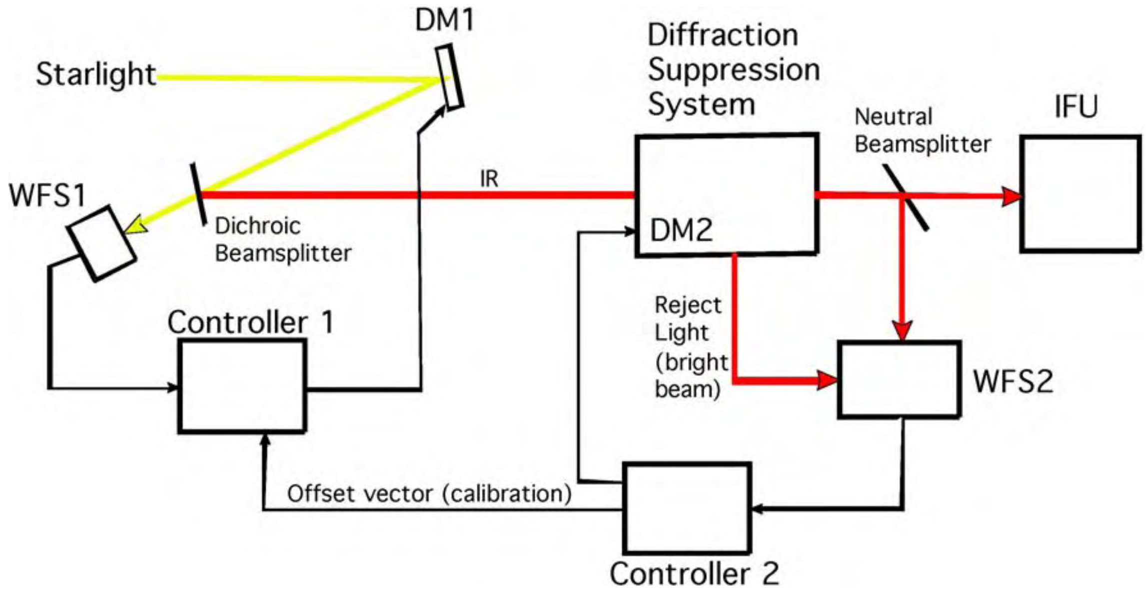


**Fig 8-73: Simplified block diagram of the PFI system [5].**

Fortunately, the Gemini Planet Finder (GPI) project is the perfect PFI pathfinder, and there is considerable overlap between the GPI and PFI teams. The PFI team has suggested a strategy in which further PFI design efforts are undertaken only when GPI has reached a higher level of maturity. The PFI feasibility study schedule indicates that the fabrication phase is short enough that we can wait for more advanced GPI developments before finalizing the PFI design and fabricating it and still deliver it within 1-2 years from TMT first light.

**Table 8-26: Critical AO components for PFI.**

| Component or Subsystem | Key Requirements | Design Options | Ongoing Development Activities |
|---|---|---|---|
| Deformable Mirrors | ~$128^2$ actuators | - MEMS<br>- 2-d actuator arrays | -$64^2$ MEMS for GPI<br>-Xinetics $66^2$ photonics module for PALM 3000 |
| Visible WFS detectors | - ~$128^2$ subapertures<br>- 2-4 kHz<br>- 1 electron | - JFET amplifiers<br>- APD amplifiers | - AODP project at MIT/LL<br>- E2V $L^3$ arrays |
| Visible WFS designs | - ~$128^2$ subapertures<br>- Maximum sensitivity | - Zernike phase contrast WFS<br>- Pyramid WFS | Pyramid WFS testbed at LAO |
| IR WFS detectors | - ~$128^2$ subapertures<br>- 500-1000 Hz | - HgCdTe ADP arrays<br>- CMOS readout elec. | Gemini/ESO/NMT consortium for IR detector development |
| IR WFS designs | - ~$128^2$ subapertures<br>- Maximum precision | Mach-Zehnder or nulling interferometer | Nuller testbed at JPL |

#### 8.7.2.2 Mid-Infrared Echelle Spectrometer (MIRES)

MIRES [10, 11] brings diffraction-limited, high spatial-resolution imaging and high-resolution spectroscopy in the thermal infrared (5-25μm) to the TMT instrumentation suite. The MIRES concept (co-Is: Jay Elias - NOAO and Alan Tokunaga - U. Hawaii) was reviewed by an independent expert panel in March 2006 [12]. Some of its science objectives require a high (>4000m) and dry (< 3mm of water vapor) observatory site. The MIRES science case features many fascinating objectives: the origin of stellar mass, the exploration of the inner parts of protoplanetary disks, astrochemistry, and the deposition of pre-biotic molecules onto planetary surfaces.

The main MIRES requirements listed in the TMT Observatory Requirement Document [4] are:

- Wavelength range: 8-18µm, 5-28µm goal
- Field of view:
  - Acquisition camera: 10'', Nyquist-sampled at 5 µm (0.017''/pixel)
  - Science camera: Same as acquisition; operating in N band with possibly narrow-band filters
- Slit length: 3 arcsec sampled at 0.04 arcsec / pixel; slit or IFU
- Spectral resolution: 5000< R <100000 with diffraction-limited slit; 50,000-100,000 is prime scientific region; single exposure at R = 100000 should give continuous coverage over all orders imaged
- Thermal background: Should not increase N band background by more than 15% over natural sky + telescope background (assuming 5% emissivity at 273K)
- Spatial sampling: 17 milliarcsec pixels; 2K detector
- Sensitivity: Background should be limited by photon statistics in integrations up to 8 hours long

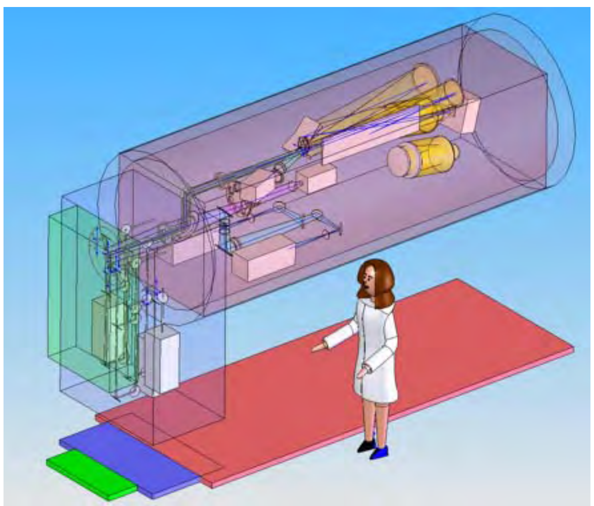

**Fig 8-74: – MIRES with the front-end WFS system ready for interfacing with an adaptive secondary.**

Until an adaptive secondary becomes available, this concept will use a dedicated AO module (MIRAO) optimized for operation at the above wavelengths. MIRAO has five main subsystems: a 1:1 relay with a deformable mirror, three LGS WFSs, a fast, low-order (tip/tilt/focus/astigmatism) NGS WFS, a slow, high-order NGS truth WFS, a deployable calibration unit and a real-time controller. MIRAO will provide wavefront compensation of order $30^2$ with a requirement for a residual wavefront error of 750 nm rms.

MIRES offers three parallel optical channels: a near-IR (K-band) acquisition camera with a 60″×60″ FOV, a mid-IR slit viewer that could double as a 4.5-25 µm science imager were the reflective slit to be replaced by a mirror, and a mid-IR, cross-dispersed spectrograph capable of delivering R~100,000 spectra over the range 4.5-25 µm. The design of the MIRES spectrograph is similar to that of TEXES. The cross-dispersed light is focused on a 2k × 2k detector using two interchangeable cameras: one for the 10µm window (f/2.7, 0″.024/pixel, R=120,000 with 0″.10 slit) and another for the 20µm window (f/1.4, 0″.038/pixel, R=78,000 with 0″.15 slit). The minimum slit length is 3″. MIRES fits inside a cylinder 1.3-m in diameter and 3.6-m long.

#### 8.7.2.3 InfraRed Multiple Object Spectrometer (IRMOS)

IRMOS, as envisaged by SAC, is simultaneously perhaps the most ambitious and the most exciting of the TMT instruments. Its goal is to deliver 2D integral field spectroscopy of many objects over a 5 arcmin field of regard using MOAO to deliver quasi-diffraction-limited spatial resolution in the NIR. Key IRMOS science includes the physical properties of galaxies (internal velocity fields, star formation rate, chemical abundance) at the epoch of peak galaxy assembly ($z$ ~ 2-3) and the physical conditions in star-forming regions. IRMOS will allow many outflows around newly-forming stars to be resolved and their interaction with the interstellar medium to be studied.

The main IRMOS requirements listed in the TMT Observatory Requirement Document [4] are:

- Wavelength range: 0.8 – 2.5 µm

- Deployable Integral Field Units:
    - N > 10 with 2'' field-of-view per IFU
    - Minimum separation between IFUs of 20 arcsec
    - Patrol area of 5' in diameter
    - 50 milliarcsec spatial sampling
- Image quality: diffraction-limited images, tip-tilt ≤ 0.015 arcsec rms
- Spectral resolution: R=2000-10000 over entire J, H, K bands, one band at a time.
- Thermal background: Instrument and AO system should not increase the (inter-OH line) background by more than 15% over sky and telescope backgrounds

**Design Concepts**

Two teams were awarded feasibility contracts to respond to this challenge, and two very different concepts emerged from these studies. One concept (PI: Steve Eikenberry, U. Florida, [13, 14, 15, 16, 17, 18]) uses essentially existing components for image slicers, deployable arms, WFS and spectrographs, to build up a multiplexed system for each target. The other concept (PI: Richard Ellis, Caltech [19, 20, 21] ) uses a novel segmented mirror for target selection. Both IRMOS concepts were reviewed by the same independent expert panel in March 2006 [22, 23].

The Caltech/LAM IRMOS concept consists of three main subsystems: an Offner relay, a focal plane tiled with steering mirrors for object selection and a set of four cryostats housing the spectrographs. The focal plane tile of articulated mirrors (**Figure 8-75**) provides a flexible and elegant way to select targets for IFU spectroscopy. Each flat mirror can be adjusted in three axes (tip/tilt/piston) to direct the light onto one of the 16 steering mirrors that feed 16 individual d-IFU spectrographs. The mirror orientations in the object selection mechanism can be re-configured "on-the-fly" during long exposures to acquire new subsets of targets without loss of observing time. The 16 d-IFU spectrographs (each including its own collimator, grating, camera and 1k × 1k HgCdTe detector) are housed in four different cryostats.

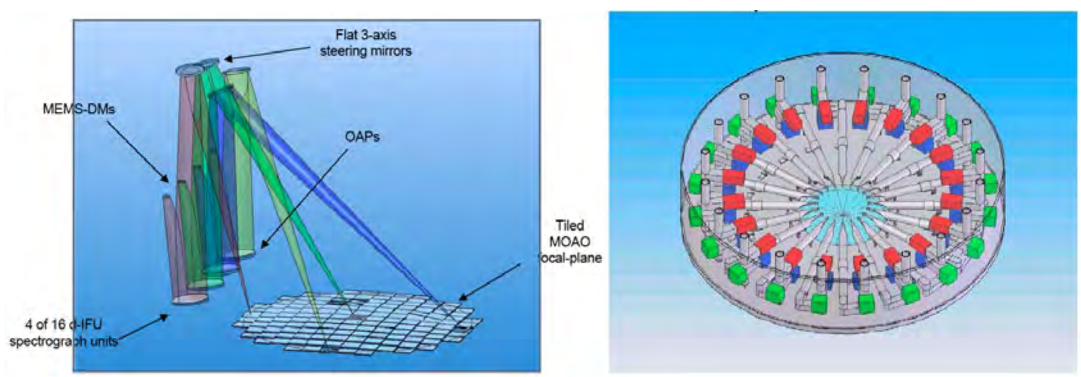


**Fig 8-75: Object selection mechanism concepts for IRMOS: (Left) Tiled focal plane (Caltech) and (Right) Movable probe arms in a "slice of pie" configuration (U. Florida).**

The IRMOS concept proposed by the U. Florida/NRC/HIA team (IRMOS-UF) has two basic subsystems: a MOAO system for adaptive corrections and a science backend for target selection and integral field spectroscopy. These systems reside in two separate vacuum spaces held at two different operating temperatures. The "meatlocker" (~230K) includes the pickoff optics and detectors for the LGS and NGS wavefront sensors, the pickoff optics for the science fields and the deformable mirrors for MOAO corrections. The "deep freeze" (~80K) contains the final re-imaging optics for the MOS pickoffs, the integral field units and the spectrograph optics, mechanisms and detectors. The MOS probe mechanism (**Figure 8-75**) uses 20 independently-controlled/actuated MOS pick-off probe arms. The MOAO woofer-tweeter pair in each arm will consist of a 31-actuator CILAS bimorph mirror and of a 64x64 actuator MEMS DM. Each MOS arm will feed its own spectrograph in the "deep freeze". Each spectrograph will be individually configurable (e.g. to record the same rest-frame spectral range for a sample of objects at different redshifts) and serviceable. Like the Caltech concept, arms can be reconfigured "on-the-fly".

**AO Development**

Both IRMOS concepts rely on the implementation of Multi-Object AO (MOAO). Rather than trying to provide high-order AO corrections over the entire 5′ field, MOAO seeks to provide these corrections only over much smaller fields of view (a few arcseconds) along the IFU lines-of-sight. This is achieved by incorporating a sophisticated AO system into the feed for each IFU. Two key technologies are required for MOAO: high stroke MEMS deformable mirrors and on-sky, open-loop control. On a 30-m telescope, an atmosphere under modest seeing conditions ($r_0$ = 16 cm) would demand a DM surface stroke range of about 10 microns and of the order of ~$60^2$ actuators. Corrections would have to be accurate to 20-40 nm rms with no optical feedback.

These requirements are well beyond the current state of the art, since present technology MEMS DMs have strokes of only 1-2 microns. A variety of "hybrid" architectures have been proposed to off-load some of the wavefront correction to one or several "woofer" deformable mirrors. As indicated in **Table 8-27**, these concepts may reduce the requirement on open-loop wavefront corrections using MEMS to somewhere in the range from 1 to 4 μm. For example, using NFIRAOS as the woofer reduces the required MEMS open-loop wavefront correction to approximately 1 μm over the 2 arcmin diameter FOV. Alternatively, using an adaptive secondary (AM2) as the woofer for MOAO enables a larger FOV, but the requirement for open-loop wavefront correction also increases to about 4 μm due to anisoplanatism. The "N-barrel" designs described in the last two lines of **Table 8-27** could conceivably reduce this requirement to 1-2 μm over a large FOV, at the expense of increased system cost and complexity.

The first key development task for MOAO is to design, fabricate, and test MEMS with ~$64^2$ actuators, increased stroke, and highly repeatable/predicable wavefront correction. CfAO and Gemini Observatory are already funding such an effort to develop a wavefront corrector for the Gemini Planet Image (GPI). Prototype devices will be fabricated and tested during 2007 and 2008. The second key development task is to demonstrate MOAO in the laboratory and on the sky. Work on three such testbeds is already underway at Lick Observatory, the Observatoire de Paris-Meudon, and the University of Victoria. Longer term MOAO projects on 8-10 m class telescopes include the NGAO system at Keck and the FALCON project at ESO. We will remain in contact with all of these projects, with the intention of resuming work on MOAO and IRMOS under the TMT operations.

**Table 8-27: Summary of "Hybrid" MOAO architectures suitable for IRMOS.**

| **Offload wavefront correctors** | **Open-loop correction (μm)** | **MEMS stroke (μm)** | **FOV diameter (arc min)** |
|---|---|---|---|
| None | 10 | 10 | 5 |
| Low-order bimorph DM for each IFU | 10 | 4 | 5 |
| NFIRAOS | 1 | 1 | 2 |
| AM2 | 4 | 4 | 5 |
| "N-barrel" of conventional AO relays | 2 | 2 | N fields, each with ~2 arc min diameter |
| AM2 + "N-barrel" of AO relays with DMs conjugate to a range of ~10 km | 1 | 1 | |

**Development Strategy**

Both teams have estimated that it would take about 10 years to bring a full version of IRMOS on-line at TMT. The technologies (MEMS deformable mirrors, open loop control, etc) required to fulfill these ambitions have also not yet been proven, and the instrument will likely be very expensive. Consequentially, other simpler and cheaper options are also being considered by the TMT SAC, most notably a system with fewer IFUs deployed over the 2 arcmin technical field of NFIRAOS. If the IRMOS is not realizable within, say, 5 years after first light, then a NFIRAOS-based version may be attractive because it is recognized that integral field spectroscopy of several targets simultaneously will enable TMT to reach many of its science goals very effectively. An "IRMOS-

NFIRAOS" system with deployable IFUs could be built with existing technology. When available, MEMS deformable mirrors could be incorporated providing true MOAO capability albeit with only a 2 arcmin field. Thus the IRMOS-NFIRAOS option could serve as a pathfinder towards the true IRMOS requested in the SRD.

#### 8.7.2.4 High Resolution Optical Spectrometer (HROS)

High-resolution optical spectrographs have occupied center stage in recent years thanks to a range of exciting work: the very productive Doppler searches for exoplanets, the measurements of chemical abundances in absorbing intergalactic matter along the lines-of-sight to distant quasars and the surveys of the outer reaches of the Milky Way in search of the most metal-poor stars. HROS is fundamentally a seeing-limited, high-resolution optical spectrometer, although it is recognized that its performance could be enhanced by the use of LTAO (Laser Tomography AO).

The main HROS requirements listed in the TMT Observatory Requirement Document [4] are:

- Wavelength range: 0.31 – 1.0 µm; 0.3 – 1.3 µm (goal)
- Field of view: 10 arcsec
- Slit length: 5 arcsec
- Image quality: ≤ 0.2 arcsec FWHM at detector
- Spatial sampling: < 0.2 arcsec per pixel
- Spectral resolution: R = 50000 (1 arcsec slit) or R ≥ 90000 (image slicer)
- Sensitivity: Must maintain 30m advantage over existing similar instruments
- Stability: Long-term stability of 1 m/s velocity precision over 10 years

TMT feasibility study contracts were awarded to two separate groups with two very different HROS concepts. The University of California – Santa Cruz team led by Steve Vogt is proposing a classical Moderate- to High-Resolution Spectrometer ("MTHR") echelle concept [24, 25, 26] and the University of Colorado team led by Cynthia Froning is proposing a multiplexed 1$^{st}$ order spectrograph concept ("HROS-CU", [27, 28, 29]). Both HROS concepts were reviewed by the same independent expert panel in March 2006 [30, 31]

The MTHR concept builds upon the heritage of the VLT/Ultraviolet and Visual Echelle Spectrograph (UVES) and Keck/ High Resolution Echelle Spectrometer (HIRES) spectrographs as it combines the best advantages from both: the dual-white-pupil/dual-arm configuration of UVES to limit the sizes of the echelle, cross-disperser and camera and a HIRES-style camera to allow for a much larger camera size as the spectrometer is scaled up to match TMT. The footprint of MTHR is 10 × 11 × 4m. Like WFOS, this is not a small instrument, but the UCSC team demonstrated the flexibility of their design by finding a way to actually fit MTHR *inside* one of the TMT Nasmyth platforms. Based on the largest gratings currently available, the echelle would have to be a 3 × 5 mosaic. The large echelle is clearly a challenging element of this design. The gratings will be supported by a 330mm-thick piece of Zerodur, 3.3 meters long and 1 meter wide, and they will be aligned using a Zygo interferometer. The predicted throughput efficiency of MTHR will exceed 20% (~1.5× HIRES and UVES), and this efficiency coupled with the TMT aperture should lead to a 20-40-fold improvement in relative observing speed over existing spectrographs. The MTHR concept also includes an interesting lower resolution mode ("MODRES") in which a large fiber positioner capable of patrolling the full 20′ field of view of TMT would feed MTHR with the light from up to 667 different targets to deliver spectra with a resolution of R=2300-11000.

The University of Colorado team took a completely different approach with their HROS concept. HROS-CU uses an array of high-performance (>95%) dichroic mirrors to direct light into 32 narrow-band first-order spectrographs that covers the wavelength range 310-1100 nm at R=100,000 in a single integration. Each channel will go through five dichroic reflections. Although all spectrographs will be identical, gratings and detectors will be optimized at each wavelength to maximize performance. HROS-CU will have an array of 5-7 one square arcsec IFUs to allow sampling multiple points of an extended object and/or to provide well-separated sky channels. The dichroic tree will need to be shielded from ambient thermal fluctuations and from acoustical vibrations. Thermal gradients of 0.1°C across the dichroic optical mounts and motions induced by vibrations with amplitudes larger than 0.1 arcsecond rms could affect instrument performance. The collimator, grating and camera optics in each channel are greatly simplified by the narrow wavelength range over which they have to operate. As an example, there is no longer a need for the camera to be achromatic. The total footprint of the current HROS-CU design is 9 ×10 × 4.5 meters, but this footprint could be reduced by more efficient packing.

#### 8.7.2.5 Near-Infrared Echelle Spectrometer (NIRES)

NIRES [32] is a straightforward instrument that fits behind NFIRAOS. In fact, NIRES could effectively be a clone of existing or planned diffraction-limited NIR spectrographs (e.g. Keck NIRSPEC, [33]). The NIRES feasibility study clearly identifies the enormous potential of such an instrument on TMT for gamma-ray bursts and precision radial velocities. It was reviewed by an independent expert panel in March 2006 [12].

The main NIRES requirements listed in the TMT Observatory Requirement Document [4] are:

- Wavelength range: simultaneous 1-2.4µm
- Image quality: Should not degrade the image quality delivered by NFIRAOS by more than 10%
- Slit length: 2 arcsec; spatial sampling: Nyquist sampled (l/2D)
- Spatial sampling: Nyquist-sampled (0.004 arcsec / pixel)
- Spectral resolution: 20,000<R<100,000
- Stability: Should be efficient to enable Doppler searches for exoplanets

### 8.7.3 First Decade Facility AO

#### 8.7.3.1 Overview

Adaptive optics systems are either required or highly desirable for virtually the entire suite of SRD science instruments. At the same time, it must be understood that some of these AO systems will not be immediately available following TMT first light for reasons of technical readiness and/or cost. It is therefore useful to define a set of initial and upgraded AO modes for each TMT scientific capability, as summarized in **Table 8-28** below. The three initial modes consist of (i) the facility LGS MCAO system NFIRAOS, already described in detail in **Section 8.5**; (ii) possibly a laser tomography AO (LTAO) system optimized for mid-IR science instruments such as MIRES, utilizing similar (but lower order) conventional AO components, and (iii) seeing-limited operation without AO, for those instruments and observations where AO is useful but not genuinely required.

The upgraded AO modes and capabilities can similarly be divided into three categories. These include: (i) an adaptive secondary mirror (AM2), (ii) multi-object AO (MOAO) for IRMOS as previously discussed in **Section 8.7.2.3**, and (iii) extremely high-order AO components and systems for an upgraded version of NFIRAOS and ExAO. Each of these options provides significant performance improvements for one or more TMT science instruments.

#### 8.7.3.2 Adaptive Secondary Mirror

An adaptive secondary mirror is potentially of great interest to TMT, since it provides a first stage of wavefront correction for all science instruments on both Nasmyth platforms with no additional warm surfaces, windows or dichroics. This enables some degree of atmospheric turbulence compensation at all TMT wavelengths over the full telescope field-of-view with no penalties in optical throughput, background emissivity, or small-angle scatter. Specific applications that have been proposed include a wide field-of-view, ground-layer AO (GLAO) system for WFOS, a narrow field-of-view AO system for HROS,[27] and a mid-IR-optimized AO system for MIRES. AM2 could improve observing efficiencies by factors of 1.2 to 1.5 for these three instruments, factors which are not insignificant given the demands which will be placed upon TMT observing time.

Additional benefits from AM2 include reducing the dimensions of large spectrometers (e.g. HROS) by reducing the required slit widths, correcting telescope windshake, and serving as “woofer” to relax actuator stroke requirements on very high order DMs (e.g. ~120$^2$ actuators) for future AO systems such as PFI or a NFIRAOS upgrade.

[27] Such a system would otherwise be impractical, since a conventional AO relay with 4-5 surfaces would cause unacceptable throughput losses in the near UV.

**Table 8-28: TMT science capabilities and supporting AO modes.**

| Science Capability (Instrument) | Initial AO Mode | Upgraded AO Mode |
|---|---|---|
| Narrow field, NIR spectroscopy and imaging (IRIS, NIRES, WIRC) | Multi-Conjugate AO (MCAO); NFIRAOS | MCAO with very high-order components; NFIRAOS upgrade |
| Moderate field, NIR multi-object spectroscopy (IRMS, IRMOS) | 2' FOV behind NFIRAOS | Multi-Object AO (MOAO) with open-loop MEMS |
| Narrow field, MIR spectroscopy and imaging (MIRES) | Laser Tomography AO (LTAO) with standard DM | LTAO with an adaptive secondary mirror (AM2) |
| High resolution optical spectroscopy (HROS) | None (seeing-limited observations) | LTAO with AM2 |
| Wide field optical spectroscopy (WFOS) | None (seeing-limited observations) | Ground-Layer AO (GLAO) with AM2 |
| High contrast imaging and spectroscopy (PFI) | None at TMT first light | Extreme AO (ExAO) with very high-order components |

**Table 8-29** summarizes the top-level requirements for AM2 as developed during the TMT conceptual design phase. Of the three possible applications listed above, diffraction-limited AO at mid IR wavelengths for MIRES[28] places the most stringent requirements on the mirror's temporal control bandwidth and its order of wavefront correction. Additionally, the use of AM2 for seeing-limited observation imposes important requirements upon AM2 figure quality and its stability in the absence of optical feedback from high-order wavefront sensors.

**Table 8-29: AM2 requirements summary.**

| Parameter | Requirement |
|---|---|
| -3dB control bandwidth, Hz | 10 (goal 15) |
| Number of Zernike modes corrected | 250 (goal 400) |
| Peak-to-valley higher order stroke, μm | 10 |
| Peak-to-valley tip/tilt stroke, μm | 40 (goal 100) at mirror edge |
| RMS figure quality, nm | 20 (goal 10) |
| Maximum mass, kg | 6000 (including electronics) |
| Maximum power dissipation, kW | 4 |

**Figure 8-76** illustrates the AM2 design concept developed by SAGEM during the TMT Conceptual Design Phase in response to the above requirements.[29] Key features of the design include the 4-5 mm thick, segmented Zerodur facesheet, a light-weighted reference body fabricated from silicon carbide or possibly ULE, and a reduced (i.e. leveraged) voice coil actuator design. The order of correction is approximately 1800 actuators with a pitch of 7-8 cm. The mirror design is, therefore, in some sense "less adaptive" than current concepts for 8-10 m class secondary mirrors, since the values for facesheet thickness and inter-actuator pitch are both larger by approximately a factor of two. This approach serves to reduce actuator costs and facesheet

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[28] Defined as a Strehl ratio of 0.9 (goal 0.95) at $\lambda$=7.0 μm under nominal atmospheric conditions.
[29] This design was developed for the original Gregorian optical prescription for TMT, and has not been updated for the new Ritchey-Chrétien design.

fabrication risks, while still meeting all of our requirements for control bandwidth, atmospheric turbulence fitting error, safe actuator stroke, and the RMS figure error for gravity-induced actuator "quilting." The reduced actuator design provides adequate force to meet the stroke requirement for this facesheet thickness with very acceptable power dissipation.

Remaining development issues for an AM2 design include (i) developing designs for the lightweighted reference body and the lateral mirror support system which meet the TMT requirements on facesheet stability and figure quality with a variable gravity orientation, (ii) demonstrating the actuator, facesheet, and reference body designs in a subscale prototype, and (iii) producing the final delivered system at an acceptable cost. At this point, further work on an AM2 has been dropped from the TMT construction budget on account of the estimated cost and the limitations of our overall budget. We intend to remain informed of ongoing work on large adaptive mirrors at ESO and other observatories, and we will restart the AM2 development effort under TMT operations funding as directed by SAC priorities, technical progress, and the available budget. We retain the goal of enabling an AM2 early in the overall lifetime of the observatory.

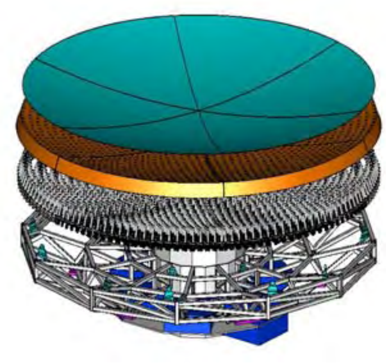

**Fig 8-76: SAGEM AM2 design concept.**

#### 8.7.3.3 NFIRAOS Upgrade

Two science instruments from the TMT SRD suite will require particularly high order wavefront sensors and correctors. These instruments are the Planet Formation Imager (PFI, described in **Section 8.7.2.1**), and an upgraded version of NFIRAOS that would achieve the SRD requirements for an RMS wavefront error of about 130-135 nm over a 30 arcsec FOV and a Strehl ratio of 0.5 at $\lambda$=1 $\mu$m. The required order of AO correction for both systems is approximately $120^2$, but their design options and technical readiness issues are significantly different.

**Table 8-30** outlines the critical AO components for the NFIRAOS upgrade. The proposed concept for this upgrade is to replace the baseline NFIRAOS DM ($61^2$ actuators, 5 mm pitch) with a higher-order mirror ($121^2$ actuators, 2.5 mm pitch), while retaining the pupil diameter and overall optical design of the original system. The first generation polar coordinate CCD array would be similarly upgraded to $120^2$ subapertures. Guidestar laser power requirements would normally be expected to scale by a factor of approximately 4 to compensate for the reduction in WFS subaperture area, but this can be reduced to approximately a factor of two if pulsed lasers are used to eliminate guidestar elongation. The resulting laser power requirement is then roughly 6x50W=300W for the NFIRAOS asterism of 6 guidestars; it is possible that this requirement may be further relaxed by some combination of reduced detector read noise, so-called "uplink AO" to sharpen the LGS that is projected onto the sky, and/or rebalancing the NFIRAOS error budget. Finally, the RTC processing requirements will also grow with the increased number of DM actuators and WFS subapertures.

**Table 8-30** also indicates some of the ongoing R & D projects that are closely related to these four classes of AO capability for the NFIRAOS upgrade. Some of this progress is encouraging, but further iterations of development and prototyping will clearly be necessary over the next 5-10 years to meet these goals.

### 8.7.4 Instrument Development Office (IDO)

An instrumentation team will be built up in the early phases of the construction project to support the development and commissioning of TMT AO systems and instruments, to establish detailed interfaces and requirements, and to oversee work packages and contracts for early light instrumentation. Although the team will be composed of a relatively small (~10) group of engineers, they will be focused on instrumentation, and they will not have other responsibilities for aspects of construction or routine operations. NFIRAOS and the early light science instruments will be produced by the TMT partners in close coordination with TMT. Successive instruments will be procured through a competitive process, open to the broader astronomical community. IDO staff will begin to initiate the development of the instrumentation described earlier in this section soon after construction of the early light suite begins, and eventually they will be fully occupied with the ongoing instrumentation activity. Thus the funding for this group, and all instruments beyond the early light suite, will come from a post-construction budget. The IDO will play a critical role in maintaining continuity and momentum following the early-light instrumentation effort.

Detailed analyses of the personnel required for the IDO was prepared for Cost Review, as well as a straw man plan of how the instruments and AO systems might be developed [34, 35].

**Table 8-30: Critical AO capability for the NFIRAOS upgrade.**

| Component | Key Requirements | Design Options | Ongoing Development Activities |
|---|---|---|---|
| Deformable Mirrors | $121^2$ actuators 2.5 mm pitch | One- and two-d actuator modules | Xinetics photonics modules of $7^2$ actuators (currently integrated into $42^2$ DMs) |
| LGS WFS detectors | $120^2$ subapertures | AODP polar coordinate CCD | Current design for $60^2$ subapertures may be scalable |
| RTC Processors | Order $120^2$ MCAO wavefront control at 800 Hz | PCG algorithms, FPGA and DSP processors | Feasibility study for the order $60^2$ NFIRAOS baseline |
| Guidestar lasers | Pulsed lasers 40-50 W per LGS | SFG using solid-state or fiber lasers | AODP projects at LLNL and LMCT |

The precise size and composition of this group will depend on the number and types of instruments being developed (i.e. on the size and details of the development budget). In order to deliver the complete instrument suite (including AO capability) in the first decade, considerable oversight will be required since about one instrument or major AO capability should be ready for commissioning every year. To provide appropriate leadership and systems engineering expertise for the contracts and work packages, to fully participate in reviews and acceptance tests, and to lead the commissioning activity at the telescope a staff of at least 10 will be required: IDO manager (astronomer/instrumentalist), AO group leader/engineer, Instrumentation group leader/engineer, Instrumentation Systems Engineer and 6 engineers with expertise in lasers, optics, mechanics, controls, software and cryogenics. This group will be located in North America, most likely at a partner facility, and will be supported by an administrative assistant.

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# 9 Assembly, Integration and Verification

## *9.1 AIV Concepts & Strategy*

### 9.1.1 Definitions

Assembly, Integration and Verification (AIV) is a TMT Construction sub-phase activity that occurs on-site. In particular, the focus is on activity at the site summit.

By fiat, AIV is defined to begin when telescope erection begins, i.e. after site preparation and enclosure erection have proceeded to the point where telescope erection can begin.

In the abstract, AIV is the process of re-assembling (if necessary) all TMT subsystems delivered to the TMT site, integrating them into the growing system (observatory) and verifying their performance – both individually and as an ensemble. In reality, it is well known from experience that the AIV process is more organic than that.

The fundamental AIV product is a completely integrated TMT system (observatory) that meets a defined sub-set of the high-level performance requirements specified in the Observatory Requirements Document (ORD). Additional tuning will be required during the post-construction commissioning phase (see **Section 10.1.2**).

The end of AIV is defined as the delivery of an integrated and functioning system that includes a fully phased M1 with all segments installed and fully functioning M2, M3, and APS subsystems.

At that time, IRIS, WFOS, and the major AO systems (i.e. LGSF and NFIRAOS) will have been assembled and integrated into the observatory, but will not be completely verified. The completion of IRMS assembly, integration, and verification is expected to occur later. Verification completion for these subsystems will be a post-Construction activity (see **Section 10.1.2**).

### 9.1.2 System level activities

A high-level AIV Plan will be written and contain:

- An AIV overview
- The high-level, subsystem integration sequence
- A summary of resources and infrastructure expected to be provided by a central facilities and technical support group
- A performance verification plan tied to specific AIV milestones. For each such milestone, the following will be provided:
    - List of Level-1 performance requirements to verify
    - Description of the validation procedures for each requirement
    - Resources needed to complete tests

A preliminary draft of this plan was implicitly developed during preparations for the 2006 September TMT Cost Review. A more formal preliminary draft of this plan is a TMT PDR deliverable. A final version is a TMT FDR deliverable.

The TMT System Engineer will write this plan in coordination with the various technical department heads (telescope, AO, instrumentation, Design Operations) and assisted by the TMT project schedulers.

The TMT Project and Observatory Scientists will review the plan (especially the proposed performance verification procedures) to assure that the overall technical and operational goals have been addressed.

Based on the AIV Plan, the TMT Project Manager in coordination with his department heads will create an AIV activity timeline, staffing plan, and budget. In practice, such planning is a natural and necessary byproduct of on-going TMT Project planning.

An AIV Manager will coordinate all on-site AIV activity. This person reports to the TMT Project Manager and has the authority to authorize and/or schedule all work on-site. A daily coordination meeting led by the AIV Manager and attended by the leaders of all on-site activity is anticipated.

During the actual AIV phase, the TMT System Engineering team will provide centralized system-level quality assurance and performance verification checks. As needed, the System Engineering team will assist subsystem AIV teams.

During the last 24 months of TMT AIV, a nascent science operations team will be built-up on site and participate in AIV activities (as discussed in more detail below).

### 9.1.3 Subsystem level activities

Each major TMT subsystem Construction team (i.e. telescope, AO, instrumentation, observatory software) will be responsible for completing AIV for their deliverables and must plan AIV staffing accordingly. Construction phase planning and budgeting must include all technical resources (personnel and equipment) needed to complete the required subsystem AIV.

For planning purposes, all subsystem teams can assume that a defined set of support services will be provided from a central pool. A preliminary list of these services is available. As part of their detailed planning, each subsystem team should provide a list of additional requested central services so that this list can be revised.

For planning purposes, all subsystem teams may assume support from the nascent science operations team described in more detail below.

As part of their overall AIV work, each subsystem team must also execute the following tasks in preparation for observatory operations:

- Verification (or development) of all maintenance procedures
- Verification (or development) of start-up and shut-down procedures under normal and emergency (i.e. power failure) situations
- Verification of all safety systems, especially where human death or injury are possible (in coordination with the TMT Safety Manager).
- Verification of safe system operation under computer control.
- Establishment of site tools and spare parts list(s) (location and quantity of each)
- Validation of delivered documentation (e.g. drawings, maintenance plans) relative to the as-built, as-delivered subsystems
- As appropriate, receive training from vendors; validate and/or develop training documents
- Create initial maintenance work order database entries
- Operate and maintain technical subsystems until AIV has been completed

### 9.1.4 Nascent science operations team

For the purposes of: (1) assisting in system testing and verification and (2) preparing for science operations, a nascent TMT Observatory Science Operations team shall be formed during the last 24 months of TMT AIV (see **Table 9-1**).

### 9.1.5 Facilities operations & maintenance during AIV

As described in **Section 10.1.1**, a Facilities Operations Group will be formed during the Early Operations phase. This group will be responsible for the operation and maintenance of all completed non-technical services and systems (e.g. on-site accommodations, roads/grounds/buildings maintenance, local/last-minute procurement, warehouse management).

Operation and maintenance of major technical subsystems (e.g. telescope, AO, instrumentation) shall remain the responsibility of the subsystem delivery teams until AIV is completed.

### 9.1.6 AIV personnel management

As part of their planning, each subsystem team will assume whatever personnel mix is best suited to successful completion of their tasks (subject to the review and approval of the TMT Project Manager).

Fundamentally, current TMT operations planning assumes that personnel who participate in AIV will become the observatory staff when AIV is completed. Hence, relevant Construction phase personnel will be recruited and hired under the condition that they transition to the operations staff at the completion of AIV.

For skill mix and attrition reasons, it is anticipated that additional personnel will be recruited during the last 12 months of AIV activity to achieve the staffing level and skill mix needed for operations.

### *9.2 Integration Flow*

**Fig. 9-1** is the integration flow diagram indicating the sequence as the various subsystems become part of the observatory system. The diagram is not a schedule; it does not show the extent of time the assembly and integration of a given subsystem requires. Rather, it illustrates the logic of the integration: for the integration and test of a given subsystem, all the other subsystems above it need to be fully operational and available.

**Table 9-1: Nascent science operations team.**

| Title | Responsibilities |
|---|---|
| SCO Head | • Recruit and manage SCO personnel<br>• Coordinate planning with AIV Manager and System Engineer<br>• Lead development of detailed SCO procedures |
| System Scientists (2) | • Participate in system testing & verification<br>• Become ops staff system experts |
| Instrument Scientists (2) | • Follow instruments from pre-shipment review into steady-state operations<br>• Become ops staff instrument experts |
| AO Scientists (2) | • Follow AO systems from pre-shipment review into steady-state operations<br>• Become ops staff AO experts |
| System Operators (2) | • Learn and operate TMT system (telescope, AO, instrument subsystems)<br>• Support AIV activity, especially at night |

AIV is a highly parallel process. In fact, one of the major challenges of AIV is managing access to the skeleton observatory on the mountain. Various teams are expected to be working on the observatory at same time, assembling their subsystems and then functionally integrating them into the overall system. Although an on-site AIV Manager with broad authority, and daily coordination, are essential for a successful AIV phase, a detailed schedule reflecting the parallel nature of the process is equally important.

**Fig. 9-1** indicates the point in the integration flow where a given subsystem is fully assembled and integrated within the overall system, with a few exceptions. The M1 Optical and M1 Control Systems are broken into 3 phases. Phase A encompasses the first 120 segments with images stacked by the Prime Focus Camera, while in Phase B they are also co-phased by the APS. Phase C ends with a fully phased, 492 segment primary mirror. The Telescope Control System is also phased in the diagram: Phase I only supports M1 Phase A activities, while Phase II indicates the fully operational system.

The telescope structure provides the mechanical skeleton and utility services to the other subsystems that are attached. The first subsystem to be fully operational is the Observatory Safety System to ensure protection of both personnel and equipment during assembly. The first major milestone is the integration of the Mount Control System, i.e. the capability of moving the telescope structure in azimuth and elevation, in order to facilitate the installation of segments and mirrors. Another prerequisite to integrating the optical surfaces is the availability of the optical test and alignment systems.

In the last phase, the assembly and integration of the facility AO system and early light instruments are running parallel to the work on the telescope, in order to be ready to start their commissioning as soon as the entire primary mirror is fully phased.

**Fig 9-1** reflects AIV, which is a construction phase activity, as opposed to commissioning of the various subsystems and the overall system, which belongs to operations.

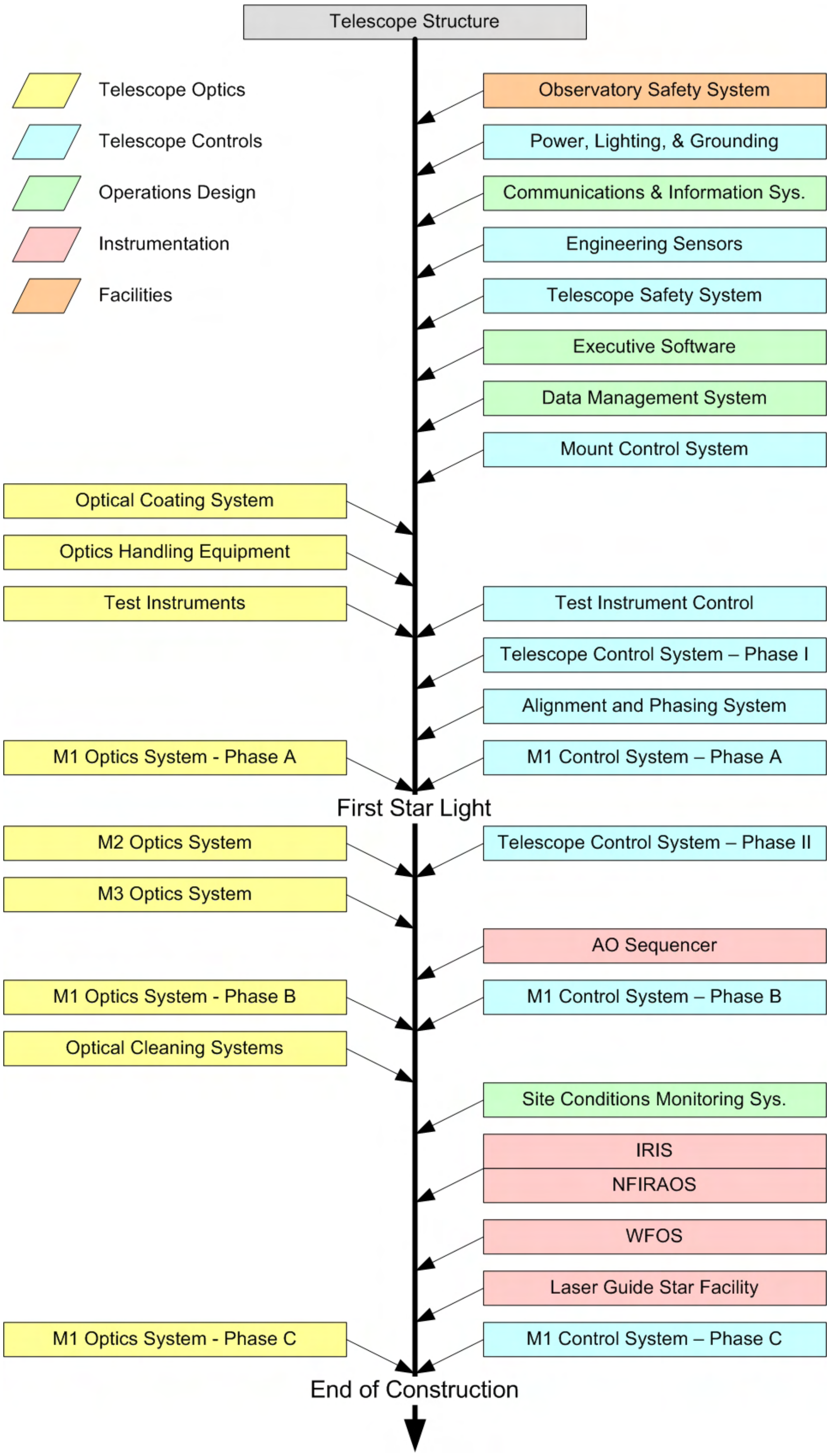



**Fig 9-1: Subsystem integration sequence in the AIV phase of the project.**

## *9.3 Obervatory Erection Sequence*

### 9.3.1 Enclosure

The enclosure erection sequence is based around a central falsework structure that provides stability to the enclosure during all phases of the erection sequence. The major lifting is done with a 275 tonne crawler crane that is positioned around the outside of the enclosure base. Additional mobile cranes are located at the summit and staging site at the base of the mountain. The enclosure shell is assembled into large modules in jigs at the staging site allowing the majority of the structural assembly to be carried out near ground level and at lower elevation, therefore improving safety and efficiency. The shell modules are then transported to the summit site and erected into their final position. The alignment of the mechanical interfaces is a critical aspect of the erection. During fabrication, steps can be taken to improve the efficiency and accuracy of the field alignment, including trial assembly and adjustment of ring girders to very tight tolerances, and painting all structural components white prior to shipping to minimize thermal distortion.

The following figures illustrate the erection sequence:

- **Figure 9-2**: The falsework tower is erected. The azimuth bogies and lateral guides are installed and rough aligned. The azimuth ring girder and rail are erected and rigidly supported by temporary posts on the fixed base structure so that the bogies remain unloaded until the entire structure is erected.
- **Figure 9-3** and **Figure 9-4**: The enclosure shell modules are assembled in jigs at the staging site and then trucked to the summit. The ventilation structure modules (**Figure 9-3**) and base shell modules (**Figure 9-4**) are erected and supported on the falsework.

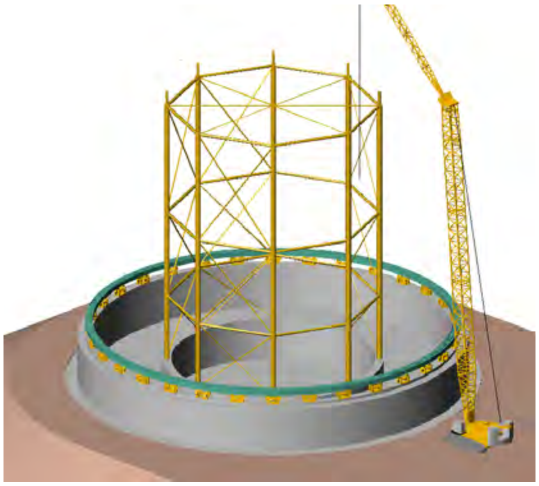


**Fig 9-2: Falsework and azimuth ring erected.**

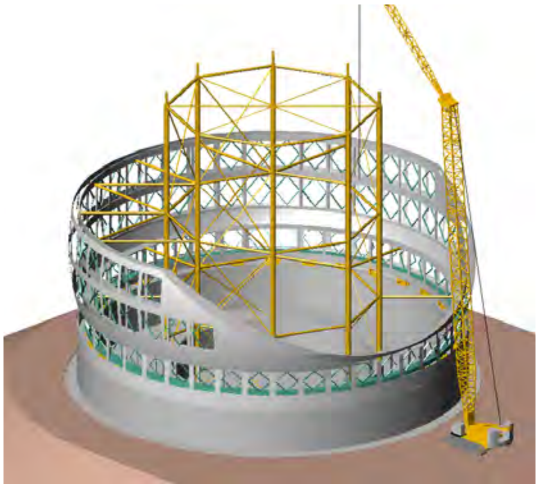


**Fig 9-3: Ventilation structure erected.**

- **Figure 9-5**: The base ring girder is erected and aligned, followed by the installation and rough alignment of the cap bogies. The cap ring girder and rail is then erected and rigidly secured to the base ring girder so that the cap bogies remain unloaded during the erection.
- **Figure 9-6**: The shutter ring girder and bogies are erected and secured to the cap ring girder. The shutter structure is then erected on top of the falsework tower.
- **Figure 9-7**: The aperture ring girder is assembled on top of the falsework tower. The pre-assembled cap shell modules are erected in two levels, with the falsework tower providing intermediate support.

Following erection of all structural components, the final alignment of the structure is made, and the enclosure shell is welded. The structural load is then transferred off of the falsework and onto the bogies, and the final alignment of the bogies is made and the falsework is taken down. At this point the erection of the telescope structure can begin. The remaining major enclosure construction tasks include insulation and electrical installation and acceptance testing.

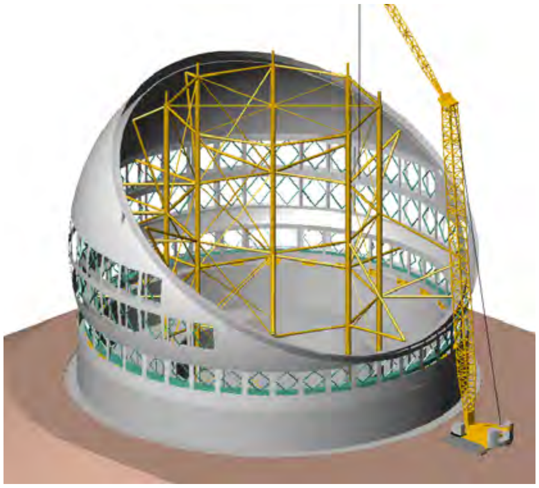


Fig 9-4: Base shell erected.

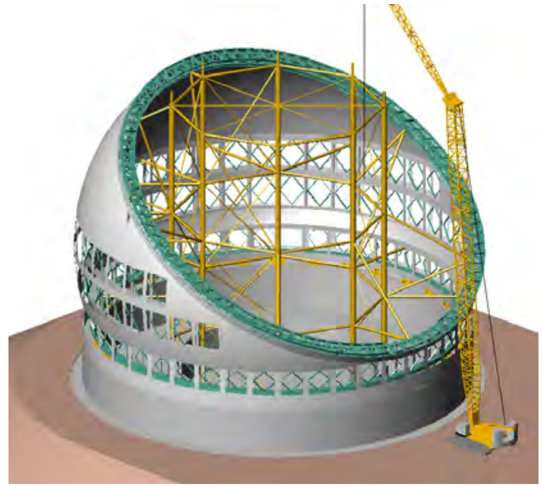


Fig 9-5: Base and cap ring girders erected.

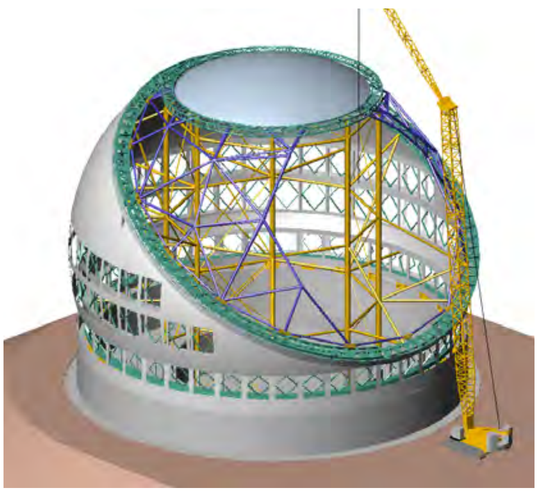


Fig 9-6: Shutter erected.

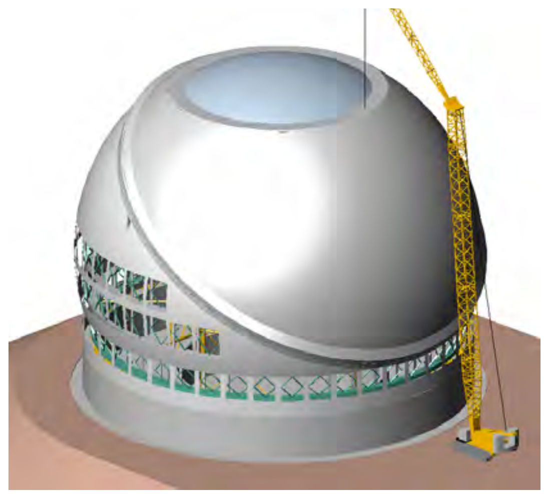


Fig 9-7: Cap shell erected.

### 9.3.2 Telescope

The erection of the telescope structure begins after the enclosure shell is closed and the interior falsework supporting the enclosure is dismantled and removed. An extensive system of falsework is used to provide stability to the many pieces that make up the structural frame of the telescope during erection. Additionally, the falsework is used to elevate the structure so that hydrostatic bearings on the azimuth and elevation axes can be installed after the structural frame is complete. Due to limited clearances between the telescope and enclosure, many of the large structural components cannot be installed using a mobile crane within the enclosure. Therefore, this lifting capacity is provided by a bridge crane whose support structure also serves as falsework for telescope components. Installation of smaller telescope components and falsework is done using a rough terrain crane inside the enclosure. Additional lifting capability is supplied by a 275 tonne lattice boom crawler crane positioned outside the enclosure base, which accesses the telescope through the shutter, as well as the enclosure crane. The following figures illustrate the erection sequence:

- **Figure 9-8**: The azimuth track consists of steel box sections, which are fastened to the concrete pier by embedded anchor rods. The sections are installed over the rods, connected, leveled, and grouted in place. A protective cover is installed over the track. The pintle support is a cylindrical steel weldment, which is installed on anchor rods embedded in the pier. The pintle support is aligned and grouted in place. Large components of the azimuth cable carrier are brought into the central pier area before access is restricted by the construction of the azimuth structure.

- **Figure 9-9**: Falsework is installed to support the azimuth structure above the azimuth rail, and to temporarily support individual pieces of the central azimuth structure before they form a stable frame. A bridge crane is installed on the observatory floor. The bridge crane will unload telescope components directly off trucks, which are driven into the enclosure fixed base through an opening aligned with the crane runway axis. The bridge crane has a hoist running on a trolley along the bridge. An articulating boom crane on the bridge provides additional lifting capacity.

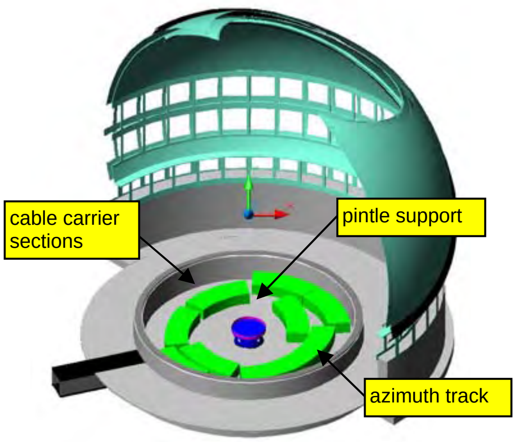



Fig 9-8: Azimuth track installed.

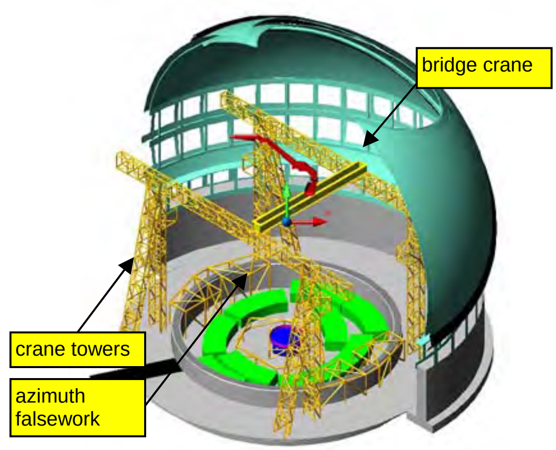



Fig 9-9: Falsework erected.

- **Figure 9-10**: Components of the azimuth cradles are lifted into place on the azimuth falsework and connected together.
- **Figure 9-11**: Components of the azimuth central structure are installed on the azimuth falsework. The cradles are aligned and the central structure is connected to the cradles.

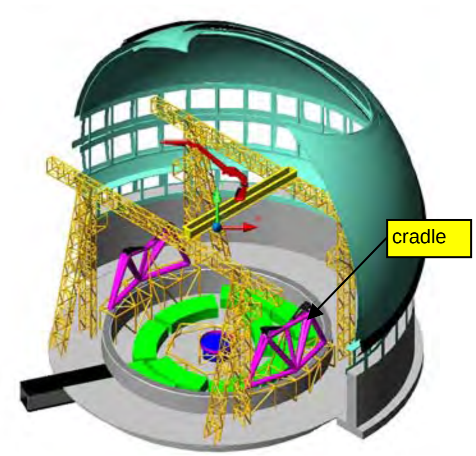



Fig 9-10: Azimuth cradles installed.

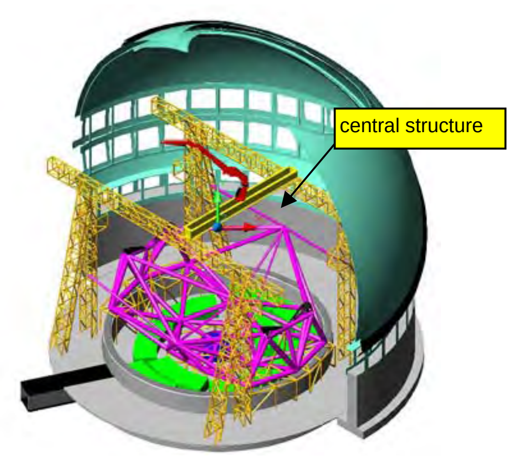
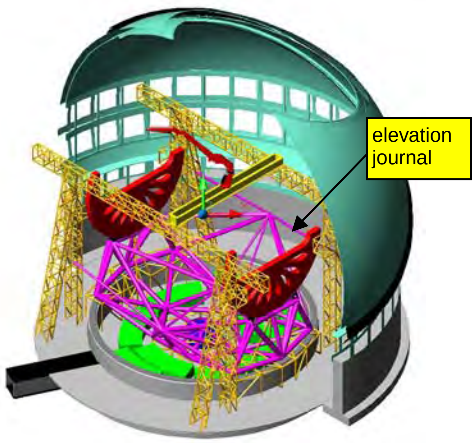



Fig 9-11: Azimuth central structure erected.

- **Figure 9-12**: Components of the elevation journals are lifted into place on falsework supported on the azimuth structure. The bridge crane towers provide additional support to the journals. The journals' components are drawn together, then aligned and bolted to reestablish the complete machined journal surface.
- **Figure 9-13**: M1 cell support structure is positioned on falsework supported on the azimuth structure and connected together. The azimuth journals are accurately aligned and the cell support structure is connected to the journals. The M1 cell structure is lifted into place as large (16x6 meter) rafts, which are temporarily connected to the M1 cell support structure. The M3 support structure is installed on the M1 cell support structure.



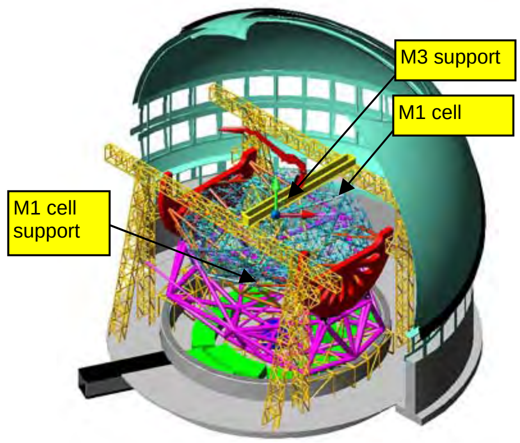
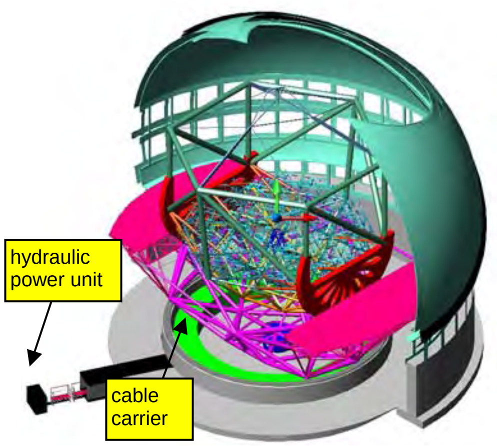




**Fig 9-12: Elevation journals installed.**

**Fig 9-13: M1 mirror cell installed.**

- **Figure 9-14**:  The Nasmyth platforms are installed. Falsework is used to temporarily support the components of the platform before they are connected into a stable frame.
- **Figure 9-15**:  The bridge crane is dismantled using a combination of a lattice boom crawler crane outside the enclosure, the enclosure crane, and a rough terrain crane inside the enclosure. The components of the M2 support structure are installed with the crawler crane and enclosure crane. Temporary falsework under the M1 cell support structure is removed, the elevation structure is aligned and the M1 cell connections are completed. Members of the M2 support are tensioned.
- **Figure 9-16**:  The hydrostatic bearings are installed, and the elevation and azimuth structures are lowered on to the bearings. The hydraulic power unit and plumbing to the telescope are installed. The azimuth falsework is removed. The drives, locks, hard stops, shock absorbers, limit switches and seismic restraints are installed and aligned. Azimuth and elevation cable carriers are assembled and aligned with a partial load of cables, sufficient to operate the drive system. Covers are installed over the azimuth track.
- **Figure 9-17**: M1 segment handling cranes are installed using the enclosure crane and commissioned. The segment handling cranes are used to install the M1 dummy masses. Laser enclosure dummy masses are installed using a crawler crane from outside the enclosure.



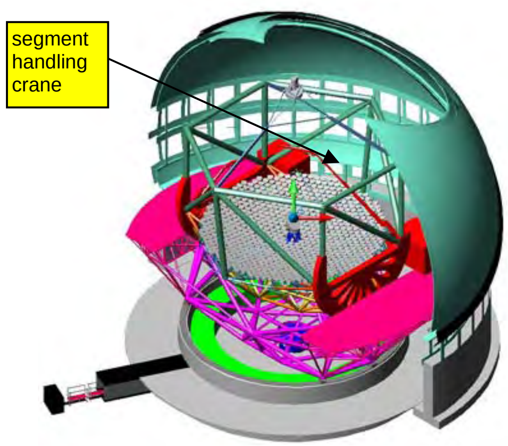




**Fig 9-14: Mechanical systems installed.**

**Fig 9-15: Dummy masses installed.**

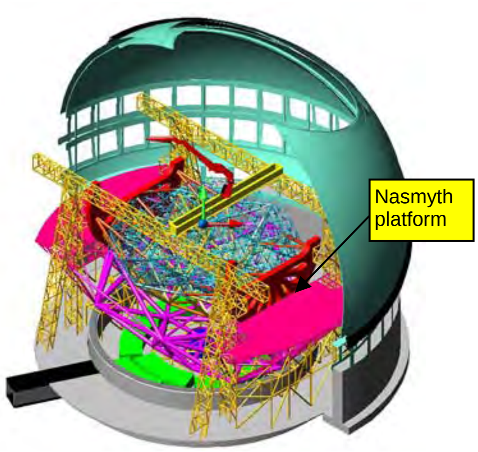



Fig 9-16: Nasmyth platforms installed.

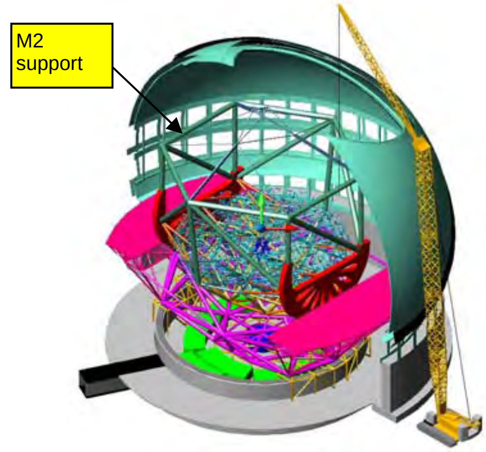



Fig 9-17: M2 support components installed.

Following installation of the telescope structural and mechanical components, commissioning of the drive systems commences. The oil supply system for the hydrostatic bearings is flushed and tested. A static load test is conducted to check the fluid connections and basic operation of the hydrostatic bearings without telescope motion. Static tests are conducted on the braking systems to verify control and initial alignment. The azimuth mount system is surveyed to establish runouts and clearances for drives, brakes, encoders and hard stops. The elevation structure is coarsely balanced and the M2 and M3 dummy masses are installed. Next the elevation and azimuth drive systems are tested. Utility services are installed on the telescope and the telescope is ready for acceptance testing. Testing includes verification of dimensions at critical interfaces between the telescope structure and other parts of the telescope and enclosure, mount control system functional and performance tests, and a test of the utility system.

### 9.3.3 Instruments

NFIRAOS, IRIS, and WFOS will be integrated and tested on the Nasmyth Platforms at the same time that the primary mirror optics are being installed. NFIRAOS, with IRIS installed on its bottom port, will be installed on one platform, while WFOS is installed on the other. This will enable science commissioning of AO and seeing limited capabilities to occur in the same time frame as the first-light-all-segments-phased milestone. IRMS, which will be mounted on the side port of NFIRAOS, will be commissioned after IRIS. The early light instrumentation will be built at TMT partner institutions and extensively tested before shipment to the observatory site. An important part of this process will be the integration and testing of IRIS mounted on NFIRAOS at a partner site before shipment to the observatory.

Since these systems are quite large, they will have to be disassembled into sub-units before shipment. These units will be hoisted to an instrument laydown area on the Nasmyth platform where they will either be partially reassembled or lifted directly into the appropriate location. If required, a portable clean tent will be erected over all or some of the instrument. For example, it is currently envisaged that NFIRAOS will be shipped in ~15 subunits that will be reassembled into larger units before being built up into the finished instrument. Similarly, after reassembly on the platform, IRIS will be moved under and lifted up to the bottom port of NFIRAOS. IRMS may be sufficiently small that it can be shipped as a unit and mounted directly onto the side port of NFIRAOS. WFOS will be composed of very large units or subunits and will have to be assembled on a laydown area on the platform, and then lifted into place to form the finished instrument.

The LGSF will also be built and tested at a partner institution before it is disassembled and shipped to the observatory site. At the summit, the laser service enclosure (LSE) will be reassembled in its final location on the telescope elevation journal, after which it will be populated with its 3 laser systems, their associated electronics and cooling systems, the air filtration system, and the laser switchyard. The laser launch telescope, asterism generator, and LGSF diagnostics bench will be partially reassembled and then hoisted into their locations behind the TMT secondary mirror. The remaining, relatively small, components of the beam transfer optics will be reassembled and then mounted at their locations on the telescope truss.

Clearly, the integration schedules for the telescope and the LGSF must be properly sequenced so that the latter is ready for testing as soon as possible following telescope first light.

# 10 Observatory Operations

Although TMT will be a very complex machine running on a remote mountain summit, decades of operational experience with other ground-based astronomical observatories provide a firm foundation for operational planning. In particular, TMT Project team members have direct operational experience with the Gemini, Keck, and ESO Very Large Telescope observatories, among the most complex ground-based observatories in operation today.

High-level operational concepts were presented in **Chapter 5**. Chapter 10 has two parts: a discussion of the transition from the construction period to steady-state operations and a high-level summary of the current TMT operations plan. Further details are available in such supporting documents as the *Operations Concept Document* and the *Operations Plan*. Estimated annual operations costs are summarized in **Section 12.8**.

## *10.1 Operational phases and the transition from construction*

### 10.1.1 Early operations: facility operations start-up

As TMT construction proceeds, the observatory itself as well as the infrastructure needed to support it is completed in stages. At each stage, a well-defined transition from a construction team (often an external contractor) to an operations and maintenance team must occur.

This transition process begins with the basic civil works and non-technical infrastructure (e.g. roads, grounds, and buildings). As time goes on, operations and maintenance responsibilities grow to include more technical facilities like power generation, communications, and IT systems. Furthermore, various goods and services (i.e. water, diesel fuel, housekeeping & catering) must be purchased – the required quantity of each item ramps up with time. Eventually, integration of the major technical components of TMT is completed and a trained team capable of operating and maintaining the entire TMT physical plant must be in place. This team is supported by an administration group based in headquarters offices located in the most appropriate local governmental jurisdiction.

The initial operations ramp-up phase begins roughly 30 months before the completion of AIV. It starts with a small facilities operations team. By the time AIV is completed, all facility and technical operations personnel and services are in place along with most of the science operations team, all of who are supported by an appropriate level of administrative support.

One key assumption is that engineering and technical staff destined for operational roles will be hired and trained during the AIV phase. Hence, many construction phase personnel will be recruited and hired under the condition that they will participate in TMT AIV on-site and then become part of the TMT operations staff. Naturally, some positions will have to be filled independently of the AIV effort due to unplanned staff departures and the need to achieve the proper personnel skill mix.

During this period, the TMT Project Manager retains overall responsibility for all on-site activity. On a case-by-case basis, on-site activity is either charged to the construction or (early) operations budget.

### 10.1.2 Early operations: science operations start-up

When AIV is declared complete, the TMT Director assumes overall authority and responsibility for all TMT activity in recognition that TMT has segued from being mainly a construction project to becoming a new observatory with rapidly improving performance and capabilities.

At this point, TMT will not be tuned well enough to achieve all its specified technical performance and operational efficiency goals. Such tuning is likely to continue for months to years; nevertheless, it is important to allow science observations to begin as soon as possible. Naturally, there is tension between these activities. Managing this tension and advancing TMT to the era of steady state operations is the main goal of the second phase of early operations.

This phase has three major activities: science commissioning, completion of Guaranteed Time Observations (if any), and initiation of science operations for the general TMT user community.

**Science commissioning**
Science commissioning is essentially a continuation of AIV, but with an emphasis towards optimizing the overall scientific and operational performance of TMT, particularly the initial suite of science instruments. The operations staff personnel responsible for this activity will be essentially the same staff responsible for AIV.

In coordination with instrument commissioning, staff personnel will develop (if not already available), verify, and document high-level operations sequencer scripts, guiding and acquisition procedures, calibration procedures, science operations workflows, and checklists for operational procedures.

TMT personnel will also test and tune the high-level observatory software system including operator and observer interfaces, tools for observation preparation and scheduling, quick-look applications, and data management tools.

A preliminary *TMT Science Commissioning Plan* is a TMT PDR deliverable. A final plan is a TMT FDR deliverable. The plan will describe:

1. All procedures, sequences, and workflows to establish
2. All performance tests with procedures, measurables and links to original requirements
3. Anticipated event sequence with links to instrument delivery schedule
4. Revised staffing plan
5. Revised infrastructure requirements

The TMT Observatory Scientist is responsible for creating the initial plan with assistance from the Project Scientist and the System Engineer. Eventually, this plan will be turned over to operations team leaders for revision and execution.

The core product of science commissioning is a report describing the as-built science performance of the commissioned observatory with supporting scientific datasets demonstrating that performance for each commissioned and released instrument mode.

To generate meaningful datasets, a small number of observations will be executed to demonstrate TMT readiness to handle science programs from proposal submission to data delivery as well as science and technical performance for representative science targets. These demonstration observations will be drawn from the TMT Detailed Science Case (which for the time being acts as a surrogate for a Design Reference Mission plan) with oversight from the TMT Science Advisory Committee. During the selection process, those suitable for generating exciting TMT press releases will be given consideration.

When each demonstration observation has been successfully completed, both raw and calibrated science data will be made available to the general community as soon as possible (i.e. weeks, not months, after observation) via the TMT Web portal.

The constant influx of new capabilities during Operations implies an on-going level of science commissioning activity. The TMT operations plan must account for this activity and provide enough resources to support it in parallel to steady-state operational activity.

**Guaranteed Time Observations (GTO)**
It has been suggested informally that it might be useful to provide instrument teams with an additional incentive and/or compensation for their work in the form of Guaranteed Time Observations (GTO). From an operations start-up perspective, GTO can be advantageous because it encourages the instrument team to actually use their instrument and tune it for maximum efficiency. In principle, everyone gains from this experience.

This possibility has not been discussed formally and therefore the TMT Board has no official position on this issue at this time. However, if GTO time is allocated, it would be allocated during this phase of early operations.

**General science operations**
Ideally, science commissioning work will proceed smoothly and rapidly so that TMT can start science operations for its user community as quickly as possible.

Realistically, general science operations time cannot ramp up to hundreds of nights per year immediately. For planning purposes, the model shown in **Table 10-1** has been adopted.

**Table 10-1: General science operations: ramp-up of scheduled nights.**

| Interval after AIV completion | Scheduled Nights (minimum) |
|---|---|
| First 12 months | 50 |
| Second 12 months | 100 |
| Third 12 months | 200 |
| Steady-state | 300 |

The actual minimum number of general science operations nights per interval will require approval by the TMT Board.

As Early Operations progresses, it may become clear that more general science operations nights per interval can be scheduled – however, our goal must remain: *under promise, over deliver*.

Due to lack of experience and a need to achieve a sufficient level of technical readiness, it seems safe to assume that the initial 50 general science operations nights will be scheduled towards the end of the first 12-month interval.

Observing time during early operations could be allocated to users in many different ways from many 0.5 night observing runs to using a significant fraction of time for one or more Key Projects. As time allocation comes closer to a reality, the SAC will be asked to discuss this topic and make a recommendation to the Board.

#### 10.1.3 Steady-state operations

After roughly 36 months, steady-state operations will be achieved if the following criteria are met:

- Stable and robust telescope systems
- At least two (and hopefully as many as five) working and commissioned facility instrument packages
- Tuned and efficient science operations systems
- Circa 320 nights scheduled for science operations per year
- Data quality assurance process operational

## *10.2 Steady-state operations organization*

#### 10.2.1 Management structure overview

The TMT Board will act as the ultimate financial and management authority for the TMT Observatory. The composition and responsibilities of the Board are TBD subject to future negotiation between the TMT Partners. It is anticipated that the Board will meet on a semi-annual basis.

The TMT Science Advisory Committee (SAC) will provide technical and scientific oversight of TMT Observatory activity. The SAC will report to the Board. It is composed by a proportionate number of scientists from each

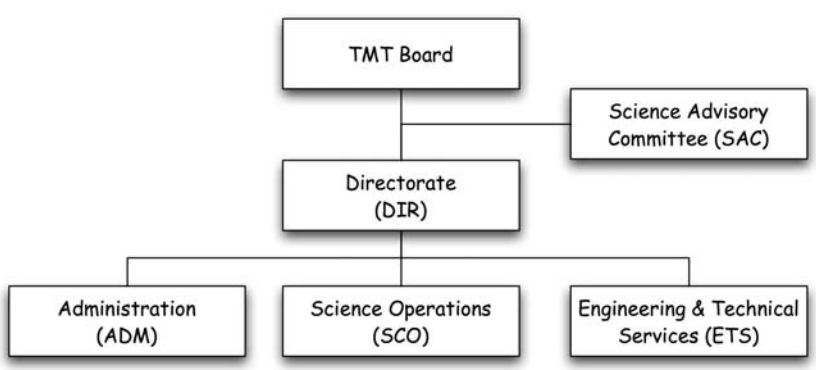



**Fig 10-1: TMT Management Structure.**

TMT Partner. SAC members will be appointed by their Partner. Setting the length of service is left to the discretion of each Partner. The SAC Chair will rotate amongst the Partners on an annual basis. It is anticipated that the SAC will meet in advance of each Board meeting to review on-going TMT technical and scientific activity (including any development projects). Written minutes of these SAC meetings will be provided to the TMT Board and Director. It is anticipated that the SAC Chairperson will attend TMT Board meetings to present reports and recommendations.

The TMT Directorate (DIR) contains the TMT Director, Deputy Director, and various personnel necessary to carry out high-level management responsibilities including: safety management, human resources management, community relations management, facilities development, and instrument development.

The Administration (ADM) department contains all the business, financial, and logistics services necessary to run the observatory. It also contains all activities related to the operation of non-technical facilities including dormitory management, food service management, site security, power generation and distribution, general transportation scheduling, and the maintenance of roads, grounds, buildings, and vehicles. Many services contained within this department will be provided by external contractors.

The Science Operations (SCO) department contains all the system ("telescope") operators and user support astronomers necessary to support night time operations. In addition, SCO hosts scientists who are specialists in the instruments and AO systems as well as the TMT Observatory system as a whole.

The Engineering & Technical Services (ETS) department is responsible for all technical system operations, maintenance and improvement activity. It contains engineers and technicians in all major engineering disciplines including mechanical, electrical, optics, software, and IT systems.

Within the Directorate, TMT will maintain an active instrument development office. The role of this office is one of specification, management, and oversight. Engineering and technical design and implementation work will be sub-contracted to various vendors. This office may be located in a separate location from the rest of the observatory (i.e. within continental North America). An overview of this office and a preliminary instrument development plan is given elsewhere in this document.

### 10.2.2 Staffing plan summary

A complete staffing plan has been developed under the assumption that TMT will be located on Cerro Armazones. Skill mix and estimated staffing levels have been patterned on real-world experience at the ESO Very Large Telescope (already located near Cerro Armazones) as well as the Gemini and Keck Observatories. If a different site is selected, this staffing model will be adjusted.

Three key assumptions are worth highlighting here: (1) Santiago de Chile (roughly 1400 kilometer away) is a more desirable home base for TMT staff and headquarters offices than the major population center (Antofagasta) nearest to Cerro Armazones; (2) due to system complexity and overall maintenance work load, key engineering and technical skills should be physically available seven days a week, at least during the early years of operation; and (3) many non-technical services can be procured from vendors in Antofagasta.

As a result of the first two assumptions, many TMT staff members will commute from Santiago by commercial airline and work on-site for an entire week. They will then return to Santiago and spent one week off-duty. In turn, this implies that approximately 60 people must be housed and fee per day near the TMT summit.

The current TMT staffing plan is summarized in **Table 10-2**. These numbers are preliminary and should be viewed cautiously. The left columns show the total staff complement. In these columns, personnel are separated into three categories: direct hires recruited internationally, direct hires recruited locally, and contract staff. The right columns summarize the average daily work force at the TMT headquarters offices and on-site (both day and night). For estimated annual costs, see **Section 12.8**.

### 10.2.3 Other operational costs

Operational costs unrelated to direct personnel costs fall into a number of categories as described in **Table 10-3**.

Currently, estimates are available for more than 60 separate line items under the assumption that TMT will be located on Cerro Armazones. These estimates are reviewed and updated on a regular basis. For an estimated cost summary, see **Section 12.8**.

**Table 10-2: TMT Staffing Plan.**

| | Staff Count | | | | Work Site | | |
|---|---|---|---|---|---|---|---|
| | **Int'l** | **Local** | **Contract** | | **HQ** | **Site/Day** | **Site/Night** |
| ***Directorate (DIR)*** | | | | | | | |
| Director, Deputy, Assistant | 2 | 1 | 0 | | 3 | 0 | 0 |
| TMT Safety Office | 0 | 1 | 2 | | 1 | 1 | 0 |
| Human Relations Office | 0 | 3 | 0 | | 3 | 0 | 0 |
| Community Relations Office | 0 | 2 | 0 | | 2 | 0 | 0 |
| System Engineering Office | 0 | 0 | 0 | | 1 | 0 | 0 |
| Facility Dev Office | 0 | 0 | 0 | | 0 | 0 | 0 |
| Instrument Dev Office | 10 | 0 | 0 | | 0 | 0 | 0 |
| | | | | | | | |
| ***Administration (ADM)*** | | | | | | | |
| Department Head, Ass't | 0 | 2 | 0 | | 2 | 0 | 0 |
| Business Services Group | 0 | 8 | 0 | | 8 | 0 | 0 |
| Logistical Services Group | 0 | 2 | 8 | | 2 | 3 | 0 |
| Facilities Operations Group | 0 | 8 | 22 | | 0 | 15 | 0 |
| Travel Support Office | 0 | 0 | 3 | | 2 | 0 | 0 |
| | | | | | | | |
| ***Eng/Tech Services (ETS)*** | | | | | | | |
| Department Head, Ass't | 1 | 2 | 0 | | 2 | 1 | 0 |
| Mechanical Group | 0 | 20 | 0 | | 0 | 10 | 0 |
| Optics Group | 0 | 6 | 0 | | 0 | 5 | 0 |
| Controls Group | 0 | 12 | 0 | | 0 | 6 | 0 |
| Instrumentation Group | 2 | 12 | 0 | | 0 | 6 | 0 |
| Software Group | 0 | 10 | 0 | | 8 | 2 | 0 |
| IT Support Group | 0 | 8 | 0 | | 1 | 3 | 0 |
| | | | | | | | |
| ***Science Operations (SCO)*** | | | | | | | |
| Department Head, Ass't | 1 | 0 | 0 | | 1 | 0 | 0 |
| System Operations Group | 0 | 5 | 0 | | 0 | 0 | 2 |
| System Support Group | 7 | 0 | 0 | | 2 | 2 | 0 |
| Observing Support Group | 3 | 0 | 0 | | 1 | 0 | 1 |
| Queue Support Group | 0 | 0 | 0 | | 0 | 0 | 0 |
| TMT Fellows | 3 | 0 | 0 | | 2 | 1 | 0 |
| | | | | | | | |
| **Total** | **19** | **102** | **33** | | **41** | **54** | **3** |

**Table 10-3: Operations running cost categories.**

| Category | Examples |
|---|---|
| Management | Community relations activities, site access fees, oversight committee travel support, etc. |
| Running costs (HQ) | Utilities, custodial, facility rental fees, internet service, etc. |
| Running costs (Summit/Support Facilities) | Utilities, facility development, technical consumables (e.g. gases), spare parts, dormitory housekeeping and food services, maintenance of non-technical facilities (roads, grounds, buildings, vehicles) |

# 11 Project Execution Plan

## 11.1 Objectives and Scope

TMT is intended to fulfill the first ground-based astronomy priority of the 2001 NAS decadal survey of astronomy [1]. Achieving the survey's vision is enabled by the dramatic, but feasible, technology leap that is the TMT design. Building upon the technological legacy of the Keck 10 meter telescopes, with filled aperture, finely segmented mirrors, and the new generation of adaptive optics systems currently emerging as catalysts of a powerful new astronomy, TMT is the first astronomy telescope intrinsically designed for diffraction limited performance. With its 30 meter aperture, TMT will provide partner astronomers an unprecedented capability to address the science goals defined by the TMT Science Advisory Committee (SAC) as well as national and international scientific study groups.

## 11.2 Project Description

The TMT Construction Project will deliver a fully developed set of summit and support facilities, the telescope enclosure, the complete telescope including structure, optics and controls systems, the facility adaptive optics system and laser guide star facility, the observatory software and initial operational infrastructure, and a suite of early light instruments. The delivered observatory will be ready to complete scientific commissioning, support classical and other basic modes of observing, solicit and review observational proposals and allocate observing time, and provide the required data products and data archiving. The observatory will be able to support additional instrumentation development and upgrades to its systems.

The Construction project will commence with the completion of the site-dependent design and development phase (DDP) and the first significant ground-disturbing activities at the observatory site. The project scope will include completion of all final design activities, commercial or contracted fabrication of all components and subsystems of the observatory, delivery to the site, and assembly, integration and verification of systems performance consistent with established early light goals. These first light goals define the required performance of the TMT facilities, including the enclosure, the complete telescope, and the facility adaptive optics systems and early light instruments. During the course of the construction project, early subsystems ready for routine operations will be delivered by the project to the operating team. This initiates the overlapping Early Operations phase of TMT. The detailed definition of the transition from DDP to Construction activities and, in turn, from Construction to Early Operations is defined for each element of the TMT Work Breakdown Structure (WBS).

## 11.3 Institutional Roles and Responsibilities

TMT is managed by the TMT Observatory Corporation (TMTCo), a legally established non-profit membership corporation formed by the partners. The partners are the Association of Canadian Universities for Research in Astronomy (ACURA), the University of California (UC) and the California Institute of Technology (Caltech). Each partner is represented on the TMT Board. **Fig. 11-1** displays the relationships between the governing TMT Board and the TMT Project.

The TMT Project receives direction from the TMT Board. The Project is responsible for executing the DDP, Construction and Early Operations phases of the project. It is expected that the Project will be replaced by an operating TMT Observatory organization by the beginning of TMT Science Operations. The TMT Observatory organization will develop from the on-site assembly, integration and verification team and be formed during Early Operations.

## 11.4 Organization of the Project

The TMT Project is managed by the TMT Project Manager. The Project Manager reports to the TMT Board and has the necessary authority for and is responsible to carry out all elements of the TMT design, development, construction and early operations activities of the project. The Project Manager supervises and directs all directly employed project staff and provides project direction through local line supervisors for all partner staff engaged in approved project activities. All project tasks are authorized by the Project Manager through prior signed Work Packages. The Project Manager is responsible for the scientific, technical and cost and schedule performance of the TMT Project.

The project organization is displayed in **Fig. 11-1** and it is structured to deliver the elements of the project defined in the WBS. Level 2 and Level 3 managers are responsible to deliver the corresponding deliverables at those levels in the WBS.

The Project Scientist is responsible to assure the scientific performance of the delivered TMT Observatory. The Project Scientist serves as the project contact with the Science Advisory Committee (SAC), consulting the SAC for requested scientific advice and communicating SAC advice to the project. The SAC may also initiate its own advice to the project. The Project Scientist is responsible to deliver the Science Requirements Document (SRD), the highest level TMT requirements document that initiates the flowdown of technical requirements to the TMT project.

The Observatory Scientist is responsible to assure the operating effectiveness of the delivered TMT Observatory, developing operational requirements and operating plans and consulting with the SAC and other external experts in observatory operations. The Observatory Scientist is also responsible to the project, and advises the System Engineer and Project Scientist, on detailed science requirements, on requirements traceability to the SRD and on observatory software and operating systems requirements. The Observatory Scientist is responsible to specify the progression of activities at the observatory site from assembly, integration, verification, Early Operations through full Science Operations.

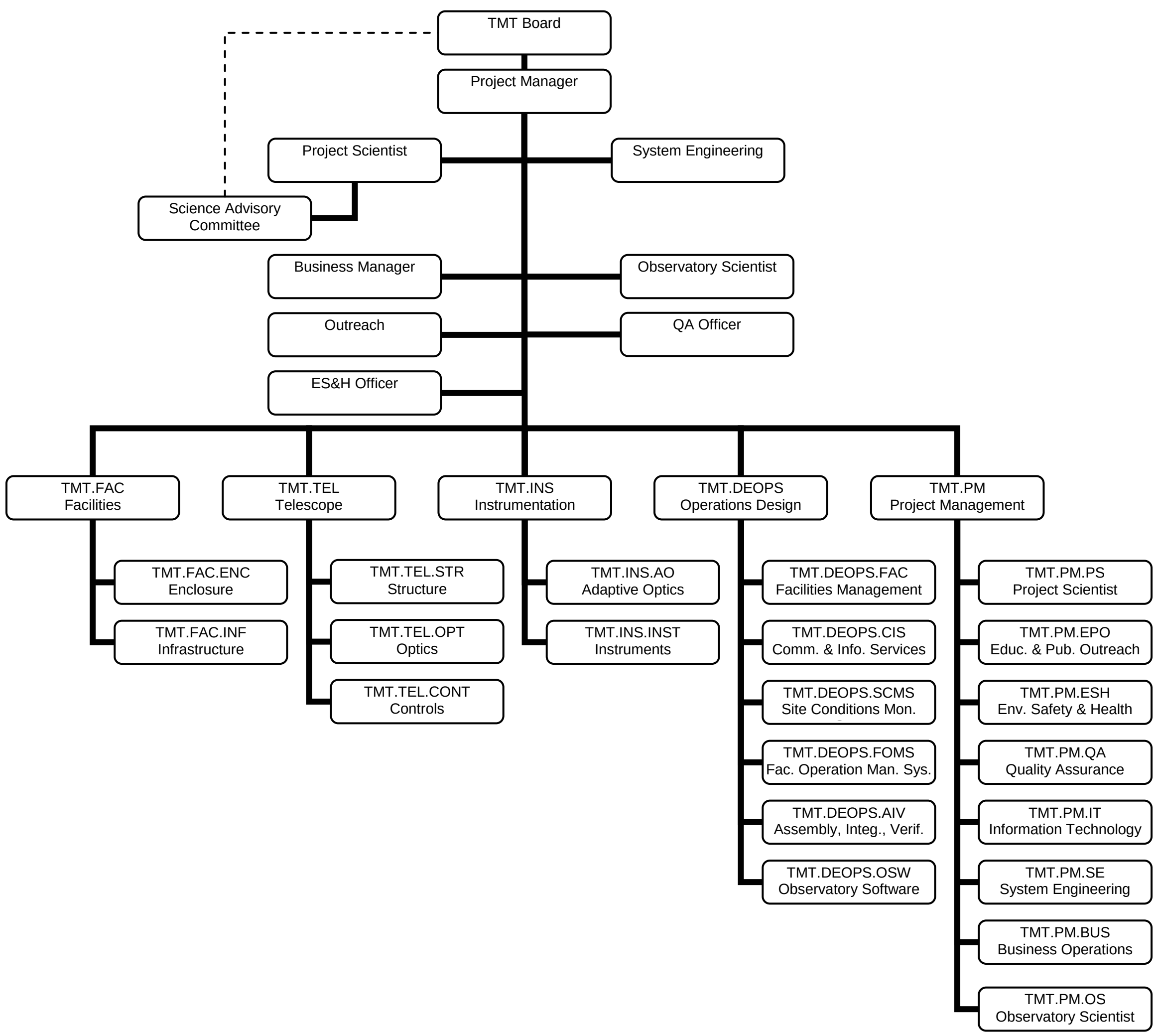



**Fig 11-1: Organization of the TMT Project during construction, showing the governing TMT Board, the Level 1 Project Office, and levels 2 and 3 in the organization. The organization closely parallels the Work Breakdown Structure (WBS).**

The System Engineer is responsible for defining and maintaining the definition all TMT technical requirements, for specifying and managing the TMT design process and configuration control, for analyzing performance of the design and for assuring the success of the integration process and verifying delivered system performance.

The Business Manager is responsible for funds management, accounting, procurement, human resources, business processes, audit support, cost estimating, project scheduling, and performance measurement. All corporate legal and financial activities are coordinated by the Business Manager.

The Science Advisory Committee (SAC) represents the partner and community science priorities to the project. The SAC is appointed by the TMT Board with each partner appointing three members. The SAC Chair is approved by the TMT Board and is expected to rotate among the partners annually. The SAC interacts with the project formally through the Project Scientist.

The External Advisory Panel (EAP) provides expert non-advocate review of all activities of the project. The EAP is appointed by the Board and delivers its review reports to the Board. The EAP is guided by a standing written Charge and each specific review is carried out to address a specific written charge. Members of the EAP are appointed for three year overlapping terms following the initial appointment of the panel. Representatives of the partner institutions and funding sponsors will be invited to attend reviews carried out by the EAP.

The Project Office represents Level 1 in the TMT organization, corresponding to Level 1 in the WBS. Level 2 managers are the Telescope Department Head, Facilities Manager, Instrumentation Manager, and Operations Design Manager. Level 3 managers are displayed in **Fig. 11-1**.

## *11.5 Collaborative Relations*

The TMT Project will establish formal relations with groups and institutions outside the partnership through written Memoranda of Understanding (MOU). These may include agreements with institutions involved in the TMT site, other astronomy or observatory entities, non-partner institutions contributing technical or scientific deliverables to the project, advisory or oversight entities, or entities involved in education and public outreach. MOUs are best effort agreements and they may be accompanied by formal contractual agreements where transfer of resources is involved. MOUs will be approved by the project and the TMT Board.

## *11.6 Work Breakdown Structure*

The WBS is displayed in tabular format to Level 3 in **Table 11-1**.

## *11.7 Work Plan*

The TMT Project will be managed by the Project Office. Effort will be provided by staff directly employed by TMTCo, and by partner institutions, under the direction of the TMT Project Manager.

All work will be authorized in written Work Packages specifying the Statement of Work, the Period of Performance, responsible managers, deliverables, schedule milestones and funding sources. Work Packages will correspond to scheduled work in the project baseline plan. Deliverables will be described in the Budgeted Cost of Work Scheduled (BCWS) in the baseline. Delivery earned value (Budgeted Cost of Work Performed (BCWP)) and project cost performance will be measured by the Actual Cost of Work Performed (ACWP). This earned value system will provide project performance measurement, structure variance analysis and provide early visibility of project areas requiring corrective action.

Site specific design and development will be carried out by the project team and selected industrial partners. Construction activities will primarily involve industrial production of hardware and embedded software deliverables with management of industry efforts by the cognizant Level 2 and Level 3 managers. Specialized observatory software and some specialized hardware elements of TMT may be produced by project or partner institutions. Given the scale of TMT, most make-or-buy decisions will result in industrial sourcing.

Construction will commence with any remaining final design activities not planned within the DDP phase, and with the first significant ground-disturbing activities at the observatory site. Early construction activities will also include first-article and low rate initial production of serial production items.

Early construction phase activities will be focused on final design of the summit and support facilities, the telescope enclosure and structure and mobilization on the site. Civil construction will be initiated with site grading, road construction, and construction of the foundations, pier and fixed enclosure. Erection of the rotating enclosure is prerequisite to installation of the telescope structure. A key project milestone is completion of the enclosure enabling structure erection. This milestone initiates construction of the major technical elements of the TMT observing systems. Prior to this milestone, the TMT Observatory site is dominated by the presence of industry construction personnel. Mobilization of project team members and relocation of project staff to the site locale accelerates during erection of the telescope structure.

Completion of the structure permits serial installation of primary mirror segment assemblies and elements of the facility AO systems. Work at the site focuses on the technical components and systems of TMT. The Assembly, Integration and Verification (AIV) subphase of Construction constitutes the activities at the site.

Construction is completed by accomplishing the major milestone of fully phasing the entire primary mirror with starlight, including operation of the secondary and tertiary mirrors in the testing program. First light images with starlight through the facility AO system and first instrument is also included in the construction project funding though completion of these activities may extend into Early Operations.

**Table 11-1: The WBS is displayed to level 3.**

| WBS Element (<= Level 3) | Title |
|---|---|
| TMT | Thirty Meter Telescope - Entire System |
| TMT.FAC | Facilities |
| TMT.FAC.MGT | Facilities Group Management |
| TMT.FAC.ENC | Enclosure |
| TMT.FAC.INF | Facilities Infrastructure |
| TMT.TEL | Telescope |
| TMT.TEL.MGT | Telescope Management |
| TMT.TEL.SYS | Telescope Systems Engineering |
| TMT.TEL.STR | Structure |
| TMT.TEL.OPT | Telescope Optics |
| TMT.TEL.CONT | Telescope Control Systems |
| TMT.TEL.INT | Telescope System Ins/Int/Test |
| TMT.INS | Instrumentation |
| TMT.INS.MGT | Instrumentation Group Management |
| TMT.INS.AO | Adaptive Optics Systems |
| TMT.INS.INST | Instruments |
| TMT.DEOPS | Operations Design |
| TMT.DEOPS.MGT | Design Operations Management |
| TMT.DEOPS.OBS | Operations Planning and Preparation |
| TMT.DEOPS.FAC | Facilities Management |
| TMT.DEOPS.CIS | Communications and Information Services |
| TMT.DEOPS.SCMS | Site Conditions Monitoring System |
| TMT.DEOPS.FOMS | Facility Operations Management Systems |
| TMT.DEOPS.AIV | TMT Assembly, Integration, and Verification |
| TMT.DEOPS.CSV | TMT Commissioning & Science Verification |
| TMT.DEOPS.SD | TMT Science Demonstration |
| TMT.DEOPS.OSW | Observatory Software |
| TMT.PM | Project Management |
| TMT.PM.PMO | Project Management Office |
| TMT.PM.PS | Project Scientist |
| TMT.PM.EPO | Education and Public Outreach |
| TMT.PM.ESH | Environment, Safety, Health |
| TMT.PM.QA | Quality Assurance |
| TMT.PM.IT | Information Technology |
| TMT.PM.SE | System Engineering |
| TMT.PM.BUS | Business Operations |
| TMT.PM.OS | Observatory Scientist |
| TMT.PM.CTG | Project Contingency Account |

## 11.8 Environment, Safety, Health and Quality Assurance

### 11.8.1 Environment, Safety and Health (ES&H)

ES&H is a line management responsibility supported by the ES&H Officer who reports directly to the Project Manager. The TMT ES&H program has the specific objectives to prevent personnel injury or loss of life during all phases of the TMT project; to prevent any environmental contamination during the construction, shakedown or operation of TMT; to prevent damage to equipment caused by accidents during all phases of the project; to comply with all national, state and local laws, rules and regulations.

The TMT ES&H program is the responsibility of the Project Manager. The Project Manager has responsibility to ensure that the TMT project members identify specific ES&H issues and risks, and establish appropriate safeguards and procedures for addressing those risks. To accomplish the detailed ES&H planning, documentation and surveillance, a TMT ES&H Officer will be appointed. The ES&H Officer shall be responsible for all ES&H program activities and report to the Project Manager on matters pertaining to the ES&H program.

A major portion of the TMT project will be performed by industrial contractors. These contractors will implement their own ES&H policies and procedures, which will be subject to review and audit by the ES&H Officer and the TMT project staff.

Partner institutions manage their own safety programs. Activities at partner institutions will be governed by these programs. However, TMT systems will be designed and fabricated to safety standards established by the TMT Project.

TMT hazard analysis and safety practices will be governed by an order of precedence as follows.

- Design for Minimum Risk: The primary means for mitigation of risk shall be to eliminate the hazard through design.
- Incorporate Safety Devices: Fixed, automatic or other protective devices shall be used in conjunction with the design features to attain an acceptable level of risk. Provisions shall be made for periodic functional checks as applicable.
- Provide Warning Devices: When neither design nor safety items can effectively eliminate or reduce hazards, devices shall be used to detect the condition, and to produce an adequate warning to alert personnel of a hazard. Devices may include audible or visual alarms, permanent signs or movable placards.
- Procedures and Training: Where it is impractical to substantially eliminate or reduce the hazard or where the condition of the hazard indicates additional emphasis, special operating procedures and training shall be used.

### 11.8.2 Quality Assurance (QA)

QA is a line management responsibility represented by the QA Officer who reports directly to the Project Manager. The Quality Assurance program, as applied to the TMT Project, defines Quality Control. It is an integral part of the design, procurement, fabrication and construction activities of the TMT project. The program objective is to ensure the completion of a high quality, reliable observatory. Achieving this goal requires all project participants to employ sound and accepted engineering practices, and to comply with all applicable procedures defined by the project.

The TMT Project Manager has the responsibility to define the appropriate QA level for the different phases of the project.

Procedures will be in place, describing the processes to be followed for all aspects of Quality Control (QC). Procedures will be established by the Project to cover procurement, construction inspection, documentation, component inspection, parts inspection, vendor audits and indoctrination/training of personnel. Contractors performing design, fabrication, assembly and construction tasks for the TMT project will implement their own QC procedures and processes. These contractor programs will be subject to review and audit by the TMT QA Officer.

## 11.9 Acquisition and Procurement

All major acquisitions will be planned with the strategy to be followed recorded in a written acquisition plan that will address the acquisition deliverables, commercial and technical risks, identification of sources, recommended contract types for developmental and production phases of the acquisition and the methods of source selection.

Generally, acquisitions will be carried out by competitive bidding employing Request for Proposal and Source Selection procedures. All competitive selections will be offered after documenting ranked evaluation criteria to be used in the selection. The evaluation criteria and ranking will be described in the offerings to proposers.

Sole source procurements are justified when there are clear rationales for the proposed source based upon test and evaluation goals, past procurements, technical expertise, compatibility with other TMT systems or prior acquisitions, or based upon source surveys that support the advantage to TMT of sole source procurement. In all cases of sole sourcing, a basis must be established for the fairness of the offered price in the absence of competitive bidding. Sole sourcing is considered to be an exceptional practice to the prevailing custom of competitive procurement. Sole source justifications must be documented in writing in accordance with TMT Project or partner procurement policies.

All TMT procurements will be offered in good faith. All competitive TMT procurements will be competed in fair and unbiased selection processes.

TMT procurements will be placed by the TMT Business Office or partner procurement organizations following the TMT acquisition strategy for the particular item. The management of procurements will be carried out solely by the TMT or partner contract representative and the designated contract technical representative.

### *11.10 Cost Estimate*

A detailed cost estimate has been prepared for the TMT project and is documented in the Cost Book [2]. The estimate has been prepared according to the TMT Cost Estimating Plan [3]. This estimate will be adopted as the cost baseline. The Cost Estimate will be maintained and reviewed in depth as a part of the annual Estimate to Complete activity Further details of the cost estimate, including risk analysis and contingency estimating, are provided in **Chapter 12**.

### *11.11 Schedule*

A schedule for TMT construction has been prepared following the WBS, in the same manner as the cost estimate. The schedule has been prepared to define a technically-paced project execution with the schedule contingency added to the project duration to define a robust schedule plan that is not limited by the pace of funding authorization. This schedule, prepared in strict adherence to the WBS, will be combined with the cost estimate to define the time phased funding profile required to construct TMT according to the schedule. The integrated cost and schedule databases will provide the basis for earned value performance measurement. The organization of the schedule plan supports replanning in the event of alternate funding profiles or for changes in the project plan that are approved by the Change Control process during project execution. Further details of the schedule are provided in **Section 12.5**.

### *11.12 Staffing and Human Resources*

The TMT Project will be implemented through a combination of project office staff, partner staff, and staff employed by subcontractors. Direct effort includes all three types of effort. Purchased labor may be an element of fabrication contracts and such effort is accounted as part of the materials costs.

The staffing levels for the Construction phase, AIV subphase and Early Operations phase are displayed in **Section 12.6**.

### *11.13Cost and Schedule Control and Performance Measurement*

A Project Management Control System (PMCS) will be established combining the baseline cost estimate and integrated project schedule through the WBS into a performance measurement system employing earned value. The baseline plan will be entered into the database at the performance measurement levels of the WBS, defining a Budgeted Cost of Work Scheduled (BCWS) or Planned Value (PV). All project activities, including contracted activities will be compared to the baseline monthly, for both performance and actual costs. The resulting Budgeted Cost of Work Performed (BCWP) and Actual Cost of Work Performed (ACWP) define the Earned Value (EV) and the cost performance. The Monthly Cost Schedule Status Reports (CSSR) will include cost and schedule performance indices and variances, providing early visibility of project tasks requiring corrective actions. One monthly project meeting will review the CSSR and provide the forum for initiating and tracking corrective actions.

The PMCS will employ the project's customized cost estimate database. The integrated project schedule will be maintained in a single location using Welcom's Open Plan software. Performance measurement will be carried out using Welcom's Cobra tool.

The project cost and schedule baseline will be reviewed annually, incorporating actual performance and cost experience and revised basis of estimate information for the forecasted portion of the project, resulting in a revised Estimate to Complete (ETC). The ETC will define the amended project baseline.

CSSR reports will be provided to the TMT Board monthly as well as provided in quarterly reports, semiannual EAP reviews and annual reports.

### *11.14 Configuration Management and Change Control*

The TMT technical configuration, consisting of design requirements, specifications, interface control documents and design documentation, will be controlled in a single project documentation system consisting of a document tree structured according to the WBS and system decomposition. The System Engineer will specify the subset of all key TMT design documentation to be placed under configuration control. Controlled technical documents may not be changed without approval of Engineering Change Notices (ECN) and approval by the Change Control Board.

The project cost and schedule baseline will also be maintained centrally in the Open Plan and Cobra systems, subject to change control for all significant changes.

The Change Control Board (CCB) will meet regularly to consider proposed changes to the technical, cost and schedule baselines. The CCB is advisory to the Project Manager and is chaired by the Project Manager. The CCB membership includes the Project Manager, Project Scientist, Observatory Scientist, System Engineer, Business Manager, ES&H Officer, QA Officer, and all Level 2 and Level 3 managers. Proposed changes are to be documented in a Change Request (CR), documenting the proposed change and resulting technical, cost and schedule impacts of the change. All CRs are to be archived, together with supporting documentation, in a permanent archive supporting full traceability of the baseline change process.

Project technical, cost and schedule changes will be submitted to the CCB if they exceed the following thresholds.

- Changes to requirements, specifications or interface definitions at Level 0 or 1 in the system engineering hierarchy, or changes at Level 2 that affect other subsystems or that are deemed to be significant changes.
- Changes to baseline costs that exceed $50,000 or cumulative cost changes that exceed this threshold.
- Changes to Level 1 or 2 milestones where late dates slip by more than one month.

If any doubt exists whether a change should be submitted to the CCB, it should be submitted without exception.

### *11.15 Documentation*

All project documentation will be archived in the project Document Control Center (DCC), using Xerox Docushare software. A Document Control Plan defines the organization of the document archive, including document numbering standards. The DCC provides a means of strict version control, assuring that all project activities are informed by the current approved version of controlled documents.

An engineering drawing database will be maintained to organize technical drawings, control of versions and approved changes and distribution of current drawings to all users. The engineering drawing database will be rigorously coordinated with the DCC, including compatible document numbering and retrieval methods.

No TMT documents may be disposed of without written approval by the Project Manager. All documents are to be maintained in electronic form in the archive without expiration. Paper documents will be recorded in electronic form and paper copies will be maintained for three years after completion of the construction project.

## *11.16 Reporting to Sponsors*

### 11.16.1 Monthly Progress Report

A TMT Project Monthly Report will be prepared and submitted to the TMT Board and funding agencies as required. This report will include a statement of the TMT Project cost and schedule status, a report of any contingency allocation in excess of $1 million, and a report of any schedule slippage of key milestones greater than three months.

### 11.16.2 Quarterly Progress Report

Three TMT Project Quarterly Reports will be prepared and submitted annually for the first three quarters of each fiscal year. This report shall consist of a summary of work accomplished during the reporting period including major scientific and technical accomplishments, an assessment of current status against scheduled status, a review of current or anticipated problem areas and corrective actions, and a status of action items remaining from prior reports. This report shall also include management information such as changes to personnel, financial status report and other financial information including actual or anticipated underruns or overruns, and any other action requiring TMT Board or sponsor notification.

The financial information in the Quarterly Report will include a summary (to WBS level 3) of actual obligations compared to the baseline estimated costs and graphs showing actual obligations (to WBS level 2) versus time compared with the planned obligation profile.

Schedule status will include a statement of earned value (where appropriate) to WBS level 3 and a narrative discussion of construction and R&D progress with reference to the baseline schedule. The Report will include a description of all Change Control actions for key milestones or contingency usage, and any changes in the annual acquisition plan.

### 11.16.3 Annual Report

An Annual Report will be prepared and submitted in lieu of a fourth Quarterly Report, containing a summary of overall progress, including results to date, and a comparison of actual accomplishments with the proposed goals of the period, indication of any current problems or favorable or unusual developments and a summary of work to be performed during the succeeding year and any other pertinent information. Financial and schedule status information similar to that given in the Quarterly Report will be included in the Annual Report.

## *11.17 Meetings and Reviews*

### 11.17.1 Internal TMT Meetings

Technical and design reviews within the TMT project will be conducted by TMT Project Management on a regular basis, to assess the status of design, construction and R&D activities, to update plans for future activities, and to resolve technical problems. Reviews of acquisitions and procurements and source selection meetings will be scheduled as required. There will also be regularly scheduled Project Control Meetings, System Engineering Meetings, and meetings of the Change Control Board.

### 11.17.2 External Advisory Panel

The TMT Board shall convene the External Advisory Panel (EAP) as necessary, but at least once a year. This committee shall conduct a system-level review of TMT at least annually. It shall review status and plans of the Project, major design decisions, and any other issues which TMT management brings forth. The committee shall provide analysis and advice to the Board and Project Manager. Sponsors shall be informed of all meetings, invited to attend, and shall receive copies of relevant reports.

### 11.17.3 Sponsor Reviews

TMT sponsors may convene visiting committees to conduct periodic reviews of the TMT Project, covering technical and management issues. Sponsors shall provide the Project with a copy of the charge to the review committee prior to the review, with adequate time to agree on the agenda and to prepare the necessary presentation material.

### *11.18 Publication and Dissemination*

To enhance the participation of the general scientific community in TMT research, the TMT Project will publish all research results in refereed journals, and will make all unpublished internal technical reports available to the public. TMT information will be disseminated publicly via a web collection. Only privileged personnel, medical, proprietary and export controlled information will be restricted.

### *References*

[1] Astronomy and Astrophysics in the New Millennium, Prepared by the National Research Council; the Commission on Physical Sciences, Mathematics, and Applications (CPSMA); the Board on Physics and Astronomy (BPA); and the Space Studies Board (SSB). The National Academies Press (2001).

[2] TMT Cost Book, TMT.BUS.CST.07.005.

[3] Cost Estimating Plan, TMT.BUS.SPE.05.001.

# Acronyms and Abbreviations

| | |
|---|---|
| *AAPs* | *Adjustable attachment points* |
| *ACWP* | *Actual Cost of Work Performed* |
| *Alt/Az* | *Altitude and Azimuth* |
| *ADC* | *Atmospheric Dispersion Compensator* |
| *AIV* | *Assembly, Integration and Verification* |
| *ALMA* | *Atacama Large Millimeter Array* |
| *AM2* | *Adaptive Secondary Mirror* |
| *aO* | *Active Optics System* |
| *AO* | *Adaptive Optics* |
| *AOSQ* | *Adaptive Optics Sequencer* |
| *AODP* | *Adaptive Optics Development Program* |
| *APD* | *Avalanche Photodiode Detector* |
| *API* | *Application Programming Interface* |
| *APS* | *Alignment and Phasing System* |
| *Arcmin* | *Arc-minute* |
| *Arcsec* | *Arc-second* |
| *ASCAM* | *All Sky Camera* |
| | |
| *BaF2* | *Barium Fluoride* |
| *BCWP* | *Budgeted Cost of Work Performed* |
| *BCWS* | *Budgeted Cost of Work Scheduled* |
| *BOCAM* | *Bore Sited CAMera* |
| *BOE* | *Basis of Estimate* |
| *BTO* | *Beam Transfer Optics* |
| *BTOOB* | *Beam Transfer Optics Optical Bench* |
| | |
| *CADC* | *Canadian Astronomy Data Center* |
| *CAGS* | *Commissioning Acquisition and Guiding System* |
| *CCB* | *Change Control Board* |
| *CCD* | *Charge Coupled Device* |
| *CER* | *Cost Estimating Relationship* |
| *CFD* | *Computational Fluid Dynamics* |
| *CMOS* | Complementary Metal-Oxide Semiconductor |
| *CoDR* | *Conceptual Design Review* |
| *CSIE* | *Control Structure Interaction Effects* |
| *CSSR* | *Cost Schedule Status Reports* |
| *CTE* | *Coefficient of thermal expansion* |
| *CW* | *Continuous wave* |
| | |
| $D_{80}$ | *80% Encircled Energy Diameter* |
| *DCC* | *Document Control Center* |
| *DDL* | *Direct Drive Linear* |
| *DDP* | *Design & Development Phase* |
| *DEOPS* | *Design Operations* |
| *DH* | *Direct Historical Data* |
| *DIMM* | *Differential Image Motion Monitor* |
| *DM* | *Deformable Mirror* |
| *DoF* | *Degree of Freedom* |
| *DSP* | *Digital Signal Processing* |
| | |
| *EAP* | *External Advisory Panel* |
| *EE* | *Engineering Estimate* |
| *ELT* | *Extremely Large Telescope* |
| *ESEN* | *Engineering Sensors* |

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|---|---|
| *ES&H* | *Environment Safety and Health* |
| *ETC* | *Estimate to Complete* |
| *EV* | *Earned Value* |
| *ExAO* | *Extreme Adaptive Optics* |
| *FEA* | *Finite Element Analysis* |
| *FD PCG* | *Fourier Domain Preconditioned Conjugate Gradient* |
| *FDR* | *Final Design Review* |
| *FIFU* | *Fiber Integral Field Unit* |
| *FOV* | *Field of View* |
| *FOV/SL* | *Field-of-view/slit length* |
| *FPGA* | *Field Programmable Gate Arrays* |
| *FTE* | *Full time equivalent* |
| *FWHM* | *Full Width at Half Maximum* |
| *GLAO* | *Ground-layer AO* |
| *GLC* | *Global Loop Controller* |
| *GMS* | *Global Metrology System* |
| *Gpc* | *Giga Parsec* |
| *GSMT* | *Giant Segmented Mirror Telescope* |
| *GTO* | *Guaranteed Time Observations* |
| *HALT* | *Highly Accelerated Lifetime Testing* |
| *HAST* | *Highly Accelerated Stress Testing* |
| *HIRES* | *High Resolution Echelle Spectrometer (Keck instrument)* |
| *HSB* | *Hydrostatic Shoe Bearing* |
| *HROS* | *High Resolution Optical Spectrometer* |
| *IBF* | *Ion beam figuring* |
| *IDO* | *Instrument Development Office* |
| *IFS* | *Integral field spectroscopy* |
| *IFUs* | *Integral Field Units* |
| *IGM* | *Intergalactic Medium* |
| *IPAC* | *Infrared Processing and Analysis Center* |
| *IR* | *Infrared* |
| *IRIS* | *Infrared Imaging Spectrograph* |
| *IRMOS* | *Infra-Red Multi-Object Spectrograph* |
| *IRMS* | *Infrared Multislit Spectrometer* |
| *JFET* | *Junction Field Effect Transistor* |
| *JNLT* | *(Subaru) Japanese National Large Telescope* |
| *JWST* | *James Webb Space Telescope* |
| *LGS* | *Laser Guide Star* |
| *LGSF* | *Laser Guide Star Facility* |
| *LLT* | *Laser Launch Telescope* |
| *LMCT* | *Lockheed-Martin Coherent Technologies* |
| *LN2* | *Liquid Nitrogen* |
| *LRU* | *Line Replaceable Unit* |
| *LSE* | *Laser Service Enclosure* |
| *LTAO* | *Laser Tomography Adaptive Optics* |
| *LUT* | *Look-up-table* |
| *M1* | *Primary Mirror* |
| *M1CS* | *M1 control system* |
| *M2* | *Secondary Mirror* |
| *M2CS* | *M2 control system* |

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|---|---|
| *M3* | *Tertiary Mirror* |
| *M3CS* | *M3 control system* |
| *Mas* | *Milli-arcsecond* |
| *MASS* | *Multi-Aperture Scintillation Sensor* |
| *MCAO* | *Multi-Conjugate Adaptive Optics* |
| *MCS* | *Mount Control System* |
| *MEMS* | *Micro Electro-Mechanical Systems* |
| *MIMO* | *Multiple Input Multiple Output* |
| *MIRAO* | *Mid-Infrared Adaptive Optics* |
| *MIRES* | *Mid-Infrared Echelle Spectrograph* |
| *MOAO* | *Multi-Object Adaptive Optics* |
| *MRF* | *Magneto-Rheological Fluid* |
| *MTHR* | *Medium-to-High Resolution spectrograph* |
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| *NFIRAOS* | *Narrow Field InfraRed Adaptive Optics System* |
| *NOAO* | *National Optical Astronomy Observatory* |
| *NGS* | *Natural Guide Star* |
| *NIRES* | *Near Infrared Echelle Spectrograph* |
| *NL* | *National Laboratory* |
| | |
| *OAD* | *Observatory Architecture Document* |
| *OAP* | *Off-Axis Paraboloid* |
| *OCD* | *Operations Concept Document* |
| *OCS* | *Observatory Control System* |
| *OES* | *Observation execution system* |
| *OPD* | *Optical Path Difference* |
| *ORA* | *Optical Research Associates* |
| *ORD* | *Observatory Requirements Document* |
| *OSIRIS* | *OH-Suppressing Infrared Imaging Spectrograph* |
| | |
| *PCBs* | *Printed circuit boards* |
| *PCS* | *Phasing Camera System* |
| *PDR* | *Preliminary Design Review* |
| *PFC* | *Prime focus camera* |
| *PFI* | *Planet Formation Instrument* |
| *PLC* | *Programmable Logic Controller* |
| *PL&G* | *Power, Lighting and Grounding* |
| *PMCS* | *Project Management Control System* |
| *PSD* | *Power Spectral Density* |
| *PSF* | *Point Spread Function* |
| *PV* | *Planned Value* |
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| *QA* | *Quality Assurance* |
| *QC* | *Quality Control* |
| *QSO* | *Quasi Stellar Object* |
| | |
| *RFI* | *Radio Frequency Interference* |
| *RFP* | *Request for Proposal* |
| *RFQ* | *Request for Quotation* |
| *RMS* | *Root mean-squared* |
| *ROM* | *Rough Order of Magnitude* |
| *RSS* | *Root Sum of Squares* |
| *RTC* | *Real Time Controller* |
| | |
| *SAC* | *Science Advisory Group* |
| *SALT* | *South African Large Telescope* |
| *SCO* | *Science Operations* |

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|---|---|
| *SFG* | *Sum Frequency Generation* |
| *SPHERE* | *Spectro-Polarimetric High-contrast Exoplanet Research* |
| *SiRD* | *Site Selection Requirements and Strategy Document* |
| *SKA* | *Square Kilometer Array* |
| *SMP* | *Software Management Plan* |
| *SMP* | *Stress Mirror Polishing* |
| SNR | *Signal to Noise Ratio* |
| *SODAR* | *Sound Detection and Ranging* |
| *SPHERE* | *Spectro-Polarimetric High-contrast Exoplanets Research* |
| *SPIE* | *International Society for Optical Engineering* |
| *SRD* | *Science Requirements Document* |
| *SSA* | *Segment Support Assembly* |
| *SSTA* | *Single Segment Test Assembly* |
| | |
| *TCS* | *Telescope Control System* |
| *TMT* | *Thirty Meter Telescope* |
| *TMTCo* | *Thirty Meter Telescope Observatory Corporation* |
| *TSS* | *Telescope Safety System* |
| *TSTA* | *Three Segment Test Assembly* |
| *TT* | *Tip/Tilt* |
| *TTP* | *Tip/Tilt Platform* |
| | |
| *ULAO* | *Up Link Adaptive Optics UPS* |
| *UPS* | *Uninterruptible Power Supplies* |
| *USAs* | *Unit Segment Assemblies* |
| *UV* | *Ultraviolet* |
| *UVES* | *Ultraviolet and Visual Echelle Spectrograph* |
| *VLT* | *Very Large Telescope* |
| *VPH* | *Volume Phase Holographic* |
| *VQ* | *Vendor Quotes* |
| | |
| *WBS* | *Work Breakdown Structure* |
| *WFS* | *Wavefront Sensors* |
| *WFOS* | *Wide-Field Optical Spectrograph* |
| *WIRC* | *Wide Field InfraRed Camera* |
| *WMAP* | *Wilkinson Microwave Anisotropy Probe* |