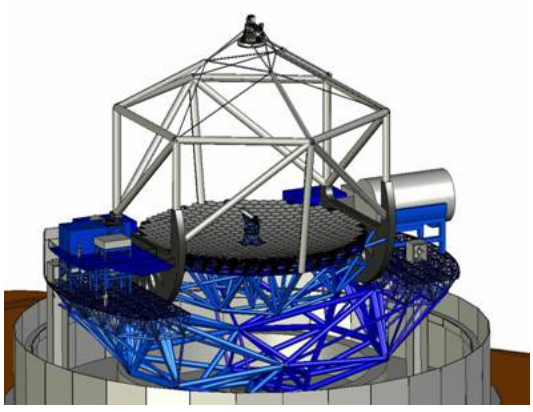
THIRTY METER TELESCOPE

STATEMENT OF WORK

TERTIARY MIRROR CELL ASSEMBLY (M3CA)

TMT.OPT.TEC.11.057.DRF01

12 May, 2011



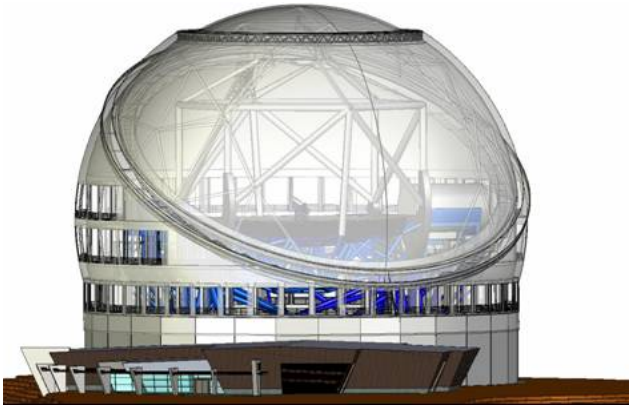


TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 PURPOSE

This document defines the phased development and fabrication program to deliver the Thirty Meter Telescope (TMT) Tertiary Mirror Cell Assembly (M3CA) to the TMT Observatory. This preliminary version of the Statement of Work is intended for discussion purposes, and it will be amended and updated as required before incorporation into the agreement for delivery of the M3CA.

1.2 ABBREVIATIONS

AIV	Assembly, Integration & Verification at the TMT Observatory
CoDP	Conceptual Design Phase
DMU	Digital Mock-Up
FAB	Fabrication Phase
FDR	Final Design Review
FEA	Finite Element Analysis
FEM	Finite Element Model
FPPSR	Final Performance and Pre-Ship Review
ICD	Interface Control Document
m	meter
M3	Tertiary Mirror
M3 Blank	Tertiary Mirror Blank
M3C	Tertiary Mirror Cell Structure
M3CA	Tertiary Mirror Cell Assembly
M3M	Completed Tertiary Mirror
M3PA	Tertiary Mirror Positioner Assembly
M3S	Tertiary Mirror System
M3S DRD	Requirements Document for Tertiary Mirror System (M3S)
M3SS	Tertiary Mirror Support System
mm	Millimeter
N/A	Not Applicable
OD	Outside Diameter
PDP	Preliminary Design Phase
PDR	Preliminary Design Review
TBD	To be determined
TMT	Thirty Meter Telescope
VRR	Verification Readiness Review

1.3 DEFINED TERMS

Capitalized terms used in this document have the specific meanings described below:

Collaborating Institution	The organization responsible for performing the Work.
Deliverables	The Deliverables include the information, hardware and software that are to be delivered to the TMT Project as a result of the activities in this Statement of Work
Support Equipment	Support Equipment includes handling equipment, polishing equipment, metrology and test equipment, a mass simulator, spare parts, and shipping containers. The Support Equipment is defined in detail in Section 2.2.2.
Work	The term Work includes all of the activities described in this Statement of Work; and, depending on the context, the term may also include the Deliverables.

2. HARDWARE DESCRIPTION

2.1 BACKGROUND

The Thirty Meter Telescope is a three mirror Richey Chrétien design configured as shown in Figure 1. The Tertiary (M3) Mirror is flat with an elliptical perimeter that reflects the telescope optical beam into the instruments located on the Nasmyth platforms.

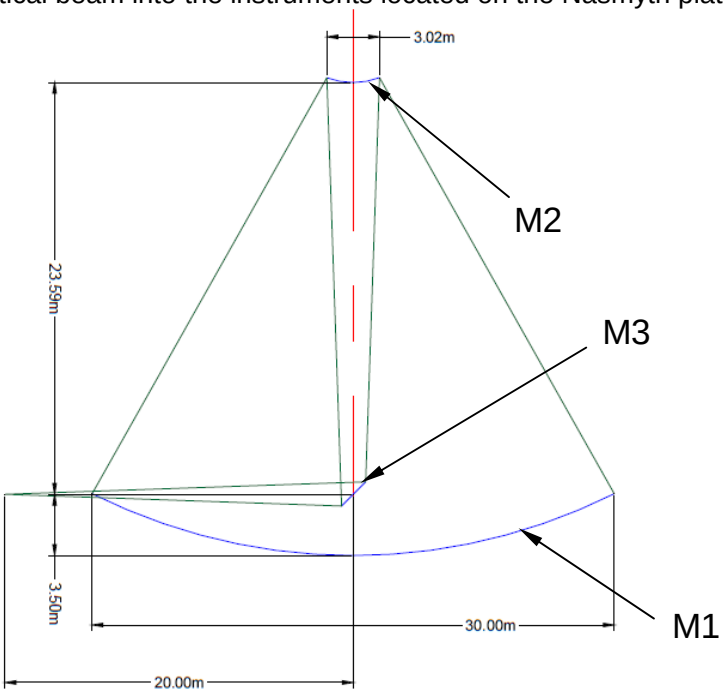


Figure 1. TMT Telescope Configuration

The parameters of the M3 Mirror are shown below in Table 1.

Table 1. Parameters of the TMT M3 Mirror

Mirror Element	Optical Beam Dimensions (m)	Coated Clear Aperture Dimensions (m)	Mechanical Dimensions (m)	Thickness (mm)	Optical Surface Radius of Curvature (m)
Finished M3 Mirror	ellipse major axis: 3.500 m minor axis: 2.448 m	ellipse major axis: >3.544 m minor axis: >2.485 m	ellipse major axis: 3.594 m minor axis: 2.536 m	100	N/A (flat)
M3 Mirror Blank	N/A	N/A	ellipse major axis: 3.596 m minor axis: 2.538 m	103	N/A (flat)

2.2 SCOPE

2.2.1 Tertiary Mirror Cell Assembly (M3CA)

An image of one design concept for the M3 System (M3S) including all subsystems is shown in Figure 2. The M3Cell Assembly (M3CA) includes a subset of the subsystems within the M3S. The major components included in the M3CA are:

- **M3C** – M3 Cell. The M3C is the subsystem which interfaces to the M3CA lift fixture and M3 Positioner, supports the M3SS and provides hardware to enable washing the M3M in situ.
- **M3M** – Tertiary Mirror. The M3M is the polished low expansion glass ceramic tertiary mirror (polished to TMT specifications) including bonded pucks that interface with the M3SS.
- **M3SS** – M3 Support System. The M3SS is the subsystem that supports the weight of the M3M and defines its position and orientation in the telescope. It includes flexure attachments to the M3M, axial and lateral support systems, and interfaces to the M3M and the M3C.

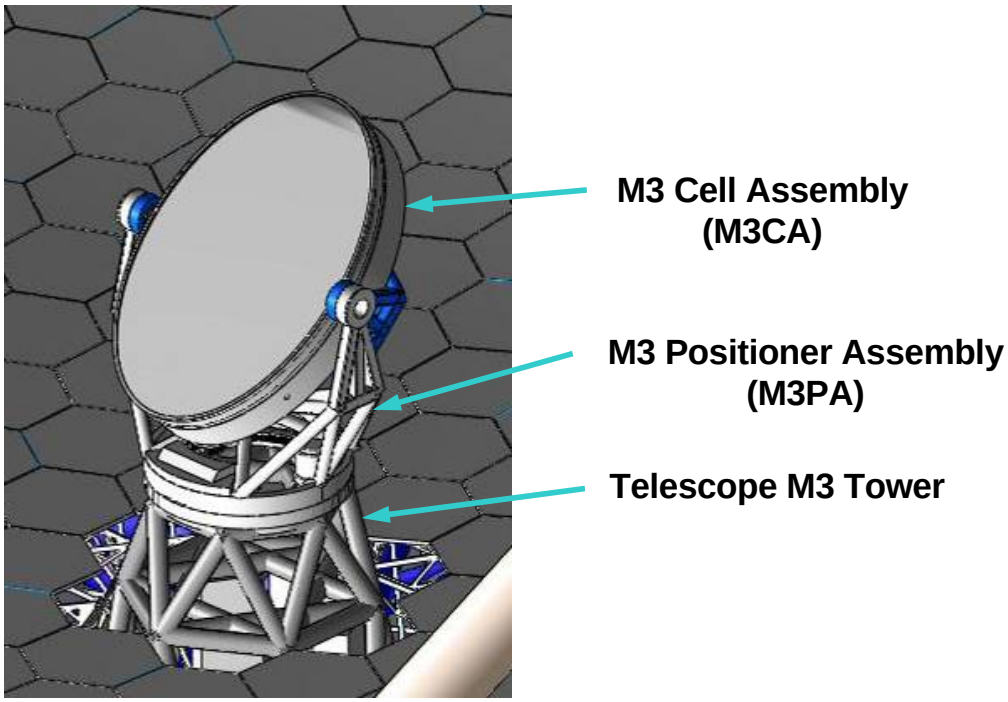


Figure 2. M3 System

2.2.2 Support Equipment

In addition to the M3CA, the M3CA program shall also be responsible for developing, fabricating, integrating and testing the following additional equipment, which is referred to as Support Equipment:

- M3 Mirror Optical Fabrication and Metrology Facility that includes supports, fixtures and equipment used for polishing and measuring the M3M as it progresses from blank to completed mirror with bonded interface pucks and also

metrology equipment used to measure the mirror surface of the completed M3CA;
- Lifting fixtures, and handling equipment needed during polishing of the M3M and for final measurement of the M3M and M3CA optical surface in the specified orientations;
- Deliverable Lifting Fixtures for the M3M and the M3CA for use at the TMT Observatory; these will be required to meet additional TMT requirements and interfaces, but may be the same equipment used for handling the M3M and the M3CA in the polishing and testing facility;
- Deliverable Handling Fixtures and Carts for the M3M and the M3CA for use at the TMT Observatory; these will be required to meet additional TMT requirements and interfaces, but may be the same equipment used for transporting or holding during polishing the M3M and handling the M3CA;
- Deliverable Surrogate M3M for initial testing of the M3CA;
- Deliverable Surrogate M3CA for testing all M3CA fixtures and metrology equipment;
- Deliverable spare parts, tools and supplies required for assembly/disassembly and maintenance or replacement of the M3CA and all deliverable M3CA support equipment. Spares should include all subsystem components that will require replacement during the 50 year lifetime of the observatory if the components are custom fabricated or difficult to obtain. The need for replacement should be assessed based on the lifetime rating of each component;
- Deliverable Shipping Containers for the M3 Blank, the M3M, the M3CA, and all related equipment; the M3 Blank shipping container will be used to transport the M3 Blank to the mirror polishing facility, and may be reconfigured to become the shipping container for the M3M.

Note that the lifting and handling fixtures listed above and delivered to the observatory will be used during the telescope Assembly, Integration and Verification (AIV) phase of TMT, as well as throughout the lifetime of the observatory (50 years) to handle the M3 for maintenance and recoating, approximately every 2 years.

Further description can be found in:
- Requirements Document for Tertiary Mirror System (M3S DRD)
- Tertiary Mirror Blank Specifications

2.3 PROJECT PHASES AND TASKS PER PHASE

The work will be divided into phases, with each phase ending in a milestone event, for example, a review meeting, that will authorize proceeding to the next phase of the work. The phases will be:

- Planning phase
- Conceptual Design Phase (CoDP)
- Preliminary design phase (PDP)
- Final design phase (FDP)
- Fabrication phase (FAB)
- Factory verification phase
- Assembly, integration and verification phase (AIV) (at the TMT Observatory)

Project Reviews will be held during each phase. For each of these, TMT will appoint an experienced Review Panel, including TMT personnel as well as independent technical and management experts. The purpose of the Project Reviews will be to guide the Collaborating Institution to ensure hardware and programmatic success. This panel will report its findings to TMT management and may recommend additional actions in order to successfully

complete the phase. TMT management will either: approve the Project Review and authorize the Collaborating Institution to proceed to the next phase; or TMT may ask for additional actions by the Collaborating Institution in order to complete the current phase.

Each phase has unique tasks that must be accomplished for the M3CA project to proceed correctly, resulting in on-time delivery of a system that meets TMT specifications. The following sections describe these tasks.

2.3.1 Planning Phase

2.3.1.1 Review and Evaluate the M3CA Requirements

The Collaborating Institution will review available TMT documents that describe the requirements for design, fabrication, assembly, integration and testing of the M3CA. In particular, the Collaborating Institution will review the Requirements Document for Tertiary Mirror System (M3S) (abbreviated "M3S DRD", where DRD stands for "design requirements document") and the Interface Control Documents for the M3S. If any of the requirements are not clearly expressed, the Collaborating Institution will request clarification from the TMT project office and TMT will provide further information or reword the requirements as required.

The Collaborating Institution should identify any potential changes to the requirements that it believes will: (1) improve performance without increasing cost; (2) lower cost without degrading performance; (3) reduce risk; or (4) provide benefits during operation (for example, changes that would simplify maintenance procedures). TMT will review all proposed changes to the requirements and will work with the Collaborating Institution to implement approved changes.

2.3.1.2 Develop the Project Plan

The Collaborating Institution will develop a Project Plan that describes how it will perform the work. The information to be included in the Project Plan is described in Section 4.1.

The Collaborating Institution will submit the Project Plan to the TMT project office for approval. Once TMT has provided Authorization to Proceed, the Collaborating Institution may proceed with the Conceptual Design Phase of the work.

2.3.1.3 Planning Phase Milestones

The Collaborating Institution shall accomplish the indicated milestones by the dates shown below. Note: These dates are for planning purposes only and may change.

MILESTONES FOR PLANNING PHASE	DATE
Start the Planning Phase	**TBD**
Submit proposed changes to the requirements	**TBD + 1 month**
Submit the Project Plan	**TBD + 1 month**
TMT Authorization to Proceed	**TBD + 2 months**

2.3.2 Conceptual Design Phase (CoDP)

To fabricate the M3 Mirror, grinding, polishing and metrology equipment will be required during all stages of fabrication of the M3 Mirror. In addition, metrology test equipment will be used to measure the optical surface of the M3 Mirror after it has been installed into the M3 Cell Assembly. The M3 Cell Assembly has performance specifications that apply to the assembly of the M3 Mirror and the M3 Cell Assembly hardware. Performance allocations

between these subassemblies are design dependent; so conceptual designs of each subsystem will be necessary to understand the allocation of specifications for each subsystem.

The conceptual Design Phase shall focus on developing and evaluating design options for the M3 Mirror Polishing and Metrology and the M3 Cell Assembly with the goal of selecting the options that meet all requirements while providing the best, most practical, lowest risk, most cost-effective solutions that can be implemented by the Collaborating Institution. The options that are studied should be well enough developed to be able to compare ability to meet requirements, cost estimate, and risk for each option.

Trade studies must evaluate ability to meet M3CA specifications, so must include developing an error budget for each option. The combinations of error budgets from Mirror Polishing and Metrology options and Cell Assembly options should be used to develop performances for sets of options that can be compared to M3CA specifications.

2.3.2.1 Conceptual Design of the M3 Mirror Polishing and Metrology Facility

The Collaborating Institution will develop concepts for measuring and polishing the M3 Mirror as it progresses from blank to completed M3 Cell Assembly. Each option should cover the progress of the mirror through grinding, polishing, attachment of interface pucks, and assembly into the M3CA.

A combination of metrology methods will be combined for the best solution. Metrology concepts that should be considered include, but are not limited to:

- Ritchey-Common test
- Fizeau Interferometer test
- Subaperture testing with data stitching
- Profilometers
- Test Plates

Polishing options also should be considered, and will depend upon the conceptual design selected for the final M3 Cell Assembly. Error budgets shall be developed for all options and used to understand the resulting performance for each option.

2.3.2.2 Conceptual Design of the M3 Cell Assembly

There are many possible methods to support the M3 Mirror. The option that meets requirements and with the least risk and lowest cost will depend on the facilities and capabilities of the responsible Collaborating Institution. In order to select the optimum conceptual design, the Collaborating Institution will perform trade studies to evaulate the best design concept for their implementation of the M3CA. The Collaborating Institution may consider several design approaches including, but not limited to the following:

- Mirror axial support systems 18 point passive axial supports based on a kinematic whiffletree approach
- Mirror lateral support systems with between 6 to 12 point passive supports based on a kinematic whiffletreel arranged around M3M perimeter
- Passive supports with gravity print-through partially polished out on the optical surface
- If desired, other TBD approaches proposed by the Collaborating Institution

Error budgets for each Cell Assembly option should be developed and used to assess performance of the options.

2.3.2.3 Conceptual Design Review

The Conceptual Design Review (CoDR) is a Project Review that will document the evaluations of the CoDP. The review should include:

- Description of the conceptual design evaluation of the options considered for the polishing and metrology of the M3 mirror including:
  - Description of each concept
  - Comparison tables summarizing how each concept performs with respect to the other options including: performance; performance verification; support equipment; costs; and risks
  - Summary of analysis performed to evaluate options
  - Cost estimates
  - Safety and Risk assessment of all options including both hardware and personnel safety and risk and programmatic issues
- Description of the conceptual design evaluation of the M3CA options considered including:
  - Description of each concept
  - Comparison tables summarizing how each concept performs with respect to the other options including: performance; requirements verification; support equipment; costs; and risks
  - Summary of analysis performed to evaluate options
  - Cost estimates
  - Safety and Risk assessment of all options including both hardware and personnel safety and risk and programmatic issues

A CoDR Report described in Section 4.6.1 will be a Deliverable at the CoDR.

The Conceptual Design Review shall be concluded with an agreement between the Collaborating Institution and the TMT Project that establishes the design architecture for the Polishing and Metrology of the M3M and for the M3CA that will be further developed in the Preliminary Design Phase

2.3.2.4 Conceptual Design Phase Milestones

The Collaborating Institution shall accomplish the indicated milestones by the dates shown below. Note: These dates are for planning purposes only and may change.

MILESTONES FOR CONCEPTUAL DESIGN PHASE	DATE
Start Conceptual Design	**Per Project Plan**
Deliver CoDR Documentation	**Per Project Plan**
Conceptual Design Review	**Per Project Plan**

2.3.3 Preliminary Design Phase

2.3.3.1 Design Activities

The Preliminary Design Phase shall be focused on advancing the preferred design concept agreed upon at the end of the Conceptual Design Phase to the preliminary design stage with CAD models of the concept and FEA to determine performance.

During this phase, the Collaborating Institution will develop performance budgets as described in Section 3.1. The Collaborating Institution will perform sensitivity analyses to

relate the parameters of the design to the performance budgets. In addition, during this phase, the Collaborating Institution will develop the preliminary designs for the Support Equipment listed in Section 2.2.2 including the Optical Fabrication and Metrology Facility.

A plan for verification of requirements including testing and test equipment that will be required shall also be developed during this phase.

2.3.3.2 Preliminary Design Review

The preliminary design review (PDR) is a Project Review that will document the accomplishments of the Preliminary Design Phase, including:

- Management section presenting the project plan and reviewing the cost and schedule performance relative to the plan
- Review of the M3CA preliminary design, CAD models and software approach
- Review the mirror testing and polishing facility design
- Presentations of the Performance Budgets, the kinematic and dynamic analysis, structural analysis, and thermal analysis
- Summary of the predicted M3CA performance showing that all requirements will be met
- Review of interfaces with other telescope subsystems to ensure interface concepts are communicated and compatible between subsystems
- Description of key program risks, and the plan for managing the risks
- Plans for developing and testing prototypes if they are needed to establish technology and mitigate risk
- Preliminary designs of the Support Equipment and preliminary plans for maintenance and spares
- Computer Aided Design files per Section 4.2
- Preliminary plans for the manufacturing approach as described in Section 4.3
- Plans for the Optical Fabrication and Metrology Facility construction or modifications to existing facilities
- Review the safety aspects of the designs and prepare a preliminary hazard / safety assessment.

The PowerPoint presentation files and a PDR Report described in Section 4.6.2 will be Deliverables at the PDR.

2.3.3.3 M3 Mirror Blank (M3 Blank)

During the Preliminary Design Phase, the Collaborating Institution will review the TMT M3 Blank Specification and present any desired changes to TMT for approval. The Collaborating Institution will place an order for the M3 Blank from the selected supplier. In addition, the Collaborating Institution will interface with the M3 Blank supplier to develop specifications for the shipping container that will protect the M3 Blank during transportation from the M3 Blank supplier to the M3M polishing facility.

2.3.3.4 M3 Mirror Optical Fabrication and Metrology Facilities

To meet the schedule it may be necessary to begin construction of the metrology facility, or modifications to existing facilities, during the preliminary design phase. If so, the Collaborating Institution will conduct a separate Metrology and Polishing Facility Review meeting to explain the facility design to TMT and to obtain TMT authorization to proceed with construction.

2.3.3.5 Preliminary Design Phase Milestones

The Collaborating Institution shall accomplish the indicated milestones by the dates shown below. Note: These dates are for planning purposes only and may change.

MILESTONES FOR PRELIMINARY DESIGN PHASE	DATE
Start Preliminary Design	**Per Project Plan**
Order M3 Blank	**Per Project Plan**
Deliver PDR Documentation	**Per Project Plan**
Preliminary Design Review	**Per Project Plan**

2.3.4 Final Design Phase

2.3.4.1 Design Activities

During the Final Design Phase, the Collaborating Institution will complete the detailed design of all components of the M3CA and of the Support Equipment listed in Section 2.2.2. This work will include analyses and performance simulations, development and testing of prototypes, and completion of manufacturing plans. During this phase, all procurement documents and manufacturing drawings must be completed.

2.3.4.2 Final Design Review

The Final Design Review (FDR) is a Project Review with the purpose of ensuring that the M3CA design is ready for fabrication. The comprehensive FDR should cover:

- Project plan and the cost and schedule performance relative to the plan
- All aspects of the final M3CA design
- Final design of interfaces with other telescope subsystems
- Final designs of the Support Equipment and the polishing facility
- Presentations summarizing all analyses described in Section 3
- Prototype testing activities and results
- Compliance with requirements in the M3S DRD and the associated performance budgets, demonstrating that the final design will meet all of its requirements
- Status of any early fabrication work, e.g., fabrication of the M3 Blank and construction of the polishing facility
- Computer Aided Design files per Section 4.2
- Describe the materials, processes and assembly fixture to bond attachment features to the mirror blank; and include a written assembly plan
- Final manufacturing approach including plans described in Section 4.3
- Quality Assurance plans per Section 4.5
- Verification plans per Sections 2.3.6 and 4.4
- Assembly Procedures and plans for recording the conditions of as-built assemblies
- Test procedures describing upcoming subsystem testing that will occur during assembly and prior to full M3PA integration
- Review the safety aspects of the designs and of the manufacturing approach and update the hazard / risk assessment.
- Maintenance plan, lifetime evaluation of components, and type and quantity of deliverable spare parts.

The FDR PowerPoint presentation files and a FDR Report described in Section 4.6.3 will be Deliverables at the FDR.

2.3.4.3 M3 Mirror Blank (M3 Blank)

The Collaborating Institution shall prepare for transportation, receipt and incoming inspection of the M3 Blank, and shall schedule completion of the M3 Blank shipping container and handling equipment per the project plan.

The M3M polisher shall be responsible for design of the M3 Blank shipping container. The design of the M3 Blank shipping container will be submitted for approval to the TMT project office prior to its fabrication. The M3M polisher will be responsible for fabrication, for transporting the empty container to the M3 Blank vendor, for supervising packing the M3 Blank into the container and for shipping the M3 Blank to the M3M polishing facility. Receipt of the M3 Blank and mirror polishing shall be scheduled as needed to maintain the schedule milestones for the M3CA project.

2.3.4.4 Optical Fabrication and Metrology Facility

During the Final Design Phase, the Optical Fabrication and Metrology Facility must be completed and prepared to process the M3M. The M3M blank and polishing are on the critical path for the M3CA, so meeting the schedule for start of polishing will be critical.

2.3.4.5 Final Design Phase Milestones

The Collaborating Institution shall accomplish the indicated milestones by the dates shown below. These dates are for planning purposes only and are subject to change.

MILESTONES FOR FINAL DESIGN PHASE	DATE
Start Final Design	**Per Project Plan**
Complete Mirror Testing and Polishing Facility	**Per Project Plan**
Final Design Review	**Per Project Plan**

2.3.5 Fabrication and Assembly Phase

Following the FDR, the Collaborating Institution shall finalize and release all necessary production drawings, procedures and test plans for the M3PA, including support equipment, facility plans, and deliverable spare parts. Fabrication shall not commence until the TMT Project has reviewed the production documents and provides authorization to proceed.

During the Fabrication and Assembly Phase the Collaborating Institution will fabricate or purchase all of the component parts of the M3CA and the Support Equipment, based on the designs that were presented and approved at the Final Design Review. If it becomes necessary to make changes to the designs in order to facilitate fabrication, the Collaborating Institution will discuss these changes with TMT Management before proceeding with fabrication.

The Collaborating Institution will maintain a quality assurance system and will conduct measurements and inspections to ensure the fabricated and purchased parts comply with their specifications.

2.3.5.1 Fabrication Activities

The Collaborating Institution will need a system to organize all parts that will be fabricated and must maintain records such as: name of part fabricator; materials used; post-machining processing; start and completion dates; and inspection results. Any changes to fabrication drawings must be documented and included in the system to create a complete record of the as-built state of all parts. Each part will be inspected to ensure crucial dimensions meet the specified tolerances and an inspection report will be produced.

2.3.5.2 Procurement Activities

The Collaborating Institution will need a system to organize all components that will be procured to maintain records of items purchased including: name of vendor, specifications, user manuals if applicable, procurement start and completion dates, and inspection results. Incoming components will be inspected to ensure vendor compliance with specified performance and an inspection report will be produced.

2.3.5.3 Mirror Blank (M3 Blank)

The Collaborating Institution will receive and inspect the M3 Blank. To prepare the M3 Blank for polishing, pads may be ground and/or etched on the blank for attaching bonded items, then attachment features will be bonded to the M3 Blank following the approved assembly plan.

2.3.5.4 Mirror Polishing and Metrology

The Collaborating Institution or its polishing subcontractor will perform the optical finishing operations required to fabricate the finished M3 Mirror, including as required: fixed abrasive generating, loose abrasive grinding, and polishing. The optical finishing and metrology methods used will follow the manufacturing plan presented and approved at the Final Design Review. If it becomes necessary to use other methods not described in the manufacturing plan, the Collaborating Institution will discuss these methods with TMT Management before proceeding with the alternate methods.

2.3.5.5 Assembly Activities

Prior to beginning assembly, Issues from the AAR shall be resolved, critical assembly processes requiring particular care or precision will be documented in written Assembly Procedures. At a minimum, procedures involving handling the M3 Mirror will be documented in a written Assembly Procedure. Assemblies that might affect the error budgets should also be documented in a written Assembly Procedure. During the assembly process, as-built records will be kept to show that Assembly Procedures were followed and to record any deviations from the Assembly Instructions. All Assembly Instructions and as-built records shall be organized and delivered to TMT upon completion of the M3CA. During assembly, major component assemblies will be tested separately to demonstrate performance prior to incorporation into higher level assembly.

2.3.5.6 Verification Phase Planning

During the Fabrication and Assembly Phase, plans for Verification testing will be finalized. These plans shall be submitted to the TMT Project for review and approval.

2.3.5.7 Verification Readiness Review

The Verification Readiness Review (VRR) is a Project Review that ensures that the M3CA is ready for full integration and verification testing. The VRR will cover:

- Project plan and the cost and schedule performance relative to the plan
- Test plans and procedures for performance of the Laboratory Verification testing of the M3CA per Section 2.3.6.
- Analyses and results based on as-built assembly records
- Requirements in the M3S DRD and the associated as-built performance budgets based upon the inspection reports and assembly records

- Preliminary AIV plan for M3CA assembly and integration onto the TMT Telescope and the functional testing that will occur at the TMT Observatory
- Review the safety aspects of the verification testing approach and update the hazard / risk assessment.

Verification Plan Documentation described in Section 4.4 will be a Deliverable at the VRR.

2.3.5.8 Meetings

In addition to the meetings listed in Section 5 and reviews, TMT engineers will attend and witness critical assembly steps at the Collaborating Institution's facility. In particular, TMT is interested in attending any assembly involving the M3M and assemblies of hardware that are affect the error budget.

2.3.5.9 Fabrication Phase Milestones

The Collaborating Institution shall accomplish the indicated milestones by the dates shown below. These dates are for planning purposes only and are subject to change.

MILESTONES FOR FABRICATION PHASE	DATE
Start Fabrication Phase	**Per Project Plan**
Assembly Readiness Review	**Per Project Plan**
Complete M3M polishing	**Per Project Plan**
Verification Readiness Review	**Per Project Plan**

2.3.6 Laboratory Verification Phase (at Collaborating Institution)

2.3.6.1 Verification Testing

After Fabrication and Assembly, the M3CA will be tested at the Collaborating Institution's facility to verify that the performance meets the requirements listed in the M3S DRD, following the procedures documented in the Verification Plan. If it becomes necessary to make changes to the verification procedures during the verification testing, the changes must be documented. If the change may affect the ability to verify requirements of the M3CA, then the changes must be discussed with the TMT Project before proceeding with testing.

The goal of the Verification tests is to determine whether the M3CA meets requirements that affect the final performance of the of the fully integrated M3CA. The optical surface of the M3M must be measured in the fully integrated configuration. Thermal or stressed– induced motion of the optical surface shall be measured with respect to the interface where the M3CA attaches to the M3PA. The Verification tests shall include but not be limited to the following:

- Optical Surface measurement with the M3CA rotation oriented TBD^{o} from vertical and the M3CA x-axis (along the tilt axis) oriented TBD^{o} from vertical to verify that the M3CA optical surface meets optical requirements in that orientation
- Determination of residual error values for each specified Zernike mode shape
- Measurement of the M3CA performance at the operational temperature range of the TMT Observatory either by subcomponent testing, full assembly testing or by a TBD approach proposed by the Collaborating Institution
- Measurement to verify that the M3CA will perform as required when oriented over the full set of tilt and rotation ranges that will be encountered during TMT telescope observation. This measurement may be achieved through a full range of angled

tests, a combination of discrete angled tests and FEA; or by a TBD approach proposed by the Collaborating Institution.

2.3.6.2 Support Equipment Testing

The deliverable Support Equipment will be tested during the Laboratory Verification Phase, including testing to verify that the equipment items have the specified factors of safety.

2.3.6.3 Update of the Plan for the M3CA AIV support

Based on the results of the Laboratory Verification Phase testing, the Collaborating Institution shall review and update the AIV Procedures for M3CA Integration onto the TMT Telescope and the functional testing at the TMT Observatory.

2.3.6.4 Final Performance and Pre-Ship Review

The Final Performance and Pre-Ship Review (FPPSR) is a Project Review that will summarize the measured performance of the M3CA and review the shipping containers and plans for transportation of the M3CA and the equipment described in Section 2.2.2. The review should include:

Final Performance:

- Project plan and the cost and schedule performance relative to the plan
- Description of each test that was conducted and the data collected
- Final Performance Budget with explanation of how the measured data was used
- Verification that the M3CA will meet the requirements listed in M3S DRD
- Plan for M3CA functional testing at the TMT Observatory and integration onto the TMT Telescope
- Quality assurance and verification plans
- Review the safety aspects of the shipping, AIV work, and functional testing approach and update the hazard / risk assessment.

Pre-Ship:

- Design and analysis of the shipping containers demonstrating that the hardware will be protected against transportation and handling environments while enroute
- The plan for transportation from the Collaborating Institution's facility by truck or train to either airport or shipping port, to Hawaiian airport or shipping port, to a TMT warehouse for staging, then to the TMT Observatory by truck
- Note: TMT prefers that the mirror (M3M) be removed from the mirror cell (M3CA) and shipped separately in order to further safeguard the mirror and the mirror cell components, however, if the Collaborating Institution has a different approach, TMT will consider it

The M3CA Final Report described in Section 4.6.4 will be a Deliverable at the FPPSR.

2.3.6.5 Packing and Shipping

Following the successful completion of the Pre-Ship Review, the M3CA and the Support Equipment shall be disassembled and packed into protective shipping containers. TMT Project will provide authorization to ship when the conditions at the TMT warehouse and the observatory site are safe for delivery of the M3CA and Support Equipment. The containers shall be transported by the M3CA Collaborating Institution to the TMT Observatory.

2.3.6.6 Meetings

During the Verification Phase, TMT personnel shall attend and witness most of the Verification Tests.

2.3.6.7 Laboratory Verification Phase Milestones

The Collaborating Institution shall accomplish the indicated milestones by the dates shown below. These dates are for planning purposes only and are subject to change.

MILESTONES FOR VERIFICATION PHASE	DATE
Start Verification Phase	**Per Project Plan**
M3CA Performance Review	**Per Project Plan**
Pre-ship Review	**Per Project Plan**
Start of transportation to TMT Observatory	**Per Project Plan**

2.3.7 Assembly, Integration and Verification (AIV) Phase (at the TMT Observatory)

2.3.7.1 M3CA Enroute Supervision, Unpacking and Inspection

Collaborating Institution personnel will supervise the transportation of the shipping containers, including inspections at the transition points when the containers change modes of transportation as needed to ensure that the containers are undamaged and have not received loads that would damage the hardware contained inside. If the M3CA and the Support Equipment is damaged enroute, the Collaborating Institution must determine when the damage occurred and who is responsible for the damage. If damage has occurred during transportation, the Collaborating Institution will prepare a plan for repairing the damage, get it approved by TMT, and then will be responsible for accomplishing the repairs with assistance from TMT personnel. A TMT warehouse will be available at Hilo for detailed inspection, any necessary repair work, temporary storage of the M3CA hardware and for unpacking the Support Equipment so that it is available when needed at the TMT Observatory. When the Observatory is ready to receive the M3CA, Collaborating Institution personnel will supervise any repacking, transportation from the warehouse to the Observatory, the unpacking and inspection of the M3CA hardware upon arrival at the TMT Observatory. TMT will provide cranes as needed for lifting and technician support for unpacking and crane operation. Following unpacking of the M3M at the Observatory, it will be coated in the TMT Observatory coating facility.

2.3.7.2 M3CA Assembly

Collaborating Institution personnel will supervise the assembly of M3CA with the coated M3M. The assembly will follow the AIV Procedures that were prepared during the Verification Phase. If it becomes necessary to make changes to the AIV Procedures during the reassembly process, the Collaborating Institution will discuss these changes with TMT Management before proceeding. Functional performance testing of the M3CA will be performed prior to mounting onto the telescope. All assembly and testing will be documented step-by-step. Any deviation from the prepared procedures will be documented. The Collaborating Institution shall provide technician support for the M3CA assembly and testing. TMT will provide space for the assembly, cranes and technicians certified to run the cranes.

2.3.7.3 Installation of the M3CA onto the TMT Telescope

Following the M3CA Assembly and functional performance testing, the M3CA will be installed onto the TMT Telescope. Collaborating Institution's personnel will support the installation effort. TMT will provide technicians to integrate the M3CA onto the telescope.

2.3.7.4 Final Acceptance Test of the M3CA

After the Installation, the Final Acceptance Test of the M3CA will be performed according to the AIV Procedures. Any deviation from the prepared procedure will be documented. The Collaborating Institution will provide the personnel to perform the Final Acceptance Test. TMT personnel shall witness the test.

2.3.7.5 M3CA Training

Collaborating Institution personnel will train TMT personnel on the handling, assembly and testing of the M3CA. They shall also train TMT personnel on the operation and maintenance of the M3CA, and regarding any diagnostic systems or procedures.

2.3.7.6 Final Acceptance

Following the Final Acceptance Test, the Collaborating Institution will organize the following data into a Final Acceptance Test Report described further in Section 4.6.5:

- Results from Acceptance Testing at the TMT Observatory
- Correlation between TMT Observatory functional testing and the Verification Testing at the Collaborating Institution verifying that the functional testing results ensure that the M3CA performs as predicted
- Performance Budget with changes resulting from the Acceptance Testing highlighted
- Summary of the Users Manual

Delivery of the Final Acceptance Test Report will be the final task of the Collaborating Institution's M3CA project team.

2.3.7.7 AIV Phase Milestones

The Collaborating Institution shall accomplish the indicated milestones by the dates shown below. These dates are for planning purposes only and are subject to change.

MILESTONES FOR AIV PHASE	DATE
M3CA Arrival at the TMT Observatory	**Per Project Plan**
Final Acceptance Test of the M3CA	**Per Project Plan**
Delivery, M3CA Final Acceptance Test Report	**Per Project Plan**

3. ANALYSES REQUIRED

3.1 PERFORMANCE BUDGETS, SENSITIVITY ANALYSIS AND PERFORMANCE EVALUATION

The Collaborating Institution will develop Performance Budgets that, for each key performance requirement, provide a breakdown of the contributions or errors among the subsystems of the M3CA. The performance requirements that should be covered in the set of Performance Budgets include, at a minimum:

(1) System mass
(2) Optical surface wavefront error
(3) Position of the optical surface in six degrees of freedom over the telescope observing conditions
(4) Maximum stresses in the glass of the M3 Mirror and on critical parts where failures may cause functional failure or unsafe conditions for personnel.

A sensitivity analysis performed on each parameter in the Performance Budgets will show how variation of each budget parameter affects the M3CA performance. The error budgets shall include contributions from polishing and metrology, support structure, optical metrology system component drift, gravitational and thermal variations, and shall address the mirror surface figure requirements described in the M3DRD.

A performance evaluation based on the Performance Budgets will ensure that the M3CA will meet all M3CA performance requirements contained within the M3S DRD.

From the beginning of the M3CA program, the Performance Budgets will be developed, then documented and presented for TMT evaluation. The Performance Budgets will be maintained throughout the entire program. At each program phase, the Performance Budgets will be updated and re-evaluated. During the early phases, the Performance Budgets will be tools for predicting the final M3CA performance that will guide design choices. During fabrication, assembly and integration phases, inspections and testing will, in some cases, provide measured values that can be included in the Performance Budgets to improve the accuracy of their predictions of as-built performance. During final acceptance testing, the Performance Budgets will be used to understand test results and to debug problems.

3.1.1 M3CA Optical Performance Budget

The Performance Budget that evaluates the optical performance of the M3CA is of particular concern. It should include as a minimum:

- **Tolerance studies**
  All performance related M3CA hardware, including metrology, relevant test fixtures and measuring instruments, shall be evaluated to understand all performance sensitivities. In conjunction with the Performance Budget, the sensitivities shall be used to establish tolerances, including but not limited to machining tolerances, mounting repeatability, and clearances that contribute to the final optical performance of the M3CA.

- **Sensor sensitivity, resolution and repeatability**
  The sensitivity to electrical and environmental variation and the resolution and repeatability of all sensors included in the optical metrology and measuring instruments shall be evaluated and included in the Performance Budget.

- **Control systems errors**

  The drift and noise in the control system of the optical metrology shall be evaluated and included in the Performance Budget.

- **Environmental Effects**

  The effects of variations of temperature, air flow, humidity, altitude, and all environmental conditions that influence the optical performance of the M3CA hardware, the metrology fixtures and measuring instruments shall be evaluated and included in the Performance Budget. These effects must be associated with both the observing environment and the environment at the Collaborating institution's facility..

- **Other influences**
  Any other factors, such as user bias, data interpretation variation or software numerical round-off, that could influence the final performance of the M3CA will be included in the Performance Budget and quantified to provide an understanding of the effects.

3.2 THERMAL AND STRUCTURAL ANALYSIS

Thermal and Structural Finite Element Analysis (FEA) will be used to evaluate the M3CA and Support Equipment throughout the development and fabrication program. To be compatible with models created by other TMT partner organizations, the Finite Element Models (FEM) should be developed in any of the following commercially available codes (in order of preference):

- Ansys
- MSC/Nastran
- NX Nastran (UGS)
- Abaqus

During the Preliminary and Final Design Phases, FEA will be used to guide design choices such as part strength and interface locations. During fabrication, assembly and integration phases, FEA will be updated to reflect changes between designed hardware and as-built hardware.

The environmental conditions to be evaluated will include TMT Observatory conditions as well as the Collaborating Institution facility conditions so that results can be compared to measurements at both sites.

The FEA results will be delivered to the TMT Observatory during Preliminary and Final Design Phases to provide TMT with information that will guide the design of other subsystems. Also, the final FEMs will be delivered to the TMT Observatory to aid with operations support of the M3CA throughout the 50 year life of the Observatory. The delivered FEMs, including all load cases, will be in the native FEA input stream and also in Preprocessor format such as Nastran *.dat input files and FEMAP *.mod files.

Thermal and structural Finite Element Analysis will be used to evaluate the following aspects of the M3CA:

- Determine M3M optical surface deformation as the gravity vector changes direction and the environmental temperatures vary. These analyses will be used to demonstrate that the M3CA will meet the performance requirements.
- Determine the sensitivity of M3CA performance to variations in component parameters, as described in Section 4.1.
- The M3S must survive the earthquakes that frequent the TMT Observatory site. FEM seismic analysis will guide the M3CA and M3CSC design to ensure earthquake survival as defined in the M3S DRD.
- Determine the vibration natural frequencies and mode shapes.

3.3 RISK EVALUATION

The Collaborating Institution will have the best understanding of problems that may occur with the hardware during its design, fabrication, integration at the observatory, and long-term operation. Because of this, the Collaborating Institution will perform a risk evaluation that lists and systematically ranks all M3CA risks, their severity and the likelihood of occurrence. Where appropriate, a Failure Mode Effects and Criticality Analysis shall be performed. Results of this evaluation will be reassessed and maintained throughout the development program. The most significant M3CA risks will be included in the TMT project risk register so that key risks can be managed appropriately.

4. DOCUMENTATION REQUIRED

4.1 PROJECT PLANNING DOCUMENTATION

During the Planning Phase, the Collaborating Institution will create a project plan that includes the information listed below, and will use the project plan to manage the progress through all phases of the Work. The project plan will be a tool to help the Collaborating Institution make decisions that keep the M3CA project within its allotted budget, on track to deliver the M3CA per the TMT schedule, with risks understood, safety addressed and with managed quality to ensure meeting requirements. The Collaborating Institution will create the project plan; present it to TMT management for approval; and, as the project progresses through its phases, will report progress to TMT management based upon this plan.

The project plan should include:
1. The organizational structure of the team of people working on the M3CA
2. The required level of staffing for each phase of the work, and plans for recruiting any team members that are not currently available
3. The procurement plan, describing when and how components will be purchased and any plans to subcontract portions of the work to other organizations
4. The plan for preparing and archiving required documentation
5. The plan for risk management and the safety program that will be followed
6. Plans for the quality assurance program
7. A schedule showing when each activity will be performed, in a form compatible with the TMT Project schedule

Using the Collaborating Institution's cost estimate, cost accounting inputs, and schedule, TMT will implement an earned-value system that links the M3CA project progress to the work performed and costs incurred. In order to do this, the schedule must include appropriate task detail for the earned-value reporting. TMT will guide the Collaborating Institution to produce an appropriate schedule as needed. In addition, the Collaborating Institution will submit a monthly report of the schedule status update along with the costs incurred. This report will be used by TMT to help track the monthly progress of all subsystems within TMT.

4.2 COMPUTER AIDED DESIGN DOCUMENTATION

In order to ensure that the TMT Telescope is an integrated design and to provide a record of hardware that can be referred to during the course of the 50 years of TMT operation, a complete set of 3D Computer Aided Design (CAD) Models documenting the M3CA will be uploaded to the TMT-provided Data Management System during the Preliminary Design Phase and the Final Design Phase. The CAD files will be in the SolidWorks format with the version specified by TMT. It is preferred that the models be natively created in SolidWorks, though converted files via STEP are acceptable. TMT engineers will work with the Collaborating Institution to integrate the M3CA models into the TMT Digital Mockup (DMU) (the global TMT CAD model).

All of the 2D drawings documenting the M3CA design will also be regularly uploaded to the TMT-provided Data Management System. A complete set is expected at the end of the Final Design Phase. It is preferred that the drawings be natively created in SolidWorks, though other formats are acceptable. Regardless of the CAD file format, the latest revision of each drawing must also be provided in the Portable Document Format (PDF).

Interface Control Drawings (ICDs) will be needed to define how the M3CA interfaces with other Telescope and Observatory subsystems. Creation and exchange of ICDs that describe the M3CA must begin during the Preliminary Design Phase so that ICDs can be finalized by the completion of the Final Design Phase. This responsibility will be shared between TMT and the Collaborating Institution.

4.3 MANUFACTURING APPROACH DOCUMENTATION

Because of the high-risk, close-tolerance nature of mirror processing and handling, a carefully-planned Manufacturing Plan will be an important tool to guide the M3CA project. During the Preliminary Design Phase and by the end of the Final Design Phase, the Manufacturing Plan for the M3CA should be fully developed, reviewed by TMT and approved. In order to provide TMT with a complete description of the M3CA that will be delivered, during Fabrication, Integration and Test Phases, the elements of the Manufacturing Plan will be updated with as-built conditions. The Manufacturing Plan should contain the following elements:

Manufacturing Process:
This element describes the manufacturing processes required for the components that will be custom manufactured.

Long-lead Items:
All long-lead items that require early procurement planning will be listed along with a schedule of when the procurements must be started.

Specification Sheets:
Specification sheets for all of the commercially-procured components that will be used in the final designs will be included in this element.

As-Built Drawing Changes:
An organized method to document changes to the fabrication drawings that occur during fabrication is needed to provide a record of the as-built state of the fabricated hardware without requiring changing CAD models or CAD drawings.

Incoming Inspections:
During Preliminary and Final Design Phases, this element will contain the plan for inspection of fabricated parts and procured components. Following those phases, this element will contain copies of all inspection documentation.

Assembly Procedures:
Assembly instructions will be required and reviewed by TMT prior to beginning complex M3CA assemblies, including but not limited to any assemblies involving M3M and critical dimensional tolerances. As the M3CA is assembled, the assembly procedures will document the actual assembly steps for the complex assemblies.

4.4 VERIFICATION PLAN DOCUMENTATION

The Verification Plan shall describe the methods that will be used to verify that the M3CA will meet the requirements listed in the M3S DRD. There are two phases that establish the full verification of the M3CA – Laboratory Verification that takes place at the Collaborating Institution facility, and Functional Verification that takes place during AIV at the TMT Observatory. Both verification phases require support equipment preparation and planning and are likely to influence the design of the M3CA hardware to accommodate the ability to test and measure the hardware performance. In the Verification Plan Documentation, the Laboratory Verification and the AIV acceptance testing shall be presented separately.

At each phase, the Verification Plan should be summarized in a Verification Matrix that lists each requirement listed in the M3S DRD and the planned method to verify that requirement. Typically, the planned verification methods include: by test; by inspection; by analysis; and by design.

The Preliminary Design Review description of the Verification Plan should be conceptual but adequate to ensure that the M3CA hardware has features enabling testing and that test equipment needed to perform verification tests is included in the project plan.

The Final Design Review documentation of the Verification Plan should include a detailed description of the hardware and test equipment required for the Laboratory Verification; the flow-down from the planned tests to the requirements; a description of measurement data and data processing; and a description of how the acceptance testing during AIV will ensure that the delivered M3CA meets requirements.

At the Verification Readiness Review, the test hardware and equipment required for Laboratory Verification should be completed, Laboratory Verification test procedures should be written for all tests that describe how to obtain all measurement data. The planned processing of the Laboratory Verification measurement data should be described completely. In addition, the review should include a detailed description of the test equipment required for the AIV acceptance test; the measurement data and data processing during acceptance test.

At the Final Performance and Pre-Ship Review, the results of the Laboratory Verification testing will be presented. The hardware required for the AIV acceptance testing should be completed and test procedures for the acceptance testing should be written including the plans for processing the data collected.

The Final Acceptance Test Report will include:

- Results from Acceptance Testing at the TMT Observatory
- Correlation between TMT Observatory functional testing and the Verification Testing at the Collaborating Institution verifying that the functional testing results ensure that the M3PA performs as predicted

4.5 QUALITY ASSURANCE DOCUMENTATION

Quality Assurance planning provides a management framework to ensure that the M3PA will operate to meet all requirements while maintaining a safe environment at the Collaborating Institution's facility and at the TMT Observatory. Safety applies to both personnel and hardware.

During the design phases, Quality Assurance should focus on ensuring that design work considers all functional requirements, as well as meeting safety, handling, and maintenance needs for the M3PA during fabrication, assembly, verification and operation on the TMT telescope. Planning should also begin during the design phases so that preparations for testing and inspection during fabrication and assembly phases are in place.

During fabrication and assembly, Quality Assurance will focus on inspection that verifies procured components meet specifications, fabricated components meet drawing specifications, and assembly proceeds as planned so that the assembled hardware is as designed. All handling must proceed safely.

4.6 M3CA REPORTS

4.6.1 Conceptual Design Report

A written report in English that is in addition to the PowerPoint files presented at the CoDR that documents the Conceptual Design Phase will be delivered along with the Conceptual Design Review. This report should describe the items listed in Section 2.3.2.

4.6.2 Preliminary Design Report

A written report in English that is in addition to the PowerPoint files presented at the CoDR that documents the Preliminary Design of the M3CA will be delivered along with the Preliminary Design Review. This report should describe the preliminary design of the items listed in Section 2.3.3.

The Preliminary Design description should present preliminary designs; show CAD layouts and describe the M3CA, support equipment and all interfaces. The report should also describe analyses that were performed to verify that the design will meet requirements. The report should contain the documentation items described above in Sections 4.1 through 4.4, developed to the level that is appropriate at the PDR.

4.6.3 Final Design Report

A written report in English that is in addition to the PowerPoint files presented at the CoDR that documents the Final Design of the M3CA will be delivered along with the Final Design Review. The report will update and expand the information from the Preliminary Design Report. The report should include a description of the design choices; the philosophy behind the design; how the M3CA and the Optical Fabrication and Metrology Facility operates, and the calculations and analyses that were performed to verify that the design meets the requirements. This report should be delivered two weeks prior to the Final Design Review.

4.6.4 M3CA Final Report

Upon completion of the Verification Phase, the M3CA Final Report shall also be delivered. The purpose of the M3CA Final Report is to provide the TMT Staff with all the background and instructions required to enable rapid maintenance, repair and upgrading that will lead to trouble-free operations of the TMT Observatory throughout its 50 year lifetime. The documentation should include, but not be limited to:

- M3CA Final Report Description

- Description of the hardware (updated from Final Design Report)
- Philosophy behind the hardware (updated from Final Design Report)
- As-built inspection reports and assembly records

- Final Analysis Package

- Calculations and Analyses performed to verify the design (updated from Final Design Report)
- Performance Budgets that present the results of the Verification Testing

- Verification Test Results

- Description of the series of tests that were performed to verify performance and calibrate the M3CA
- Analysis of the test results showing optical surface performance before and after calibration
- Description of the analysis, the systematic errors, and the process used to produce optical surface figure maps
- Comparison of the M3CA requirements, the M3CA error budget, and the analyzed test results

- User Manual containing:

- Procedures describing installation and removal of the M3M from the M3CA
- Procedures describing integration of the M3CA to TMT interfacing hardware
- Procedures for all required maintenance of the M3CA
- Procedures describing assembly and disassembly of the subsystems of the M3CA that may require replacement during the life of the Observatory
- Information on all replacement parts and where to purchase them
- A trouble-shooting guide that will enable TMT personnel to identify and repair problems with the M3CA

- List of Delivered Items:

- A list of all M3CA items mentioned in Section 2.2 that are delivered to TMT including major components, handling fixtures, test support equipment, spares, tools, and maintenance supplies

4.6.5 Final Acceptance Test Report

The Final Acceptance Test Report shall summarize the results of the functional testing performed during M3CA integration at the TMT Observatory. This report should include a roadmap that correlates how the TMT Observatory testing verifies that the M3CA will perform as predicted based on the Verification Testing at the Collaborating Institution. The report should include the Performance Budget and highlight any changes that result from the Acceptance Testing.

5. MEETINGS AND PROGRAMMATIC REPORTS

Throughout the course of the M3CA project, regular meetings and reports will enable frequent, high quality communication between the Collaborating Institution and the TMT project.

5.1 TECHNICAL INTERCHANGE MEETING (TIM)

Technical Interchange Meetings (TIM) shall be held by video or telephone conferencing regularly every two weeks. TIMs address the Collaborating Institution's progress, any issues or questions, and status with respect to the project schedule. TIMs shall also occur in person approximately every three months, alternating at the TMT office and the Collaborating Institution's facility. The Collaborating Institution will send digital slide presentations to TMT just before each TIM to document issues and track the program status against the plan.

5.2 MONTHLY SCHEDULE AND COST REPORT

At the beginning of each month, a written report updating the schedule and the costs incurred shall be sent to TMT for input into the TMT earned-value accounting system.

5.3 QUARTERLY REPORT

Quarterly reports will be scheduled to coincide with the in-person TIMs and will consist of presentations and/or a written report. The report and presentation shall include the present status of the program; work planned for the next quarter; review of the schedule; identification of concerns; proposed resolution of problems and a financial report.