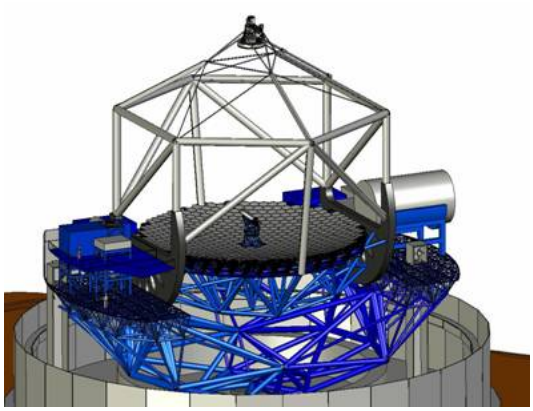
THIRTY METER TELESCOPE

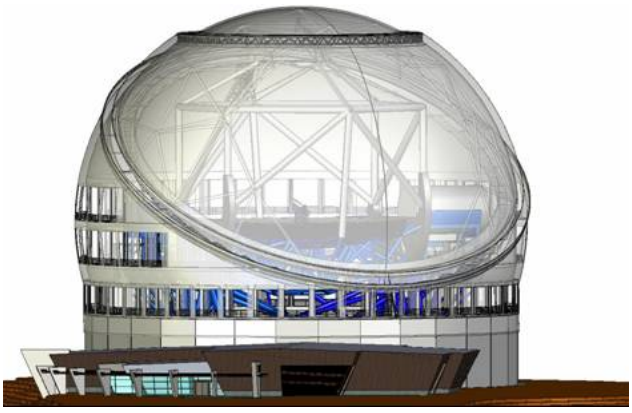
STATEMENT OF WORK

TERTIARY MIRROR POSITIONER (M3PA)

TMT.OPT.TEC.11.058.DRF01

9 May 2011





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1. INTRODUCTION

1.1 PURPOSE

This document defines the phased development and fabrication program to deliver the Thirty Meter Telescope (TMT) Tertiary Mirror Positioner (M3PA) 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 M3PA.

1.2 ABBREVIATIONS

AIV	Assembly, Integration & Verification Phase at TMT Observatory
CoDP	Conceptual Design Phase
DMU	Digital Mock-Up
FAB	Fabrication Phase
FDP	Final Design Phase
FDR	Final Design Review
FEA	Finite Element Analysis
FEM	Finite Element Model
FPPSR	Final Performance and Pre-Ship Review
ICD	Interface Control Document
LUT	Look-up Table
m	meter
M3	Tertiary Mirror
M3CA	Tertiary Mirror Cell Assembly
M3CSP	M3 Control System - Positioner
M3PA	Tertiary Mirror Positioner Assembly
M3POS	Tertiary Mirror Postioner
M3S	Tertiary Mirror System
M3S DRD	Requirements Document for Tertiary Mirror System (M3S)
mm	Millimeter
N/A	Not Applicable
OD	Outside Diameter
PDP	Preliminary Design Phase
PDR	Preliminary Design Review
TBD	To be determined
TCS	Telescope Control System
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 described in this Statement of Work
Support Equipment	Support Equipment includes handling equipment, test equipment, a mass simulator, a software 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.
Integrated Assembly	The Integrated Assembly is the fully operational assembly of the M3POS, the M3 Cable wrap, M3CSP and the M3CA mass simulator.

2. HARDWARE DESCRIPTION

2.1 BACKGROUND

The Thirty Meter Telescope is a three mirror Richey Chrétien design configured as shown in Figure 1~~Figure 1~~. The Tertiary (M3) Mirror is flat with an elliptical perimeter that reflects the telescope optical beam into the science instruments located on either of two Nasmyth platforms. For instruments that are not located on the elevation axis of the telescope, the Tertiary Mirror must rotate and tilt to track astronomical objects as the telescope rotates about the elevation axis.

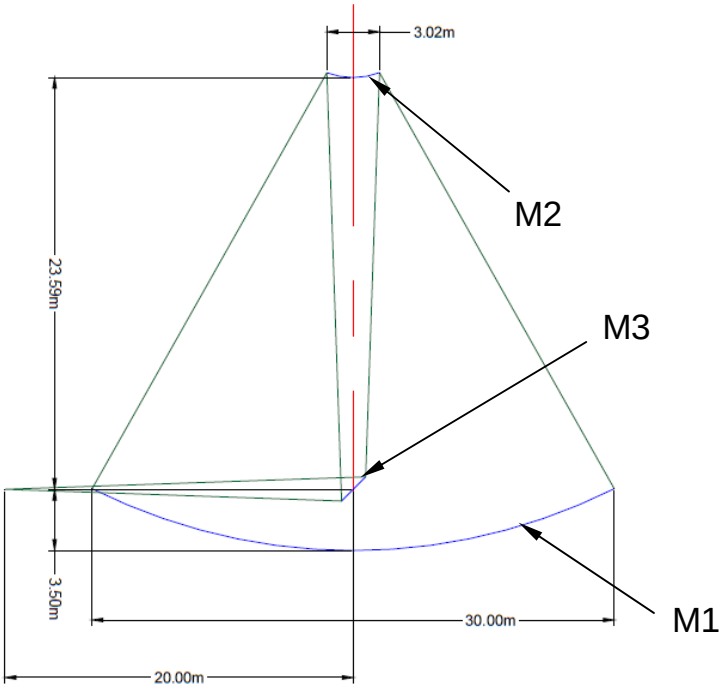

Figure 1. TMT Telescope Configuration

The parameters of the M3 Mirror are shown below in Table 1~~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 Positioner Assembly (M3PA)

An image of one design concept for the M3 System (M3S) is shown in Figure 2~~Figure 2~~. The M3PA is a subsystem within the M3S. The major components included in the M3PA are:

- M3POS – M3 Positioner. M3POS is the subsystem which rotates and tilts the M3 Cell Assembly (M3CA) to point the telescope beam towards any selected instrument on either Nasmyth Platform during observing. This subassembly is responsible for all rigid body motion of the M3 Cell Assembly (M3CA). The M3POS also rotates and tilts the M3CA to enable servicing and maintenance functions on the Telescope.
- M3 Cable Wrap. The M3 Cable Wrap carries all necessary electrical cables and hoses as they pass from the M3 Tower (an integral part of the Telescope Structure) to the rotating portion of the M3POS. This includes all necessary electrical wires, coolant hoses, hydraulics as required by the M3POS and the M3CA. Since the M3CA and portions of the M3POS move with respect to the M1 mirror cell, a cable wrap is required to support the cables and manage their motion as the M3CA is rotated by the M3POS.
- M3CSP – M3 Control System–Positioner. The M3CSP includes the electronics and software that controls the M3PA based on internal M3PA sensors and signals received from the Telescope Control System. The M3CSP also includes a safety system that autonomously responds to internal errors to place the M3PA in a safe condition when required. The safety system will interact with the Observatory Safety System (OSS) by responding to interlock demands from the OSS, and by sending interlock requests to the OSS when internal problems are detected. An image of one concept for the M3POS and M3 Cable Wrap is shown in Figure 3.

Please note that the M3PA does not include: the M3 Tower which is part of the Telescope Structure; the mechanical interface shims that position the M3POS accurately onto the M3 Tower; or the interface box on the M3 Tower that carries connections between the Telescope power and fluids and the M3S. The M3PA also does not include the lift fixture that will be used to install or remove the M3PA onto or off of the Telescope structure (see Section 2.2.2).

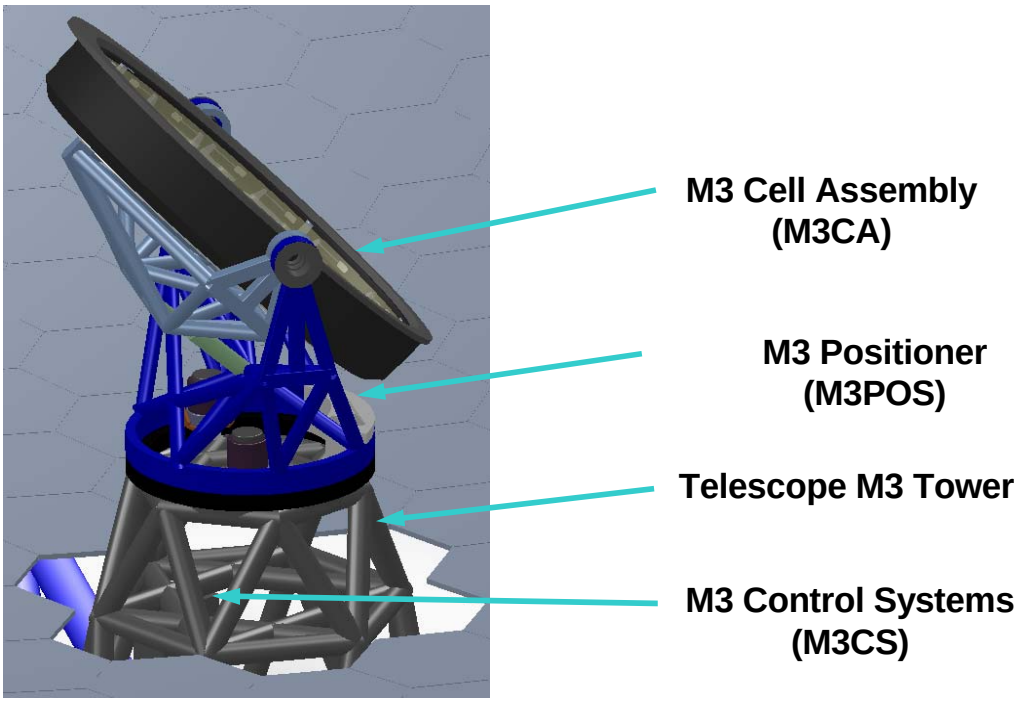

Figure 2. Concept for the M3 System

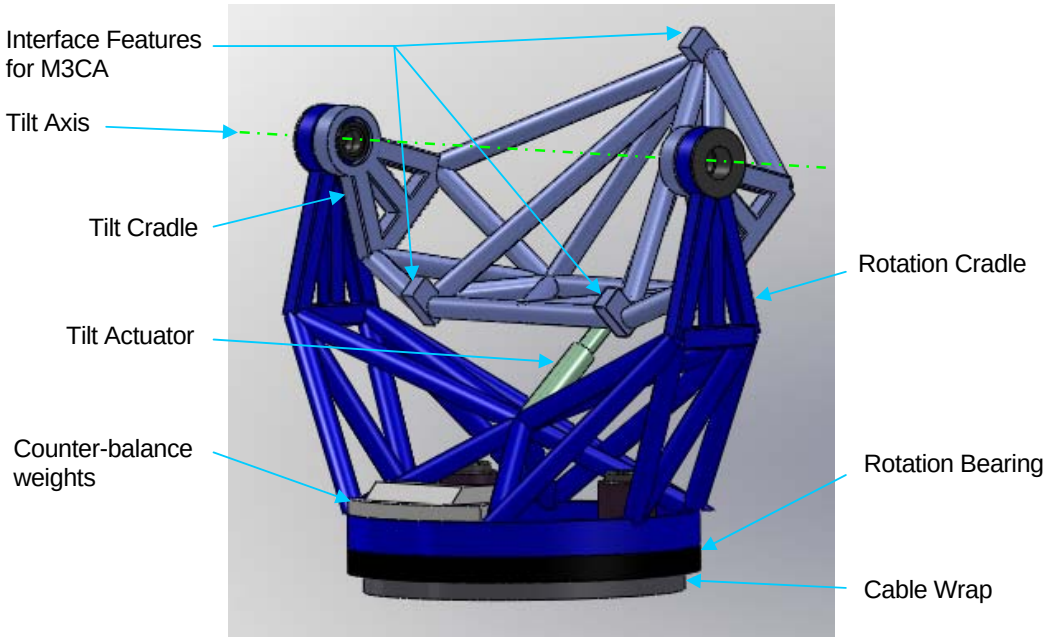

Figure 3. One Concept for the M3 Positioner and Cable Wrap

2.2.2 Support Equipment

In addition to the M3PA, the M3PA program shall also be responsible for providing the following additional equipment, which is referred to as Support Equipment:

- M3 Positioner Test Equipment including supports, fixtures, and electronics used to test the M3PA
- Lifting fixtures, assembly fixtures and handling equipment needed for handling the M3PA during assembly and testing of the M3PA at the Collaborating Institution location
- Deliverable M3CA Mass Simulator having the same mass, mass moment of inertias, center-of-mass location, and mounting features as the M3 Cell Assembly
- Deliverable lifting fixtures and handling equipment for use during verification and integration at the TMT Observatory; these may be the same equipment used for handling the M3PA during assembly and test
- Deliverable software simulator that will be used to simulate the M3CSP during Integration at the TMT Observatory for all tests when the M3PA is not connected to the Telescope Control System (TCS). The simulator may reside on a laptop computer and should incorporate trouble-shooting aids to help debug M3PA control functions
- Deliverable spare parts, circuit board extractors, tools and supplies required for assembly/disassembly and maintenance or replacement of the M3PA components and all deliverable M3PA support equipment to ensure continuous operation of the M3S to the level meeting requirements. 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 for each component.
- Deliverable Shipping Containers for the M3PA and all delivered support equipment

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 M3PA if required for maintenance or replacement of parts.

Further description can be found in:

- Requirements Document for Tertiary Mirror System (M3S DRD)

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)
- Laboratory 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 M3PA Requirements

The Collaborating Institution will review available TMT documents that describe the requirements for design, fabrication, assembly, integration and testing of the M3PA. 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 operations). 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 begin 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 with CoDP	**TBD + 2 months**

2.3.2 Conceptual Design Phase (CoDP)

2.3.2.1 Conceptual Design Evaluation

The Conceptual Design Phase shall focus on developing and evaluating design options for the M3PA with the goal of selecting the option that meets all requirements while providing the best, practical, cost-effective solution that can be implemented by the Collaborating Institution. The Collaborating Institution may want to consider several design approaches including, but not limited to the following:

- Gimbal-type positioner with linear tilt actuator
- Gimbal-type positioner with direct drive tilt axis
- Hexapod tilt positioner mounted to rotation stage

2.3.2.2 Conceptual Design Activities

During this phase, the Collaborating Institution will perform trade studies to determine the best design concept for the M3PA.

The concepts that are studied should be developed well enough to be able to compare their ability to meet requirements, cost and risk.

2.3.2.3 Conceptual Design Review

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

- Description of the options considered for the M3PA
- Comparison tables summarizing how the selected design 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 performance and programmatic issues

The presentation PowerPoint files and a CoDR Report described in Section 4.7.1 will be Deliverables 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 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 as agreed to by the Collaborating Institution and the TMT Project at the end of the Conceptual Design Phase.

During this phase, the Collaborating Institution will develop preliminary designs for the M3PA and the Support Equipment listed in Section 2.2.2. As part of this design work, performance budgets will be developed, as described in Section 3.1. The error budgets shall include gravitational and thermal variations, and control system drift and errors and shall address the required M3PA motions described in the M3 DRD. The Collaborating Institution will perform sensitivity analyses to relate the parameters of the design to the performance budgets.

For the most important aspects of the design, the Collaborating Institution will develop multiple design concepts and analyze their performance and cost, in order to do trade studies that compare the design options. The Collaborating Institution will do analyses related to safety and reliability, for example, determining the predicted stresses during strong earthquakes.

The Collaborating Institution will also develop preliminary designs of the facilities to be used for assembly and testing. Preliminary designs for support equipment should also be developed along with a preliminary plan for maintenance and spares.

2.3.3.2 Preliminary Design Review

The Preliminary Design Review (PDR) is a Project Review that will present the accomplishments of the Preliminary Design Phase in PowerPoint format, including:

- Management section presenting the project plan and reviewing the cost and schedule performance relative to the plan
- Review of the M3PA preliminary design, CAD models, control system architecture and software approach
- Presentations of the kinematic and dynamic analysis, structural analysis, and thermal analysis
- Detailed performance budgets that describe the allocation and flow-down of the key performance requirements
- Summary of the predicted M3PA performance showing that all requirements will be met
- Description of the key program risks, and the plan for managing the risks
- Review of interfaces with other telescope subsystems to ensure interface concepts are communicated and compatible between subsystems
- Review the design of the facilities that will be used for assembly and testing
- Plans for developing and testing prototypes if needed during the final design phase
- Preliminary designs of the Support Equipment and plans for maintenance and spares
- Computer Aided Design files per Section 4.2
- Control System Documentation per Section 4.3
- Preliminary plans for the manufacturing approach as described in Section 4.4
- 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 4.7.2 will be Deliverables at the PDR.

2.3.3.3 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**
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 M3PA 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. Also, components must be evaluated for lifetime, required spares must be identified, and a maintenance plan must be developed.

2.3.4.2 Final Design Review

The Final Design Review (FDR) is a Project Review presented in PowerPoint format with the purpose of ensuring that the M3PA 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 M3PA design, including the design philosophy, the controls, electronics and software architecture choices, and a summary of M3PA operation
- Final design of interfaces with other telescope subsystems
- Final designs of the Support Equipment and the assembly and testing 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
- Computer Aided Design files per Section 4.2
- Control System Documentation per Section 4.3
- Final manufacturing approach including plans described in Section 4.4
- Quality assurance plans per Section 4.6
- Verification plans per Sections 2.3.6 and 4.5
- Maintenance plan, lifetime evaluation of components and type and quantity of deliverable spare parts.
- 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, the manufacturing and assembly approach, and verification testing; and update the hazard / risk assessment.

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 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**
Deliver FDR Documentation	**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 provided an authorization to proceed.

During the Fabrication and Assembly Phase the Collaborating Institution will fabricate or purchase all the component parts required to produce the M3PA 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 Project 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 Assembly Activities

Prior to beginning assembly, critical assembly processes requiring particular care or precision will be documented in written Assembly Procedures. 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 M3PA. During assembly, major component assemblies will be tested separately as necessary to demonstrate performance prior to incorporation into higher level assembly.

2.3.5.4 Controls and Software Development

The electronics and software for the M3CSP and simulators shall be completed and debugged in preparation for their use during the Verification Phase.

2.3.5.5 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.

2.3.5.6 Verification Readiness Review

The Verification Readiness Review (VRR) is a Project Review that ensures that the M3PA 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 M3PA per Section 2.3.6.
- Test procedures for generating the gravity-based and thermally-based LUTs at the Collaborating Institution's facility
- 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 M3PA 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 as described in Section 4.5 will be a Deliverable at the VRR.

2.3.5.7 Meetings

In addition to the meetings listed in Section 4.6 and reviews, TMT Project engineers will attend and witness critical assembly steps at the Collaborating Institution's facility. In particular, TMT is interested in attending critical assemblies including, but not limited to, assemblies of hardware that affects the error budget.

2.3.5.8 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**
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 M3PA 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, changes must be documented. If the change may affect the ability to verify requirements of the M3PA, 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 M3PA meets requirements that affect the final the performance of the fully assembled M3 System. The final motion performance should be measured on the Integrated Assembly of the M3POS, the cable wrap, M3CSP and the M3CA mass simulator. The motion performance should be

measured between the interface where the M3CA attaches and the interface of the Integrated Assembly to the telescope M3 Tower. The Verification tests shall include but not be limited to the following measurements:

- Rotation and tilt motion performance that verifies that the M3PA meets requirements with the Integrated Assembly oriented to represent the TMT telescope pointing towards zenith.
- Rotation and tilt motion performance that verifies that the M3PA meets requirements when the Integrated Assembly is oriented to represent the TMT telescope pointing through the required range of zenith angles. This verification may be achieved through a full angled test, a combination of discrete angled tests and FEA, or by a TBD approach proposed by the Collaborating Institution.
- Rotation and tilt motion performance that verifies that the M3PA meets requirements through 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.

A Telescope Control System (TCS) simulator will be provided by the TMT Project. This, along with the M3CSP, will be used to control the Integrated Assembly during verification tests. The M3CSP simulator will also be tested separately with the TCS simulator to demonstrate its functionality.

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 AIV Plan for M3PA integration onto the telescope

Based on the results of the Laboratory Verification Phase testing, the Collaborating Institution shall review and update the AIV Plan for M3PA 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 M3PA and review the shipping containers and plans for transportation of the M3PA, the M3CSP and the equipment described in Section 0. 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
- A verification table that demonstrates that the M3PA will meet the requirements listed in M3S DRD
- AIV Plan for M3PA 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

The M3PA Final Report described in Section 4.7.4 will be a Deliverable at the FPPSR.

2.3.6.5 Packing and Shipping

Following the successful completion of the Pre-Ship Review, the M3PA and the Support Equipment shall be disassembled and packed into protective shipping containers. TMT management will provide authorization to ship when the TMT warehouse and the observatory site are ready for delivery of the M3PA and Support Equipment. The containers shall be transported by the M3PA Collaborating Institution to the TMT Observatory.

2.3.6.6 Meetings

During the Laboratory 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 LABORATORY VERIFICATION PHASE	DATE
Start Laboratory Verification Phase	**Per Project Plan**
M3PA 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 M3PA 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 been subjected to loads that would damage the hardware contained inside. If the M3PA 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, have 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, for any necessary repair work, for temporary storage of the M3PA 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 M3PA, Collaborating Institution personnel will supervise any repacking, transportation from the warehouse to the Observatory, the unpacking and inspection of the M3PA hardware upon arrival at the TMT Observatory. TMT will provide cranes as needed for lifting, and technician support for unpacking and crane operation.

2.3.7.2 M3PA Assembly

Collaborating Institution personnel will supervise the unpacking and assembly of M3PA upon arrival at the TMT Observatory. The assembly will follow the AIV Procedures that were prepared during the Laboratory 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 M3PA 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 M3PA assembly and testing. TMT will provide space for the assembly work, cranes, and technicians certified to run the cranes.

2.3.7.3 Installation of the M3PA onto the TMT Telescope

Following the M3PA Assembly and functional performance testing, the M3PA will be installed onto the TMT Telescope. Collaborating Institution's personnel will support the installation effort. TMT will provide technicians to integrate the M3PA onto the telescope.

2.3.7.4 Final Acceptance Test of the M3PA

After the Installation, the Final Acceptance Test of the M3PA 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 M3PA 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 M3PA, 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 4.7.5:

- 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 M3PA 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 M3PA 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
M3PA Arrival at the TMT Observatory	**Per Project Plan**
Final Acceptance Test of the M3PA	**Per Project Plan**
Delivery, M3PA 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 M3PA. The performance requirements that should be covered in the set of Performance Budgets include, at a minimum: (1) system mass; (2) the accuracy and repeatability of the position of the interface to the M3CA in six degrees of freedom over the telescope observing conditions; (3) performance variation caused by control system factors; (4) heat dissipated to the environment; and (5) stresses on critical parts where failures may cause functional failure or unsafe conditions for personnel.

The Performance Budgets will be maintained throughout the entire program. The Performance Budgets will guide the performance aspects of the development program and will assure that the delivered system meets TMT specifications.

A sensitivity analysis shall be performed on each parameter in the Performance Budgets to show how variation of each budget parameter affects the M3PA performance.

A performance evaluation based on the Performance Budgets will ensure that the M3PA will meet all M3PA performance requirements contained within the M3S DRD.

From the beginning of the M3PA program, the Performance Budgets will be developed, then documented and presented for TMT evaluation. 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 M3PA 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 M3PA Positioning and Motion Performance Budget

The Performance Budget that evaluates the positioning and motion performance of the M3PA is of particular concern. It should include as a minimum:

- **Tolerance studies**
  All performance related M3PA 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 positioning and motion performance of the M3PA.

- **Sensor sensitivity, resolution and repeatability**
  The sensitivity to electrical and environmental variation and the resolution and repeatability of all sensors included in the M3PA hardware as well as in the test equipment shall be evaluated and included in the Performance Budget.

- **Control system errors**

  The drift and noise in the control systems of the M3PA, and the test equipment 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 positioning and motion performance of the M3PA hardware and the test equipment shall be evaluated and included in the Performance Budget. These effects must be associated with both the observing environment and the testing 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 M3PA 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 Analysis, including Finite Element Analysis (FEA), will be used to evaluate the M3PA 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 actuator range of motion. 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 M3PA 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 M3PA:

- Determine the position of the M3PA interface features with M3CA relative to the telescope interface as the gravity vector changes direction and the environmental temperatures vary. These analyses will be used to demonstrate that the M3PA will meet the performance requirements.
- Determine the sensitivity of M3PA performance to variations in component parameters, as described in section 4.1.
- The FEMs will be used to understand the metrology requirements for the testing done to generate Look-Up Tables that will be used during open loop operations of the TMT Telescope.
- Determine the vibration natural frequencies and mode-shapes
- The M3S must survive the earthquakes that frequent the TMT Observatory site. FEM seismic analysis will guide the M3PA and M3CSP design to ensure earthquake survival as defined in the M3S DRD.

3.3 RISK EVALUATION

The Collaborating Institution will have the best understanding of problems that could 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 M3PA 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 M3PA risks will be included in the TMT project risk register so that key risks can be managed appropriately.

4. DOCUMENTATION REQUIRED

Note: All deliverable documentation for the M3PA shall be prepared in English.

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 M3PA project within its allotted budget, on track to deliver the M3PA 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 M3PA
2. The required level of staffing for each phase of the work, and plans for recruiting any team members who 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 M3PA 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 M3PA 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 M3PA models into the TMT Digital Mockup (DMU) (the global TMT CAD model).

All of the 2D drawings documenting the M3PA 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 M3PA interfaces with other Telescope and Observatory subsystems. Creation and exchange of ICDs that describe the M3PA 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 CONTROL SYSTEM SOFTWARE DOCUMENTATION

The conceptual and preliminary design documentation for the M3CSP should include a software requirements document, a description of the software architecture, a trade study of the various software frameworks that could be used, draft software interface documents, and a software development and implementation plan.

The final design documentation of the M3CSP should include a detailed description of all software interfaces, a description of all data flows, a description of all faults and alarms, and a draft operations manual.

Source code, build procedures, user manuals, and troubleshooting manuals should be delivered with the M3PA system in the M3PA Final Report.

In addition to all functional requirements, the control software and hardware for the M3PA will require safety features to prevent damage to the M3PA or any possible harm to personnel. Built-in trouble-shooting and debugging features will aid in M3PA controls problem debugging during the 50 year lifetime of the TMT Telescope.

The software system will need to be robust and well documented in a common, long-lived language like C++ since the system will need to be maintained for the 50 year lifetime of the observatory. Software source code and build procedures should be delivered along with the M3CA hardware.

The software shall be developed in accordance with the TMT Software Attributes Standards (Document # TBD).

4.4 MANUFACTURING APPROACH DOCUMENTATION

During the Preliminary Design Phase and by the end of the Final Design Phase, the Manufacturing Plan for the M3PA should be fully developed, reviewed by TMT and approved. In order to provide TMT with a complete description of the M3PA 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:

<u>Manufacturing Process:</u>

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 M3PA assemblies. As the M3PA is assembled, the assembly procedures will document the actual assembly steps for the complex assemblies.

4.5 VERIFICATION PLAN DOCUMENTATION

The Verification Plan shall describe the methods that will be used to verify that the M3PA will meet the requirements listed in the M3S DRD. There are two phases that establish the full verification of the M3PA – 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 M3PA 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 M3PA 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 M3PA 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

4.6 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.

4.7 M3PA REPORTS

4.7.1 Conceptual Design Report

In addition to the PowerPoint files presented at the CoDR, a written report that documents the Conceptual Design of the M3PA will be delivered along with the Conceptual Design Review. This report should describe the items listed in Section 2.3.2.3

4.7.2 Preliminary Design Report

In addition to the PowerPoint files presented at the PDR, a written report that documents the Preliminary Design of the M3PA will be delivered along with the Preliminary Design Review. This report should describe items listed in Section 2.3.3.2.

The report should contain the documentation items described above in Sections 0 through 4.5, developed to the level that is appropriate at the PDR.

4.7.3 Final Design Report

In addition to the PowerPoint files presented at the FDR, a written report that documents the Final Design of the M3PA will be delivered along with the Final Design Review. This report should describe items listed in Section 2.3.4.2. The report will update and expand the information from the Preliminary Design Report. The report should include a description of the design choices, the controls, electronics and software architecture choices, the philosophy behind the design, how the M3PA will operate, 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 and should include action items and resolutions from the PDR.

4.7.4 M3PA Final Report

Upon completion of the Verification Phase, the M3PA Final Report shall also be delivered. The purpose of the M3PA 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:

- M3PA Final Report Description

- Description of the hardware and control system details (updated from Final Design Report)
- Philosophy behind the hardware and control system (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

- Final Software Documentation

- Source code for all software
- Build procedures for all software
- Description of the software architecture
- Interface documents
- Troubleshooting manuals
- Define variables used within the code
- List and define subroutines within the code including, but not limited to,
  - M3CA operation routines
  - Safety features
  - Debugging routines

- Final Electronic Documentation

- Electronic assembly and cable schematics
- Board layout documentation
- Source code and build procedures for all firmware
- Maintenance manuals
- Interface documents
- Troubleshooting manuals

- Verification Test Results

- Description of the series of tests that were performed to verify performance and calibrate the M3PA
- Description of the analysis and any systematic errors
- Comparison of the M3PA requirements, the M3PA error budget, and the analyzed test results

- User Manual containing:

- A description of the operation of the M3PA hardware, control system and software
- Procedures describing integration of the M3PA to TMT telescope interfacing hardware
- Procedures for all required maintenance of the M3PA
- Procedures describing assembly and disassembly of the subsystems of the M3PA that may require replacement during the life of the Observatory
- Information on all replacement parts and where to purchase them
- A description of the Look-Up Tables and how to update them
- A trouble-shooting guide that will enable TMT personnel to identify and repair problems with the M3PA
- A description of the safety system within the M3CSP, what safety alarms mean and procedures to protect the M3PA and personnel if the alarms are triggered

- List of Delivered Items:

- A list of all M3PA items mentioned in Section 2.2 that are delivered to TMT including major components, handling fixtures, test support equipment, spares, tools, and maintenance supplies

4.7.5 Final Acceptance Test Report

The Final Acceptance Test Report shall summarize the results of the functional testing performed during M3PA integration at the TMT Observatory. This report should include a roadmap that correlates how the TMT Observatory testing verifies that the M3PA 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 M3PA 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 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.