THIRTY METER TELESCOPE

STATEMENT OF WORK

SECONDARY MIRROR CELL ASSEMBLY (M2CA)

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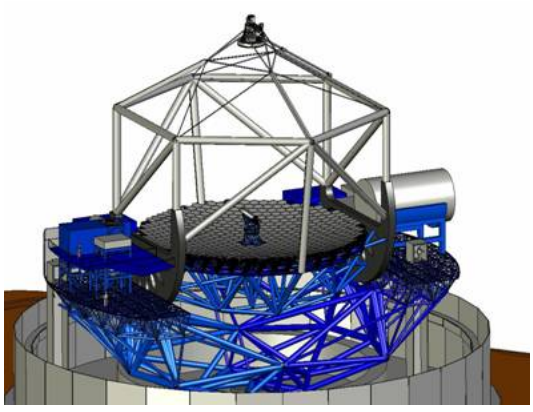
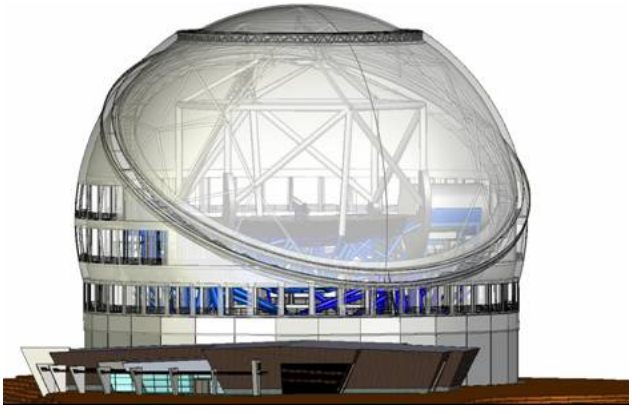
22 July 2010





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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) Secondary Mirror Cell Assembly (M2CA) 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 M2CA.

1.2 ABBREVIATIONS

AIV	Assembly, Integration & Verification Phase
ARR	Assembly Readiness Review
DMU	Digital Mock-Up
FAR	Final Acceptance Review
FDR	Final Design Review
FEA	Finite Element Analysis
FEM	Finite Element Model
FPR	Final Performance Review
ICD	Interface Control Document
ID	Inside Diameter
LUT	Look-up Table
m	meter
M2A	Secondary Mirror Assembly
M2 Blank	Secondary Mirror Blank
M2C	M2 Cell Structure
M2CA	Secondary Mirror Cell Assembly
M2CSC	M2 Control System - Cell
M2M	Completed Secondary Mirror
M2S DRD	Requirements Document for Secondary Mirror System (M2S)
M2SS	Secondary Mirror Support System
mm	Millimeter
N/A	Not Applicable
OD	Outside Diameter
PDR	Preliminary Design Review
PSR	Pre-Ship Review
RRR	Requirements Readiness Review
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	The term Support Equipment is defined in section 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 Secondary Mirror is a convex hyperboloid that faces downward when the telescope is pointing toward zenith.

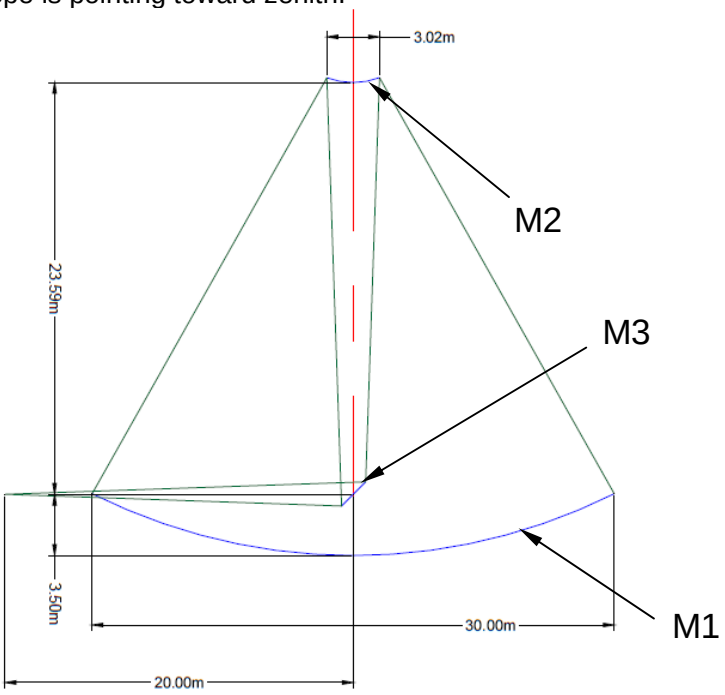

Figure 1. TMT Telescope Configuration

The parameters of the M2 Mirror are shown below in Table 1.

Table 1. Parameters of the TMT M2 Mirror

Mirror Element	Optical Beam Diameter (m)	Coated Clear Aperture Diameter (m)	Mechanical Diameter (m)	Thickness (mm)	Optical Surface Spherical Radius of Curvature (m)	Conic Constant
Finished M2 Mirror	OD: 3.0245 ID: 0.220	OD: >3.060 ID: <0.200	OD: 3.110 ID: 0.180	100	- 6.2277	-1.3182
M2 Mirror Blank	N/A	N/A	OD: 3.125	103	- 6.348	N/A

2.2 SCOPE

2.2.1 Secondary Mirror Cell Assembly (M2CA)

An image of the M2 Assembly (M2A) including all subsystems is shown in Figure 2. The M2CA includes a subset of the subsystems within the M2A. The major components included in the M2CA are:

- M2C – M2 Cell. The M2C is the subsystem which interfaces to the M2CA lift fixture and M2 Positioner, supports the M2SS and provides hardware to enable washing the M2M in situ.
- M2M – Secondary Mirror. The M2M is the polished secondary mirror (polished to TMT specifications) including bonded pucks that interface with the M2SS.
- M2SS – M2 Support System. The M2SS is the subsystem that supports the weight of the M2M and defines its position and orientation in the telescope. It includes flexure attachments to the M2M, axial and lateral support and defining mechanisms, force sensors and force actuators for deforming the M2M figure, and interfaces to the M2M and the M2C.
- M2CSC – M2 Control System–Cell. The M2CSC includes the electronics and software that controls the M2CA based on internal M2CA sensors and signals received from the Telescope Control System. The M2CSC also includes a safety system that autonomously responds to internal errors to place the M2CA in a safe condition. 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.

2.2.2 Support Equipment

In addition to the M2CA, the M2CA program shall also be responsible for developing, fabricating, integrating and testing the following additional equipment, which is referred to as Support Equipment:

- M2 Mirror Polishing and Testing Facility that includes supports, fixtures and test towers used for polishing and metrology of the M2M
- Lifting fixtures, and handling equipment needed during polishing of the M2M and for final measurement of the M2M and M2CA optical surface in the specified orientations;
- Deliverable Lifting Fixtures for the M2M and the M2CA for use at the TMT Observatory; these will be required to meet additional TMT requirements and interfaces, but may be the same handling equipment used for handling the M2M and the M2CA in the polishing and testing facility;
- Deliverable Handling Fixtures and Carts for the M2M and the M2CA for use at the TMT Observatory; these will be required to meet additional TMT requirements and interfaces, but may be the same handling equipment used for polishing the M2M and handling the M2CA;
- Deliverable software simulator that will be used to simulate the M2CSC during Integration at the TMT Observatory for all tests when the M2CA is not connected to the Telescope Control System (TCS). The simulator may reside on a laptop and should incorporate trouble-shooting aids to help debug M2CA control functions;
- Deliverable Surrogate M2M for initial testing of the M2CA;
- Deliverable Surrogate M2CA for testing all M2CA fixtures and metrology equipment, and for use by the M2 Positioner Contractor for testing;
- Deliverable spare parts, circuit board extractors, tools and supplies required for assembly/disassembly and maintenance or replacement of the M2CA and all deliverable M2CA support equipment;
- Deliverable Shipping Containers for the M2 Blank, the M2M, the M2CA, the M2CSC and all related equipment; the M2 Blank shipping container will be used

to transport the M2 Blank to the mirror polishing facility, and may be reconfigured to become the shipping container for the M2M.

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 M2 for maintenance and recoating, approximately every 2 years.

Further description can be found in:

- Requirements and Conceptual Design of M2 System
- Requirements Document for Secondary Mirror System (M2S DRD)
- M2 System Operational Concept

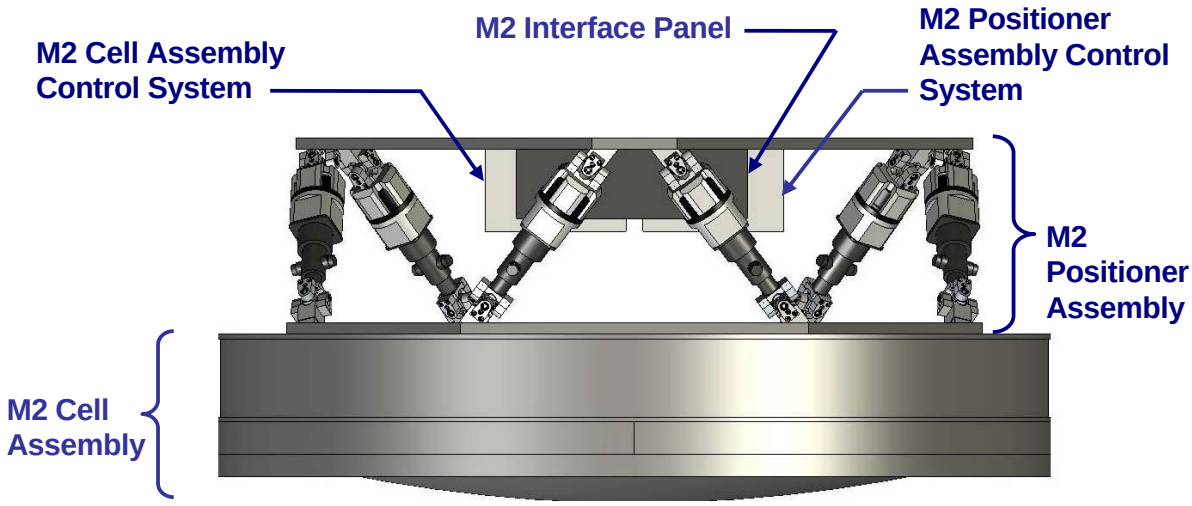

Figure 2. M2 Assembly

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
- Preliminary design phase
- Final design phase
- Fabrication phase
- Laboratory verification phase
- Assembly, integration and verification (AIV) phase (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 M2CA project to proceed correctly, resulting in on-time delivery of a system that meets TMT specifications. The following sections describe these tasks.

3.1 PLANNING PHASE

3.1.1 Review and Evaluate the M2CA Requirements

The Collaborating Institution will review available TMT documents that describe the conceptual design and the requirements for fabrication, assembly, integration and testing of the M2CA. In particular, the Collaborating Institution will review the Requirements Document for Secondary Mirror System (M2S) (abbreviated "M2S DRD", where DRD stands for "design requirements document") and the Interface Control Documents for the M2S. If any of the requirements are not clearly understood, 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 those changes that are shown to provide benefit.

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 5.1.

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 Preliminary Design Phase of the work.

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	**October 2011**
Submit proposed changes to the requirements	**November 2011**
Submit the Project Plan	**November 2011**
TMT Authorization to Proceed	**December 2011**

3.2 PRELIMINARY DESIGN PHASE

3.2.1 Design Activities

During this phase, the Collaborating Institution will develop preliminary designs for the M2CA and the Support Equipment listed in Section 2.2. As part of this design work, performance budgets will be developed, including: (1) an optical surface wavefront error budget; (2) a mirror surface position error budget; (3) a mass budget. 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 stress in the mirror as a result of a strong earthquake.

The Collaborating Institution will also develop preliminary designs of the optical fabrication and metrology facility, including the test facilities that will be used to measure gravity and temperature dependence and to develop and verify the zenith-angle-dependant and thermally-dependent look-up tables (LUTs).

3.2.2 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 M2CA preliminary design, CAD models and software approach
- Review the mirror testing and polishing facility design; if not already done
- Presentations of the Performance Budgets, the FEM analysis and Risk evaluation
- Summary of the predicted M2CA performance showing that all requirements will be met
- Plans for developing and testing prototypes as needed during the final design phase
- Preliminary designs of the Support Equipment
- Computer Aided Design files per Section 5.2
- Control System Documentation per Section 5.3
- Preliminary plans for the manufacturing approach as described in Section 5.4
- Plans for the polishing facility construction or modifications
- Review the safety aspects of the designs and prepare a preliminary hazard / risk assessment.

A PDR Report described in Section 5.6.1 will be a Deliverable at the PDR.

3.2.3 M2 Mirror Blank (M2 Blank)

During the Preliminary Design Phase, the Collaborating Institution will review the TMT M2 Blank Specification and present any desired changes to TMT for approval. The Collaborating Institution will place an order for the M2 Blank from the selected supplier. In addition, the Collaborating Institution will interface with the M2 Blank supplier to develop specifications for the shipping container that will protect the M2 Blank during transportation from the M2 Blank supplier to the M2M polishing facility.

3.2.4 M2 Mirror Polishing and Testing Facility

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

3.2.5 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	**December 2011**
Order M2 Blank	**Date As Required**
Preliminary Design Review	**December 2012**

3.3 FINAL DESIGN PHASE

3.3.1 Design Activities

During the Final Design Phase, the Collaborating Institution will complete the detailed design of all components of the M2CA and of the Support Equipment listed in Section 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.

3.3.2 Final Design Review

The Final Design Review (FDR) is a Project Review with the purpose of ensuring that the M2CA design is ready for fabrication. The comprehensive FDR should cover:

- Project plan and the cost and schedule performance relative to the plan
- All issues raised at the PDR, showing that they have been resolved
- All aspects of the final M2CA design, including the design philosophy, the controls, electronics and software architecture choices, and a summary of M2CA operation
- Final designs of the Support Equipment and the polishing facility
- Description of all analyses described in Section 4
- Prototype testing activities and results
- Compliance with requirements in the M2S 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 M2 Blank and construction of the polishing facility
- Computer Aided Design files per Section 5.2
- Control System Documentation per Section 5.3
- 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 5.4
- Quality assurance and verification plans
- Review the safety aspects of the designs and of the manufacturing approach and update the hazard / risk assessment.

A FDR Report described in Section 5.6.2 will be a Deliverable at the FDR.

3.3.3 M2 Mirror Blank (M2 Blank)

The Collaborating Institution shall prepare for transportation, receipt and incoming inspection of the M2 Blank, and shall schedule completion of the M2 Blank shipping container and handling equipment per the project plan.

The M2M polisher shall be responsible for design of the M2 Blank shipping container. The design of the M2 Blank shipping container will be submitted for approval to the TMT project office prior to its fabrication. The M2M polisher will be responsible for fabrication, for transporting the empty container to the M2 Blank vendor, for supervising packing the M2 Blank into the container and for shipping the M2 Blank to the M2M polishing facility. Receipt of the M2 Blank and mirror polishing shall be scheduled as needed to maintain the schedule milestones for the M2CA project.

3.3.4 Mirror Testing and Polishing Facility

During the Final Design Phase, the Mirror Testing and Polishing Facility must be completed and prepared to process the M2M. The M2M blank and polishing are on the critical path for TMT, so meeting the schedule for start of polishing will be critical.

3.3.5 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	**December 2012**
Complete Mirror Testing and Polishing Facility	**Date as required**
Final Design Review	**December 2013**

3.4 FABRICATION AND ASSEMBLY PHASE

During the Fabrication and Assembly Phase the Collaborating Institution will fabricate or purchase all of the component parts of the M2CA 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.

3.4.1 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.

3.4.2 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.

3.4.3 Mirror Blank (M2 Blank)

The Collaborating Institution will receive and inspect the M2 Blank. To prepare the M2 Blank for polishing, pads may be ground and etched on the blank for attaching bonded items, then attachment features will be bonded to the M2 Blank following the approved assembly plan.

3.4.4 Mirror Polishing and Metrology

The Collaborating Institution or its polishing subcontractor will perform the optical finishing operations required to fabricate the finished M2 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.

3.4.5 Assembly Readiness Review

The Assembly Readiness Review (ARR) is a Project Review to ensure that the fabricated hardware for the M2CA and the Support Equipment is ready for assembly. The ARR shall include:

- Project plan and the cost and schedule performance relative to the plan
- All issues raised at the FDR, showing that they have been resolved
- A summary of any changes made to the design or subassemblies during fabrication
- A summary of the as-built condition of any parts that deviate from their original specifications
- Assembly Procedures and plans for recording as-built assemblies conditions
- Test procedures describing upcoming subsystem testing that will occur during assembly and prior to full M2CA integration
- Analyses described in Section 4 and results based on as-built inspection reports
- Compliance with requirements in the M2S DRD and the associated as-built performance budgets based upon the inspection reports
- Quality assurance and verification plans
- Review the safety aspects of the assembly and testing approach and update the hazard / risk assessment.

3.4.6 Assembly Activities

Prior to beginning assembly, critical assembly processes requiring particular care or precision will be documented in written Assembly Procedures. At a minimum, procedures involving handling the M2 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 M2CA. During assembly, major component assemblies will be tested separately to demonstrate performance prior to incorporation into higher level assembly.

3.4.7 Controls and Software Development

The electronics and software for the M2CSC and simulators shall be completed and debugged in preparation for their use during the Verification Phase.

3.4.8 Verification Phase Planning

During the Fabrication and Assembly Phase, plans for Verification and Look-Up Table generation testing will be finalized.

3.4.9 Verification Readiness Review

The Verification Readiness Review (VRR) is a Project Review that ensures that the M2CA is ready for full integration and verification testing. The VRR will cover:

- Project plan and the cost and schedule performance relative to the plan
- All issues raised at the ARR, showing that they have been resolved
- Test procedures for performance verification testing of the M2CA
- Test procedures for generating the gravity-based and thermally-based LUTs
- Analyses and results based on as-built assembly records

- Requirements in the M2S DRD and the associated as-built performance budgets based upon the inspection reports and assembly records
- Preliminary plan for M2CA integration onto the TMT Telescope and the functional testing that will occur at the TMT Observatory
- Quality assurance and verification plans
- Review the safety aspects of the verification testing approach and update the hazard / risk assessment.

Verification Plan Documentation described in Section 5.5 will be a Deliverable at the VRR.

3.4.10 Meetings

In addition to the meetings listed in Section 5.6 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 M2M.

3.4.11 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	**January 2014**
Assembly Readiness Review	**March 2016**
Complete M2M polishing	**May 2016**
Verification Readiness Review	**August 2016**

3.5 LABORATORY VERIFICATION PHASE (AT COLLABORATING INSTITUTION)

3.5.1 Verification Testing

The M2CA will be tested at the Collaborating Institution's facility to verify that the performance meets the requirements listed in the M2S 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 Collaborating Institution will discuss these changes with TMT Management before proceeding with the testing.

Verification tests of the fully integrated M2CA and M2CSC shall include but not be limited to:

- Vertical Optical Surface measurement with M2CA facing downwards to verify that the M2CA optical surface meets the structure function requirement.
- Optical Surface measurement to determine M2SS active-optic actuator influence functions and the force sets required to produce individual Zernike mode shapes
- Residual error values for each Zernike mode shape
- Non-vertical Optical Surface measurements to verify that the M2CA optical surface responds to the changing gravity vector as predicted by analysis.
- Measurement of the thermal environment influence on the M2CA Optical Surface

A Telescope Control System (TCS) simulator will be provided by the TMT Project. This, along with the M2CSC, will be used to control the M2CA during verification tests. The M2CSC simulator will also be tested with the TCS simulator to demonstrate its functionality.

3.5.2 Look-Up Table Generation

Using the results of the Verification Testing, Look-Up Tables (LUTs) will be generated to control the M2CA optical surface during telescope operations. The LUTs will contain the optimum force settings of each mirror support actuator as a function of both zenith angle, over the range of 0 to 65 degrees, and temperature, over the range of -5 to +9 degrees C. The LUTs may be updated after operation on the telescope, but the originally supplied LUTs must be capable of controlling the M2CA so that it performs to meet specifications upon delivery to the TMT Observatory, without recalibration.

3.5.3 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.

3.5.4 Update of the Plan for the M2CA AIV support

Based on the results of the Laboratory Verification Phase testing, the Collaborating Institution shall review and update the AIV Procedures for M2CA Integration onto the TMT Telescope and the functional testing at the TMT Observatory.

3.5.5 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 M2CA and review the shipping containers and plans for transportation of the M2CA, the M2CSC 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
- All issues raised at the VRR, showing that they have been resolved
- Description of each test that was conducted and the data collected
- Derivation of the LUTs for gravity and thermal effects
- Final Performance Budget with explanation of how the measured data was used
- Verification that the M2CA will meet the requirements listed in M2S DRD
- Plan for M2CA 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 (M2M) be removed from the mirror cell (M2CA) 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 M2CA Final Report described in Section 5.6.3 will be a Deliverable at the FPPSR.

3.5.6 Packing and Shipping

Following the successful completion of the Pre-Ship Review, the M2CA and the Support Equipment shall be disassembled and packed into protective shipping containers. TMT management will provide authorization to ship when the conditions at the TMT warehouse and the observatory site are safe for delivery of the M2CA and Support Equipment. The

containers shall be transported by the M2CA Collaborating Institution to the TMT Observatory.

3.5.7 Meetings

During the Verification Phase, TMT personnel shall attend and witness most of the Verification Tests and Look-Up Table Generation Tests.

3.5.8 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	**September 2016**
M2CA Performance Review	**May 2017**
Pre-ship Review	**May 2017**
Start of transportation to TMT Observatory	**July 2017**

3.6 ASSEMBLY, INTEGRATION AND VERIFICATION (AIV) PHASE (AT THE TMT OBSERVATORY)

3.6.1 M2CA 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 M2CA 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 M2CA 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 M2CA, Collaborating Institution personnel will supervise any repacking, transportation from the warehouse to the Observatory, the unpacking and inspection of the M2CA 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 M2M at the Observatory, it will be coated in the TMT Observatory coating facility.

3.6.2 M2CA Assembly

Collaborating Institution personnel will supervise the assembly of M2CA with the coated M2M. 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 M2CA 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 M2CA

assembly and testing. TMT will provide space for the assembly, cranes and technicians certified to run the cranes.

3.6.3 Installation of the M2CA onto the TMT Telescope

Following the M2CA Assembly and functional performance testing, the M2CA will be installed onto the TMT Telescope. Collaborating Institution's personnel will support the installation effort. TMT will provide technicians to integrate the M2CA onto the telescope.

3.6.4 Final Acceptance Test of the M2CA

After the Installation, the Final Acceptance Test of the M2CA 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.

3.6.5 M2CA Training

Collaborating Institution personnel will train TMT personnel on the handling, assembly and testing of the M2CA. They shall also train TMT personnel on the operation and maintenance of the M2CA, and regarding any diagnostic systems or procedures.

3.6.6 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 5.6.4:

- 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 M2CA 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 M2CA project team.

3.6.7 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
M2CA Arrival at the TMT Observatory	**August 2017**
Final Acceptance Test of the M2CA	**January 2018**
Delivery, M2CA Final Acceptance Test Report	**February 2018**

4. ANALYSES REQUIRED

4.1 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 M2CA. 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) the position of the optical surface in six degrees of freedom; (4) heat dissipated to the environment; and (5) safety related budgets, for example, a budget of factors that can introduce stress into the glass of the M2 Mirror.

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 performed on each parameter in the Performance Budgets will show how variation of each budget parameter affects the M2CA performance.

A performance evaluation based on the Performance Budgets will ensure that the M2CA will meet all M2CA performance requirements contained within the M2S DRD.

From the beginning of the M2CA 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 M2CA 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.

4.1.1 M2CA Optical Performance Budget

The Performance Budget that evaluates the optical performance of the M2CA is of particular concern. It should include as a minimum:

- **Tolerance studies**
  All performance related M2CA 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 M2CA.

- **Sensor sensitivity, resolution and repeatability**
  The sensitivity to electrical and environmental variation and the resolution and repeatability of all sensors included in the M2CA hardware as well as in the optical metrology and measuring instruments shall be evaluated and included in the Performance Budget.

- **Control system errors**

  The drift and noise in the control systems of the M2CA, the optical metrology, and the measuring instruments 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 M2CA 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 M2CA will be included in the Performance Budget and quantified to provide an understanding of the effects.

4.2 THERMAL AND STRUCTURAL ANALYSIS

Thermal and Structural Finite Element Analysis (FEA) will be used to evaluate the M2CA 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 M2CA 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 M2CA:

- Determine M2M optical surface deformation as the gravity vector changes direction and the environmental temperatures vary. These analyses will be used to demonstrate that the M2CA will meet the performance requirements, including the active optics correction by the cell assembly.
- Determine the sensitivity of M2CA 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 that must be done to generate Look-Up Tables for controlling the M2M surface during open loop operations of the TMT Telescope.
- The M2A must survive the earthquakes that frequent the TMT Observatory site. FEM seismic analysis will guide the M2CA and M2CSC design to ensure earthquake survival as defined in the M2S DRD.

4.3 ACTIVE OPTICS PERFORMANCE

Active-optic corrections provided by the M1, M2, and M3 system are essential to maintain wavefront control of the telescope. The active control of the M2CA must meet TMT requirements and a complete analysis of the M2CA active optic performance is

required, including the analytical determination of the influence function of each actuator, and the analytical determination of optimum sets of forces to produce low-order bending modes of the mirror as specified in the M2S DRD. This work shall also include the development of gravity-dependant and temperature-dependant Look-Up Tables (LUTs) that will be used to maintain mirror shape during telescope operation.

4.4 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 M2CA 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 M2CA risks will be included in the TMT project risk register so that key risks can be managed appropriately.

5. DOCUMENTATION REQUIRED

5.1 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 M2CA project within its allotted budget, on track to deliver the M2CA 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 M2CA
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 M2CA 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.

5.2 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 M2CA 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 M2CA models into the TMT Digital Mockup (DMU) (the global TMT CAD model).

All of the 2D drawings documenting the M2CA 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 M2CA interfaces with other Telescope and Observatory subsystems. Creation and exchange of ICDs that describe the M2CA 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.

5.3 CONTROL SYSTEM SOFTWARE DOCUMENTATION

The preliminary design documentation for the M2CSC 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 M2CSC should include a detailed description of all 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 M2CA system in the M2CA Final Report.

In addition to all functional requirements, the control software and hardware for the M2CA will require safety features to prevent damage to the M2CA or any possible harm to personnel. Built-in trouble-shooting and debugging features will aid in M2CA 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 M2CA hardware.

5.4 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 M2CA project. During the Preliminary Design Phase and by the end of the Final Design Phase, the Manufacturing Plan for the M2CA should be fully developed, reviewed by TMT and approved. In order to provide TMT with a complete description of the M2CA 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.

Engineering Change Requests:
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. Changes may be caused by fabrication issues or requirements issues and provide a method of recording a change without 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 M2CA assemblies, including but not limited to any assemblies involving M2M and critical dimensional tolerances. As the M2CA is assembled, the assembly procedures will document the actual assembly steps for the complex assemblies.

5.5 VERIFICATION PLAN DOCUMENTATION

The Verification Plan shall describe the methods that will be used to verify that the designs meet the requirements based upon a Verification Matrix that the Collaborating Institution shall develop using the M2S DRD.

The preliminary design description of the Verification Plan should be conceptual but adequate to ensure that the hardware and test equipment needed to perform verification tests is included in the project plan.

The final design documentation of the Verification Plan should include a detailed description of the hardware and test equipment required, the flow-down from the planned tests to the requirements, a description of measurement data and data processing.

At the VRR, the hardware and test equipment required should be completed, verification test procedures should be written for all tests describing how to obtain all measurement data, and the planned processing of the measurement data should be described completely.

5.6 M2CA REPORTS

5.6.1 Preliminary Design Report

A written report that documents the Preliminary Design of the M2CA will be delivered along with the Preliminary Design Review. This report should describe the preliminary design of the items listed in Section 2.2 and will be useful to TMT Observatory staff and Astronomers throughout the life of the Observatory since it will provide documentation of the background for the choices and decisions that led to the final design.

The Preliminary Design description should present trade studies; show CAD layout of the preferred design; detail the actuators, control architecture, electronics 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 5.1 through 5.5, developed to the level that is appropriate at the PDR.

5.6.2 Final Design Report

A written report that documents the Final Design of the M2CA 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 controls, electronics and software architecture choices, the philosophy behind the design, how the M2CA 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 and should include action items and resolutions from the PDR.

5.6.3 M2CA Final Report

Upon completion of the Verification Phase, the M2CA Final Report shall also be delivered. The purpose of the M2CA 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:

- M2CA 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,
  - M2CA 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 M2CA
- 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 M2CA requirements, the M2CA error budget, and the analyzed test results

- User Manual containing:

- A description of the operation of the M2CA hardware, control system and software
- Procedures describing installation and removal of the M2M from the M2CA
- Procedures describing integration of the M2CA to TMT interfacing hardware
- Procedures for all required maintenance of the M2CA
- Procedures describing assembly and disassembly of the subsystems of the M2CA 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 M2CA
- A description of the safety system within the M2CSC, what safety alarms mean and procedures to protect the M2CA and personnel if the alarms are triggered

- List of Delivered Items:

- A list of all M2CA items mentioned in Section 2.2 that are delivered to TMT including major components, handling fixtures, test support equipment, spares, tools, and maintenance supplies

5.6.4 Final Acceptance Test Report

The Final Acceptance Test Report shall summarize the results of the functional testing performed during M2CA integration at the TMT Observatory. This report should include a roadmap that correlates how the TMT Observatory testing verifies that the M2CA 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.

6. MEETINGS AND PROGRAMMATIC REPORTS

Throughout the course of the M2CA project, regular meetings and reports will enable frequent, high quality communication between the Collaborating Institution and the TMT project.

6.1 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.

6.2 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.

6.3 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.