Conceptual Design of the Fast Tip-Tilt System for the MRO Interferometer

INT-403-ENG-0006 rev 0.8

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Revisions

REV	*DATE*	*AUTHOR*	*COMMENTS*
0.1	2007/10/03	RJS	First draft. (Incorporates sections of requirements document by CAH & YJ)
0.2	2007/10/04	RJS	Minor revisions based on input by TP. Also included retroreflector information based on input by CAH & DFB.
0.3	2007/10/05	RJS	Removed sub-system alignment section. Also revised optics specifications to 4” to eliminate the table height problem. Added actuators & controllers section.
0.4	2007/10/08	RJS	Updated price quotes and part numbers.
0.5	2007/10/11	RJS	Revisions based on input by CAH & DFB.
0.6	2007/10/24	RJS	Continued revisions based on CAH & DB, also incorporated changes about detector.
0.7	2007/10/26	RJS	Incorporated new information about retro-reflector and nominal pointing center. Minor grammar and spelling revisions. Added deployment plan.
0.8	2007/10/26	RJS	Revisions based on input by TP.

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1. Introduction

1.1. Background

Funds administered through the Office of Naval Research (ONR) have been awarded to the New Mexico Institute of Mining and Technology (NMT) to build the Magdalena Ridge Observatory. The observatory will be sited on South Baldy, part of the Magdalena Ranger District of the Cibola National Forest in central New Mexico. Further information about the observatory can be found on the web at http://www.mro.nmt.edu/.

One part of the observatory will be a long-baseline imaging interferometer, the Magdalena Ridge Observatory Interferometer (MROI). This will comprise an array of up to 10×1.4m-diameter “unit” telescopes arranged in a “Y” configuration. Each of these will utilise an elevation-over-elevation mounting, and deliver a parallel beam of starlight of diameter 95mm, which will be fed out horizontally towards a beam-combining laboratory located at the center of the array vertex (Figure 1).

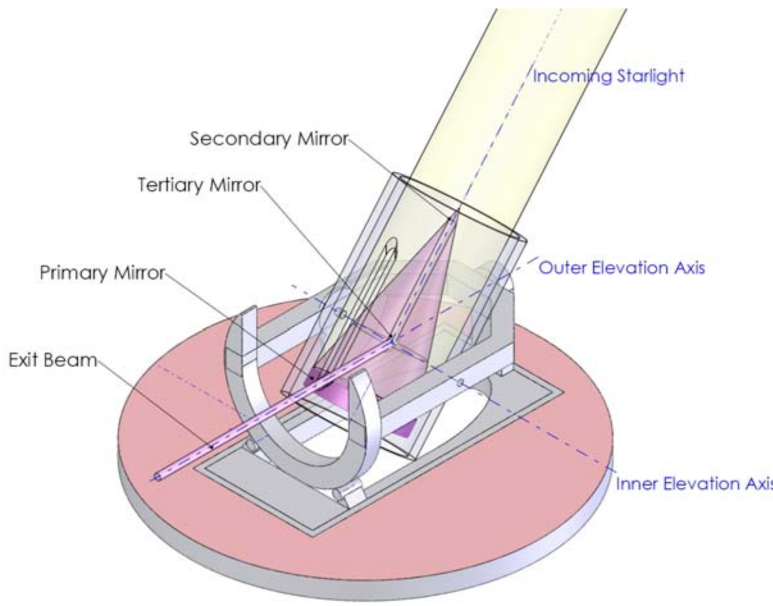

Figure 1 - Schematic cartoon of one of the 1.4m aperture MROI elevation-over-elevation unit telescopes. The detail of the mechanical arrangement is not representative of the telescope design.

An optical table (the Nasmyth table) will be mounted to the telescope 150 ± 0.5mm below the center line of the telescope exit beam. Equipment on the table will manipulate the 95mm exit beam prior to the light entering the beam relay system and being fed to the beam-combining laboratory.

The optical table will contain equipment for the narrow-angle acquisition system, the fast tip-tilt system, the alignment system and a future adaptive optics module and atmospheric dispersion corrector. A schematic cartoon of the Nasmyth table can be seen in Figures 2 & 3.

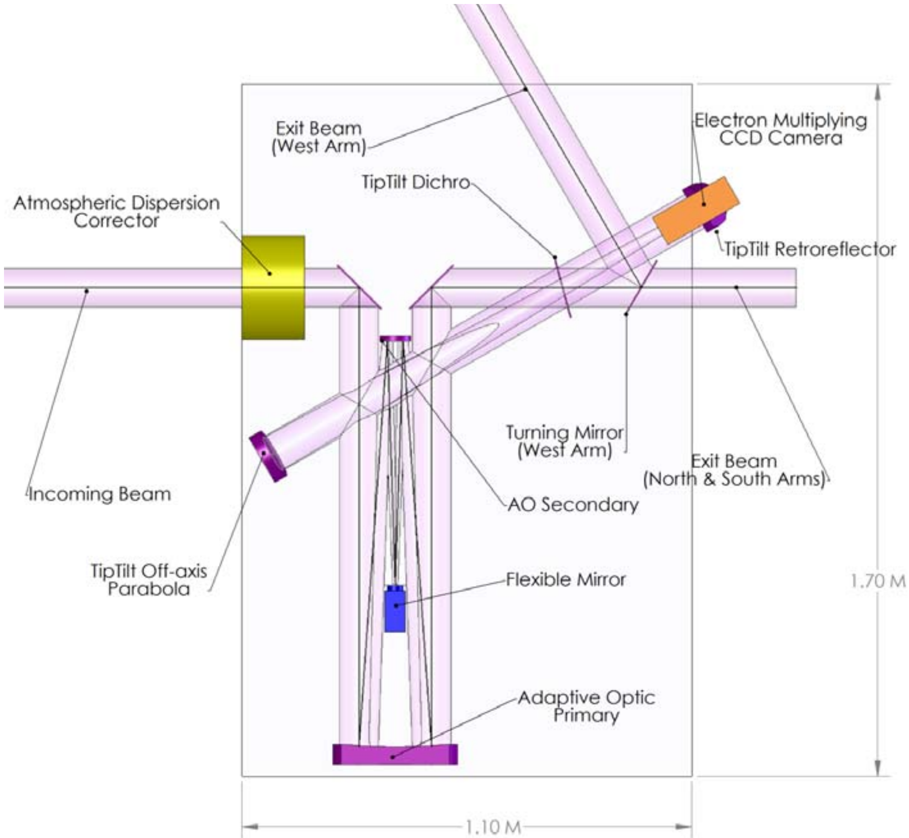

Figure 2 - Nasmyth table subsystems and elements. The beam enters on the left of the diagram and leaves the table through two different locations depending on which array arm the telescope is mounted. Note that the size, placement and orientation of these components in diagrammatic only and may not represent the detailed design. The drawing is also not inclusive of all the subsystems that may be mounted on the optical table.

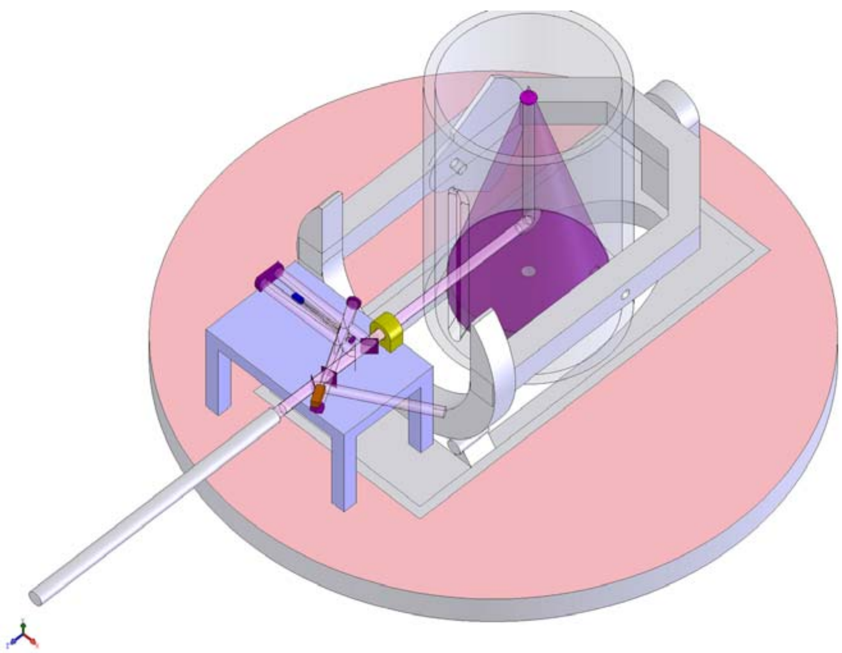

Figure 3 - Orientation of the Nasmyth table relative to the unit telescope. The design and placement of the table is diagrammatic only and does not represent the detailed design.

1.2. Scope of Supply

The scope of this effort consists of the conceptual design of the hardware for the fast tip-tilt and narrow-field acquisition systems. In particular, the following will be specified:

- Overall System Configuration
- Acquisition Sensor
- Server Configuration
- Ancillary Optics
- Optics Adjustment, Alignment & Control

In an effort to expedite the software development, the conceptual design shall also include detail typically reserved for the preliminary design when describing the CCD detector and server configuration. These components will be purchased after the conceptual design is approved by the Interferometer Design Team.

For each major component, the designs considered, their relative merits and the selection process will be outlined. The requirements met (and not met) by the sub-systems shall be listed. In addition, this document shows an approximate timeline (Section 0), dependency chart (Appendix C) as well as a system budget (Section 7).

This document will not address the software design of the Fast Tip-Tilt System and Narrow-Field Acquisition System. The software design will be presented in a separate document.

1.3. Design and Implementation Process

This document continues the design and implementation process outlined below:

- Top-level requirements definition. (Completed by JY and CH)
- Conceptual design, including:
  - Critical hardware issues. (This document)
  - Survey of Commercial Off-The-Shelf (COTS) hardware for major components. (This document)
- Procurement of COTS camera and server.
- Software Development Plan. (Document by TP)
- Preliminary design.
- Detailed design.
- Procurement & assembly of optics, actuators and ancillary equipment.
- Software implementation.
- Integration and testing.

1.4. Related Documents

The following documents are incorporated by reference:

- INT-403-TSP-0003 Technical Requirements: Unit Telescopes for the MRO Interferometer (2006 release)
- INT-403-ENG-0003-1 Fast Tip-Tilt/Narrow-field Acquisition System: Top-level Requirements
- INT-403-ENG-0001 Tip/Tilt Camera Requirements and Specifications

1.5. Acronyms Used in this Document

ADC Atmospheric Dispersion Corrector

AMOS Advanced Mechanical and Optical Systems

BCA Beam Combining Area

BCF Beam Combining Facility

BRS Beam Relay System

CCD Charge-Coupled Device

CDR Conceptual Design Review

COTS Commercial Off-The-Shelf

DMA Direct Memory Access

EM-CCD Electron Multiplying Charge-Coupled Device

FDR Final Design Review

FPS Frames Per Second

FTT Fast Tip-Tilt

FTTA Fast Tip-Tilt Actuator

FTTS Fast Tip-Tilt System

ICD Interface Control Document

ICS Interferometer Control System

MROI Magdalena Ridge Observatory Interferometer

NA Narrow-field Acquisition

NAS Narrow Angle Sensor

OAP Off-Axis Parabola

PCI Peripheral Component Interconnect

PDR Preliminary Design Review

PVM Performance Verification Milestone

RAM Random Access Memory

SMP Symmetric Multi-Processing

UT Unit Telescope

UTCS Unit Telescope Control System

UTE Unit Telescope Enclosure

UTSS Unit Telescope Supervisory System

WAS Wide-Angle Acquisition Sensor

WBS Work Breakdown Structure

2. Conceptual Design

2.1. Assumptions

The following assumptions or design criteria have been stipulated by the systems architects. The decisions are recorded in addendums to INT-403-ENG-0003.

- Use of the same camera for narrow-field (routine) acquisition and tip-tilt sensing (INT-402-MIS-0004).
- One such camera installed at each of the six Unit Telescopes (INT-402-MIS-0004).
- Splitting of starlight by color between tip-tilt sensing, fringe tracking, and interferometric science (INT-402-MIS-0008).
- For reasons of cost, the FTT/NA system shall use silicon- based detectors (which are sensitive to wavelengths in the range 350–1000nm).

In addition, the following design decisions have been made in cooperation with other work packages:

- Use the same server for the FTT/NA and WAS. This will conserve rack space and reduce heat dissipation within the unit telescope enclosure, in addition to reducing cost.
- In accordance with the Unit Telescope Requirements, the optical table shall have dimensions no larger than 1100mm by 1700mm.

2.2. System Overview

A block diagram of the system hardware is shown in Figure 4 below.

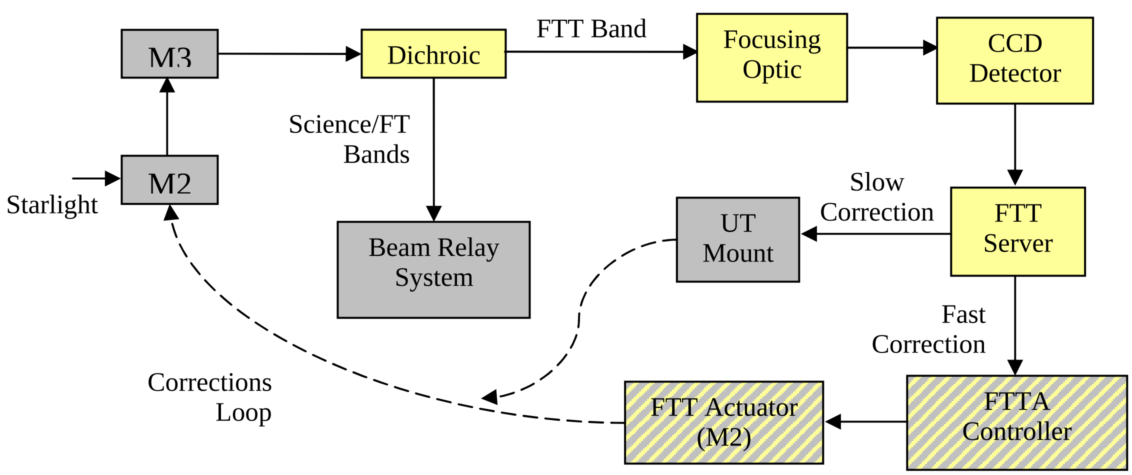

Figure 4 - Block diagram of the FTT hardware. Items in yellow are within the scope of the FTT System, items in grey are external interfaces. Only major components are shown for clarity.

The following parts of the FTT/NA system are components that are mounted on the UT "Nasmyth" optical table (see INT-403-TSP-0003):

- Dichroic: reflects the wavelengths of light to be fed to the FTT/NA CCD detector while transmitting the wavelengths used for fringe tracking and interferometric science. The system will have the capability to switch between different dichroics (needed for visible science, i.e. MROI ‘Phase 2’)

- Focusing Optic: forms an image of the sky on the CCD detector. The mount shall allow adjustment of the tip and tilt of the optic to center the beam on the CCD.
- Focusing Stage: allows the distance between the focusing optic and the CCD to be adjusted
- CCD Detector System: provides the images to the FTT Software team for centroid analysis.
- Tip-Tilt Retroreflector: reflects and alignment light source to allow determination of the nominal pointing center of the interferometer.

The following components, to be delivered as part of the UT contract (see INT-403-TSP-0003), are involved in closing the acquisition and tip-tilt loops:

- Unit Telescope Mount.
- Fast Tip-Tilt Actuator (FTTA) & Controller.

In addition, the following components shall be mounted within the UT Enclosure electronics cabinet:

- FTT Server.
- CCD Detector Power Supply.
- CCD Detector Water Chiller.
- Mount controller. (for all actuators)

At this point, it is also critical to note the components <u>not</u> included in the FTT system:

- The Nasmyth optical table.
- Any alignment system components.
- Light sources for sub-system alignment.
- The turning mirror for the west array arm.
- The atmospheric dispersion corrector.
- The adaptive optics system including the two turning mirrors.
- UPS system & network infrastructure for the hardware mounted in the UT Enclosure electronics rack.

The conceptual design of each system component is described in Section 3. In addition, a list of representative COTS components and their approximate costs can be found in Section 7.

3. System Components

3.1. Dichroic

The dichroic can be modelled as a notch filter relative to the beam relay system or a bandpass filter relative to the FTT detector. There are two bands of interest. Initially, the FTT system will function in 'Phase I' using most of the visible band. In 'Phase II' the MROI will do visible science and the FTT will be restricted to a narrower band of frequencies.

For 'Phase I', the f_{3db} points are at 350nm and 1000nm, with the filter reflecting frequencies in the 350-1000nm wavelength band. For 'Phase II', the f_{3db} points are at 350nm and 600nm. The filtered frequencies are reflected towards the focusing optic while the remainder of the signal is passed to the beam relay system.

The top-level requirements for the dichroic are:

- The dichroic shall introduce no more than 16nm RMS wavefront error into the transmitted beam (INT-402-TSP-0004). This value includes errors due to imperfect support of the optic.
- The dichroic shall deliver an average throughput of 95% in the J, H and K astronomical bands (INT-402-TSP-0004).
- The reflectivity of the dichroic in the FTT band shall be sufficient for maintaining a limiting magnitude of V = 16 for the FTT system.
- The dichroic shall allow approximately 1% leak-through in the reflected range to allow for system alignment.

The following design criteria were considered for the dichroic:

- Quantity:
    - A single dichroic meeting the specification for Phase II vs. switchable dichroics meeting the specifications for Phase I & Phase II.
- Coating & Surface Quality
- Size:
    - 4" vs. 5"
- Mount & Slide:
    - Mechanically vs. Electronically Adjustable

In an effort to meet the limiting magnitude requirements, switchable dichroics offer the best chance of success and is therefore the preferred approach. Initial estimates for a V=16 star indicate that we would have on the order of 92 photons with the Phase I dichroic and on the order of 35 photons with a Phase II dichroic for a 1ms exposure. These numbers are approximate based on a hypothetical star with a flat electromagnetic spectrum in the visible wavelengths. This was calculated as follows:

We start by determining how many photons would reach earth for a known star magnitude. In the case of Vega (Magnitude V=0) at 555.6nm wavelength, 948 photons cm^{-2} s^{-1} Å^{-1} reach the Earth's atmosphere[1].

Since 1 Å = 0.1nm, this is 9480 photons cm^{-2} s^{-1} nm^{-1} at 555.6nm wavelength.

[1] *A Rediscussion of the Atmospheric Extinction and the Absolute Spectral Energy Distribution of Vega:* D. S. Hayes & D. W. Latham, September 19, 1974

For a V=16 star with a flat electromagnetic spectrum in the visible region, we could approximate the number of photons (F_1) reaching the earth's atmosphere as:

$$F_1 = \frac{F_2}{100^{(m_1 - m_2)/5}}$$

Where F_2 = 9480 photons cm^{-2} s^{-1} nm^{-1}, m_1=16 and m_2=0.

Solving for F_1 we get:

$$F_1 = \frac{9480\, photons \cdot cm^{-2} \cdot s^{-1} \cdot nm^{-1}}{100^{(16-0)/5}} = 0.003774\, photons \cdot cm^{-2} \cdot s^{-1} \cdot nm^{-1}$$

For our 1400mm diameter primary with a 98mm diameter area obscured by the secondary and tertiary mirrors, our collection area (A) is:

$$A = (1400mm^2 \cdot \pi) - (98mm^2 \cdot \pi) = 6.12735x10^6\, mm^2 = 61273.5cm^2$$

For our 350nm to 1000nm dichroic, the number of photons (x) collected by the UT is:

$$x = (0.003774\, photons \cdot cm^{-2} \cdot s^{-1} \cdot nm^{-1})(61273.5cm^2)(1000nm - 350nm) = 150{,}312\, photons \cdot s^{-1}$$

Assuming a 1ms exposure, an ideal system would deliver 150 photons to the detector. There are 5 reflectors in the optical path as well as a lens on the detector. Assuming a 98% reflectivity for each element in the optical path, we can estimate that 133 photons reach the detector (x_D).

$$x_D = (150{,}312\, photons \cdot s^{-1})(0.001s)(0.98^{(5+1)}) = 133$$

Assuming that our detector's average QE over the 350nm to 1000nm band is 70%, then we can approximate that 93 photons are counted in our exposure. If we restrict the wavelengths to 350nm-600nm in Phase II, there may be as few as 35 photons counted by the detector in a 1ms period.

The minimum number of photons per exposure necessary to meet the requirements is not known. However it is clear that a brighter object on the detector will have a higher signal to noise ratio which should make centroid calculation more precise. For this reason, we will start with a 'Phase I' dichroic to provide greater contrast between our target and the background noise.

The size of the dichroics is dictated by the 95mm output beam of the telescope. We are restricted to a minimum 4" optic. Because part of the beam passes through the dichroic and it is mounted at an angle to the beam, the width and configuration of the mount may reduce the usable portion of the beam. In an effort to allow a more bulky and robust mount, 5" optics were also considered. However, the specification for the Nasmyth table calls for the table to be mounted 150 ± 0.5mm below the centreline of the output beam. This leaves 55mm for the mount below the optical beam. COTS mounts and slides considered for the dichroic were too tall when using 5" optics, so 4" optics are the preferred approach.

For both ‘Phase I’ and ‘Phase II’, the coating and surface quality of the optics shall be specified in the preliminary design review.

The specification for the mount is tied to our subsystem alignment criteria and switchable dichroic design choice. By selecting switchable dichroics, a slide will be required and this shall be electronically adjustable.

The slide in ‘Phase I’ requires a minimum of 150mm of motion to move the dichroic out of the beam path for alignment. For ‘Phase II’, the actuator must allow three positions: dichroic 1, dichroic 2, or no optic. This requires roughly 300mm of motion in the slide. It is our intention to purchase a single slide that will accommodate ‘Phase I’ and ‘Phase II’.

The choice of mechanical or electronic tip-tilt adjustment of the dichroic is affected by the subsystem alignment. This design choice is made in consideration with the adjustment of the other elements in the optical path and is explained in Section 3.8. The current design uses a mechanical mount with an electronic slide.

3.2. Focusing Optic

The focusing optic takes the 95mm beam reflected by the dichroic and focuses it on the CCD detector.

The top level requirements for the focusing optic are:

- The focusing optic shall provide a plate scale of 0.2 arcsec (relative to the sky) per pixel on the CCD detector.
- The focusing optic shall have sufficient reflectivity for a limiting magnitude of V = 16 for the FTT system.
- The aberrations of the optic shall be restricted to permit centroid calculation within 0.25 pixels (with all other factors considered).

The following design criteria were considered for the focusing optic:

- Quantity:
    - Single optic vs. Multiple optics
- Shape:
    - Off-Axis Parabolic Mirror vs. Spherical Mirror
    - Focal length
- Coating & Surface Quality
- Size:
    - 4” vs. 5”
- Mount:
    - Tip & Tilt
        - Mechanically vs. Electronically Adjustable
        - Software Compensated
    - Distance to Detector
        - Mechanically vs. Electronically Adjustable
        - Implemented in Focusing Optic Mount vs. Detector Mount

It is our intention to use a single optic regardless of shape. For reasons of cost and complexity, multiple reflectors (such as a cassegrain reflector) will not be used. Our current focal length (shown below) is very close to the table dimensions, but a single focusing optic should fit.

The focusing optic may be an off-axis parabolic mirror or a spherical mirror. The spherical aberrations caused by a spherical mirror may be acceptable if the centroid can still be calculated within the required accuracy. The off-axis parabolic mirror will cause coma aberrations, which would also have to be accounted for in the software routine. The magnitude of the optical aberrations and their effect on the software routine will require analysis outside the scope of the conceptual design. The decision on the focusing optic shape will be made as part of the preliminary design.

Regardless of the shape of the reflector, the reflected focal length (f) of the optic is a function of the pixel size (x), telescope magnification (M) and the angular size of a pixel (projected on the sky) in radians (θ). The focal length can be represented as derivation of the plate scale formula:

$$f = \frac{x}{M * \theta}$$

M and θ are:

$$M = \frac{1400mm}{95mm} = 14.74$$

$$\theta = 0.2arc\sec = \frac{0.2arc\sec}{206265\, {}^{arc\sec}\!/_{rad}} = 9.696x10^{-7}$$

Assuming that our CCD detector has 16 micron pixels, the focal length is as follows:

$$f = \frac{16x10^{-6}\,m}{14 * 9.696 * 10^{-7}} = 1.120m$$

The same focusing optic shall be used for both ‘Phase I’ and ‘Phase II’ of the MROI. The size of the mirror will probably be a 4” optic to reduce cost and conserve space on the optical table. The mirror surface parameters will be specified in the preliminary design.

Image position on the detector can be adjusted through the mounts of the focusing optic, the dichroic, or software. Software would be the most advantageous approach since it would eliminate cost and complexity. As you can see in section 3.4, the selected detector has an additional 22.4 arcseconds in its field of view above the minimum requirements. This would allow the image position to deviate as much as ± 0.89mm while maintaining the required field of view.

Should more adjustment be required, it is our intention to provide this functionality in the focusing optic mount. This decision is explained in Section 3.8. In this case, the focusing optic shall have a fixed position on the table, but it shall have adjustment in the focal point to center the image on the camera. The likely arrangement to achieve this adjustment may be a motorized rotation stage as well as a motorized goniometer. The decision on this implementation will be made as part of the preliminary design. The implementation of the focusing stage is discussed below.

3.3. Focusing Stage

The focusing stage is required to adjust the distance between the focusing optic and detector so that the image is focused.

This can be achieved through the following methods:

- Electronically moving the focusing optic.
- Electronically moving the detector.
- Using a low-expansion rod to set the spacing.

Moving the focusing optic would also require adjusting the tip and tilt of the dichroic and focusing optic. However, moving the camera does not require the adjustment of any other component and is therefore preferred.

The detector will be mounted on a slide regardless of whether it is electronically controlled or is maintained by a low-expansion material.

The specified range of the slide to account for thermal expansion is 1mm+. The change in the distance between the detector and focusing stage is calculated as follows:

$$\frac{\Delta L}{L_0} = \alpha \Delta T$$

ΔL is our change in length due to temperature. L_0 is the starting length, in this case the focal length of the focusing optic. α is the coefficient of linear expansion of steel (assuming a steel Nasmyth table) and ΔT is the change in temperature.

If we assume a seasonal change of 40C, twice our seasonal average, ΔL is:

$$\Delta L = (13x10^{-6} / C) * (20C)(1.120m) = 0.5824mm$$

This assumes that the radius of curvature of the optic is fixed over the course of diurnal and seasonal temperature changes. The specified range of motion for the slide may increase once the mount system for the focusing optic is defined. If a goinometer is used, additional range of motion may be required to account for any change in distance caused by the adjustment of the vertical alignment of the focusing optic. The specification will be developed as part of the preliminary design.

3.4. CCD Detector

The CCD detector shall provide a monochromatic pixel map of the light collected by the UT. Images will be captured over different exposure times and at different rates depending on the operation mode of the system.

The top-level requirements for the CCD detector are are:

- The detector shall function in both fast tip-tilt and acquisition modes listed in INT-403-ENG-0003.
- The Field of View for the detector shall be 80 arcsec minimum with a goal of 120 arcsec. In FTT mode, the detector shall use a window of 3 arcsec.
- The image scale is 0.2 arcsecs per pixel (relative to the sky).
- The limiting magnitude requirement shall be V = 16.
- The detector shall work in the wavelengths between 350nm though 1000nm which covers R & I band interferometric observations (350 – 600 nm bandpass light sent to the sensor) and J, H & K observations (less than 350-1000 nm bandpass light sent to the sensor).
- The system shall support closed-loop 3dB bandwidths in the 10–50Hz range (INT-403-TSP-0003).
- The required exposure times are from 1 millisecond up to 10 seconds.
- Operating temperature and environment as specified in INT-403-ENG-0003.
- The detector shall have an operational life of 10 years.
- The components of the FTT/NA system located on the UT optical table shall dissipate no more than 10W of power to the air underneath or within 30 cm of the beam path.

Based on the field of view and plate scale, we can see that the detector should have a minimum size of 400x400 pixels and an ideal size of 600x600 pixels. The field of view for FTT mode is 16x16 pixels. Staying with standard detector sizes, the detector shall be a 512x512 detector.

A size requirement imposed by the plate scale also defines the size of the pixels on the detector. To achieve the 0.2 arcsec/pixel plate scale, 16um pixels require a 1120mm focal length as shown in Section 3.2. With the table having a fixed dimension of 1100mm, this is the maximum focal length that can be accommodated so pixels 16um or smaller are required.

The limiting magnitude requirement helps define the sensitivity and noise level of the detector. As shown in section 3.1, we may have less than 35 photons per 1ms exposure when operating in Phase II. A single electron per frame could shift the centroid by 2.8%. In an effort maintain a quiet background and increase centroid accuracy, we propose that the detector readout noise be restricted to less than 1 electron at 1kHz.

In an effort to meet the 50Hz closed-loop bandwidth, the software team has requested (in accordance with the UT Technical Requirements document) that all sub-systems operate at a minimum of 500Hz with a goal of 1000Hz. This means that our detector must run at 500FPS minimum, with a goal of 1000FPS. The acquisition latency must also be low enough to support these frame rates. This involves a low-latency interface that does not buffer the images so that the delay is no greater than 1ms.

Based on these requirements and other practical considerations, the detector shall meet the following specifications:

- 512x512 pixels (400 minimum and 600 goal per top level requirements)
- 16um pixels or smaller (for sizing of focusing optic to fit on optical table)

- Detector readout noise of less than 1 electron at 1kHz
- 500FPS minimum at 16x16 pixel window (To achieve 50Hz closed-loop 3dB)
- No image buffering and a low-latency interface (less than 1ms)
- Sensitive to the 350nm-1100nm wavelengths.
- Mechanical shutter with software control.
- Linux SDK or drivers, ideally real-time Linux support.
- Re-window capability in software.
- Operational life of 10 years.
- Operating temperature of -15C to 25C and survival in temperatures as low as -25C.
- Heat dissipation of less than 10W on optical table.

The placement of the camera could be offset to the north or south of the dichroic or above the dichroic. The horizontal displacements, north and south, both appear to interfere with the exit beam from the table. The placement to the north of the dichroic may interfere with the exit beam for the western arm while the placement to the south appears to interfere with the exit beam for the north and south arms.

By placing the detector further off axis it may be possible to place the detector to the south of the exit beam for the north and south arms, but this would increase the off-axis optical aberrations as well as present a space constraint as the detector approaches the table edge. For these reasons, placing the detector with a vertical offset is preferred. Once the location of other elements on the optical table is better defined, this placement may be revisited since a horizontal offset may allow the use of a low-expansion rod for the focusing stage as described in Section 3.3.

3.4.1. COTS Cameras

Very few COTS cameras are close to our requirements. The following cameras were more closely scrutinized for the CCD Detector:

- Andor iXon DU-897
- Princeton PhotonMax 512B
- Hamamatsu C9100-13
- QImaging Rolera Mgi

A chart showing the specifications of each camera can be seen in Appendix A.

The Andor iXon DU-897 is the camera that meets the most listed requirements. A demo model was acquired for further testing and has been approved by the FTT software team. The cost of the camera is approximately $31,000. The specifications of the camera are attached as Appendix B.

The Andor iXon DU-897 meets all the requirements except for two. According to Andor, the operation life of the camera is approximately 8 years. The camera may need to be replaced at a shorter interval than 10 years as specified in the requirements. In addition, it can survive the environment described in INT-403-ENG-0003, but it cannot be guaranteed to operate in the 0C to -15C range. No camera evaluated had an operational range below 0C. Andor indicated that the camera has been used in Antarctic conditions at temperatures as low as -30C and the camera has functioned correctly. However, they will not guarantee its operation in our environmental conditions, voiding the warranty.

It should also be noted that the heat dissipation of the Andor iXon DU-897 is close to our heat dissipation requirement for the optical table components and meeting this requirement may require an external chiller outlined below.

3.4.2. CCD Detector Chiller

CCD detectors require active cooling to meet their optimal readout noise and dark current values. In the case of the Andor DU-897, the detector can be chilled to -85C using an internal air-cooled chiller or temperatures as low as -100C with an external 10C water chiller.

The risk associated with running the detectors at these super-cooled temperatures is that condensation builds up within the detector enclosure, causing electrical shorts and premature failure. In an effort preserve the camera while obtaining maximum performance, the CCD detector temperature should be maintained at a temperature above the dew point.

Given this constraint, an external water chiller may not be required, since the detector will never operate at temperatures in the -85C to -100C range. However, the chiller may still be desirable to eliminate the PSU for the internal air-cooled chiller as well as reduce dissipation to the air on the optical table.

This PSU is external and therefore may be mounted in the UT Enclosure electronics housing. However, should it prove necessary to reduce our heat dissipation budget, the external water chiller may reduce the heat dissipation of the FTT system. Power consumption of the Andor DU-897 is on the order of 22W (including the PCI card). However the chiller power supply dissipation is on the order of an additional 50W.

The chiller will also provide a closed loop heat dump for the detector, reducing heat dissipation to the air adjacent to the optical path. This is the primary benefit of the chiller and a decision on its inclusion or exclusion will be made as part of the preliminary design.

3.5. Tip Tilt Retroreflector

The tip tilt retroreflector is part of the alignment system for the FTT. It is required to determine the optical axis of the interferometer so that we can determine a nominal center for the UT. It will also be used to align the components of the FTT system during commissioning and after relocation.

The retroreflector will reflect light from the beam combining facility through the dichroic onto the focusing optic. The image formed on the detector will allow us to determine the ideal image center so that all UTs are aligned. This is a necessary part of the narrow-field acquisition process since this provides the reference point to which we want to move the centroid.

When the FTT components are misaligned, the light source can also be used to center the image on the detector. This will be required after system relocation and possibly on a more frequent basis.

The top level requirement for the retroreflector is that it must allow alignment of the starlight from each UT within 1/20th of an arcsecond relative to the sky. The functional and performance requirements for the retroreflector will be developed as part of the preliminary design.

The decision to use a light source in the BCF instead of a local source in the enclosure (such as the UT) is that:

- The light from the BCF is collimated so it can focus on the detector.
- The light source is reduced in magnitude by the dichroic so that it closer to the magnitude of a star.

The LEDs mounted on the primary and secondary for the UT were also considered for the alignment procedure, but they are not collimated and therefore not ideal. The sub-system alignment routine is also discussed in section 5.4.

The retroreflector is envisioned as a 2" COTS unit with an angular accuracy of at least 1 arcsec. It will have a fixed mount integrated into the CCD detector mount. It will have an electronic cover to block it when not in use.

3.6. FTT Controller & FTT Actuator

The FTT Actuator is governed by the FTT Controller. Both pieces of equipment are provided by AMOS under the UT contract. Specifications and requirements for the FTTA can be found in the UT Requirements documentation and the AMOS proposal. The design will be developed by AMOS as part of their conceptual, preliminary and final design reviews.

3.7. FTT Server

The FTT server is a rack mount server that functions as the interface to the CCD detector, UT mount, FTTA controller and mount controller. It is a real-time Linux machine that runs the acquisition and tip-tilt algorithms developed by the software team.

The FTT server has limited top-level requirements. Most of the requirements are performance driven. The only pertinent top-level requirement is that the FTT system shall dissipate less than 100W.

However, there are a number of practical requirements driven by the interfaces to the FTT system hardware and the software team's requirements. The following requirements are imposed by the hardware interfaces:

- Rack-mounted chassis for use in the equipment housing. (UT Enclosure)
- It shall accommodate the oversized PCI card for the Andor DU-897 (CCD Detector)
- PCI Bus Mastering capability (CCD Detector)
- DMA on the PCI Bus (CCD Detector)
- Clock speed greater than 3.0GHz. (CCD Detector)
- USB and Serial Ports (Optical Table Actuators)
- Open PCI Slot and Serial Port (Possible FTTA Controller Interface)
- 60MB minimum dedicated RAM (for CCD Detector)

The following requirements are driven by the software team's needs:

- High Clock-Speed: Xenomai real-time Linux has limited SMP support, so multi-core and dual-CPU systems may offer limited performance, at least during initial development. (Real Time Linux)
- ’32-bit’ x86 Support: Xenomai real-time Linux has limited ’64-bit’ support, so ’32-bit’ x86 support is required. (Real Time Linux)
- Symetricom BC635/BC637 Timing/Frequency Card (Real Time Linux)
- 100Mb Ethernet for communication with the UT Mount (UTSS)
- 100+ GB Hard Drive (Image Storage)
- VGA Video (Testing/Commissioning)
- Chipsets with Linux support (Real Time Linux)

In an effort to minimise hardware within the UT Enclosure, the WAS shall use the same server as the FTTS. To serve this dual function, the server shall have the following functionality:

- USB 2.0 interface
- Firewire interface

Based on these requirements, the following is a minimum specification for the FTT server:

- 3.2GHz AMD Athlon64 X2 6400+
- PCI Controller with DMA and PCI Bus-Mastering Support
- 2GB RAM
- USB 2.0 Port
- Firewire Port
- 100+ GB SATA Hard Drive
- 3+ PCI Expansion Slots
- Oversized PCI Expansion Slot for Andor DU-897 PCI Card
- Symmetricom BC635/BC637 PCI Timing/Frequency Card.
- Serial Port
- 100Mb Ethernet, 1000Mb Ethernet Preferred
- ’80 Plus’ Certified Power Supply
- VGA Video
- Linux Support for All Major Chipsets

These performance specifications meet all the requirements with the possible exception of the heat dissipation target. It is likely that the server will consume on the order of 60W at idle, but may have peak consumption during operation in excess of 100W. Accounting for all FTT system components, it will be very difficult to stay within the 100W heat dissipation requirement. An estimated heat dissipation budget is shown in Section 5.1.

If the heat dissipation target of 100W is a hard target, it is recommended that the chilled glycol loop that is being considered be sized so that the UT Enclosure electronics housing is actively cooled during observation, allowing higher heat dissipation for the FTT system.

It should also be noted that the storage specification does not allow for long term (year+) storage of engineering images and data. The specification assumes an archive system is available on the ridge.

3.8. Optics Mount Actuators & Controller

The mounts and actuators are discussed with their associated optics above. This section attempts to provide a more focused view of the actuators and their associated controllers.

There are two top-level requirements associated with the actuators and controllers:

- That they fit within the total heat dissipation requirement of 100W.
- That they operate in environmental conditions described in INT-403-ENG-0003.

The functional & performance requirements are largely driven by the sub-system alignment criteria and these will be developed as part of the preliminary design.

A design goal with the actuators and controller will be minimizing redundant parts. It is our intention to have the minimum number of electronically adjustable mounts required of FTT system to increase system reliability and decrease cost and complexity.

There are the following components mounted in the optical path that may require alignment:

- Dichroic
- Focusing Optic
- Detector

The following adjustment is required:

- Removal of the dichroic for the alignment system.
- Switching of dichroics.
- Placement of the image on the detector.
- Focus of the image on the detector.

The alignment system has requested that the dichroic move out of the optical path for tilt and shear adjustment. We are also planning on using switchable dichroics. These two requirements necessitate a slide under the mount for the dichroic.

To adjust the placement of the image on the detector, there are five possible methods:

- Adjustment of the image center in software.
- Fixed mounts on the dichroic and focusing optic with adjustment in the placement of the detector.
- Adjustable mount on the dichroic, adjustable mount on the focusing optic.
- Fixed mount on the dichroic, adjustable mount on the focusing optic.
- Adjustable mount on the dichroic, fixed mount on the focusing optic.

Adjusting the image center in software is the preferred approach since it eliminates cost and complexity. As you can see in section 3.4, the selected detector size has an additional 22.4 arcseconds in its field of view above the minimum requirements. This would allow the image position to deviate as much as ± 0.89mm while maintaining the required field of view.

Should electronic alignment be required to maintain the image position within the range specified above, the adjustment could be achieved through moving the detector, dichroic, focusing optic or multiple system components.

Moving the detector seems to be the most complicated method to achieve sub-system alignment since the detector would have to move vertically. The additional mounts will also increase the height of the detector, moving it further off-axis and increasing the necessary height of the UT Enclosure. Adjustable mounts on both the dichroic and focusing optic provide the most flexibility, but also some redundancy and added complexity.

Misalignment of the dichroic may be tolerated so long as the optical beam remains fully on the focusing optic. Misalignment may increase aberrations visible on the detector, but this will eliminate a pair of actuators reducing cost and complexity. The impact of the misalignment on the image quality at the detector will be analyzed as part of the preliminary design.

Adjustment at the dichroic with a fixed focusing optic presents a space constraint. The area around the focusing optic is less crowded than the area around the dichroic. Therefore, adjustment of the focusing optic is preferred to adjustment of the dichroic.

A repeatable slide under the dichroic with tip and tilt adjustment of the focusing optic seems to offer the best price/complexity/performance balance. In the event that misalignment of the dichroic proves troublesome, tip and tilt adjustment of the dichroic could be implemented at a later date if space permits.

The focusing stage can be implemented at the focusing optic or detector. The detector is preferred because moving the focusing optic would also require adjustment of the dichroic and focusing optic tip and tilt. By only moving the detector, a single actuator can be used to adjust the focus of the detector. The alternative to using an electronic slide may be the use of a low-expansion rod and free-moving mount under the detector. This approach is preferred for ensuring alignment over the course of a night, but is hard to implement on the crowded Nasmyth table. The idea will be explored as part of the preliminary design, but the focusing stage will be implemented on the detector mount regardless of whether it is electronically adjustable or fixed with a low-expansion rod and manually adjustable mount.

Based on these considerations, the current conceptual design calls for the following electronically actuated mounts:

- The dichroic shall be mounted on a linear slide actuator to shift the mount approximately 300mm, allowing three positions on the slide as discussed in Section 3.1. The accuracy and repeatability of this slide are not yet specified, but we expect that we will require a high degree of repeatability since we cannot measure the alignment of this optic directly. The accuracy and repeatability will be specified as part of the preliminary design.
- The CCD detector shall be mounted on a linear slide actuator to adjust the image focus. This slide needs limited travel to accommodate thermal expansion/contraction as well as distance changes from adjustment of the goniometer supporting the focusing optic. The slide may be electronically controlled or positioned with a low-expansion rod. The decision will be made as part of the preliminary design.

The position of the image on the detector will be adjusted in software so long as it remains within the detector's field of view. Adjustment from outside this range will be performed manually.

In addition to minimizing the number of mounts, an associated challenge is minimizing the number of controllers required. Each actuator needs a controller to drive its motion. Different vendors use different specifications for their controllers and interface, so finding a common vendor for all actuators will eliminate redundant components. However, we have not yet found a vendor who can deliver all the necessary actuators. The 300mm slide is proving the most challenging to source, and may require a separate controller. Multiple controllers will use up more space in the UT enclosure electronics housing as well as dissipate more heat. They will also increase the cost of the system. For these reasons, we will try to eliminate any duplicate controllers as part of the preliminary design.

4. Interface Specifications

4.1. FTTA Controller

The interface to the FTTA Controller is an unknown part of the design. The UT Vendor has the responsibility of defining this interface and there is insufficient information in the requirements documentation or the AMOS Proposal to determine the extent of the interface hardware.

The UT Requirements document states:

“The FTTA control interface shall accept tilt actuation commands at rates of up to 1kHz with a step response time (command received to 95% response) of less than 2 milliseconds for angular step sizes (physical motion of the mirror) of up to 2 arcseconds. The response to a step input shall have overshoot and ringing of less than 10% of the commanded step size and shall settle to within 2% of the step size within 4 milliseconds of receipt of the command.”

The requirements for step response time, response overshoot and ringing indicate that AMOS is responsible for the signal generator and amplifier for the FTTA. References to the FTTA Controller in the AMOS conceptual design documentation also support this position.

This indicates that no significant hardware development will be required by the FTT team for the FTTA. The interface to the controller will be specified as part of the UT preliminary design. It will later be documented in an ICD.

4.2. UT Mount

The interface to the UT mount, through the UTSS, is over TCP/IP. The interface is therefore the responsibility of the FTT software team.

4.3. Beam Relay System

The interface to the beam relay system is on the optical table. The turning mirror for use on the west arm is in close proximity to the anticipated placement of the CCD detector. Careful coordination will be required for the development of the mounts for both pieces of equipment as well as communicating any changes in the placement of the equipment.

4.4. UT Optical Table

The interface to the UT Nasmyth optical table is documented in the UT Requirements document. The table is positioned $150\text{mm} \pm 0.5\text{mm}$ below the center line of the output beam. The lateral placement of the table is not yet defined. The shock loads the table (and all mounted equipment) will be subjected to during relocation are also not yet defined.

4.5. Alignment System

The alignment system shares space with the FTT system on the Nasmyth optical table as well as sharing control of two components. The alignment system needs control of the dichroic slide. The FTT system will also use a light source provided by the alignment system in the BCF to determine the nominal pointing center. This will require a software-level interface as well as coordination on the specifications for this light source.

4.6. ADC

The ADC system functions independently of the FTT system, but they occupy the same optical table so space allocations are a concern. The FTT team will keep the ADC team apprised of the placement of FTT hardware on the Nasmyth table.

4.7. AO System

The AO system functions independently of the FTT system, but they occupy the same optical table so space allocations are a concern. The FTT team will keep the AO team apprised of the placement of FTT hardware on the Nasmyth table.

4.8. UT Enclosure

The primary interface to the UTE is the electronics housing. In particular, rack space allocations need to be determined and the placement of the UT electronics housing is partly dictated by the FTT CCD Detector. The maximum cable length between the detector and the FTT Server is 20ft.

4.9. ICD Documents

Each ICD should list the specifications for any interface as well as the dependencies on that interface. In addition, a change order communication procedure shall be developed. Due to the interfaces documented above, the following ICDs will be required:

- FTT to UT
- FTT to UTE
- FTT to AO System
- FTT to ADC
- FTT to BRS
- FTT to Alignment System

5. Risks

The following risks are identified. These may be technical or logistical and are listed in no particular order.

5.1. Heat Budget

A 100W heat dissipation budget is allotted to the FTT System. An estimated heat dissipation budget is shown below:

Item:	Power Consumption	Location:
FTT Server	60W-120W	EH*
Andor DU-897	22W	Split between EH and OT**
Andor Chiller	50W	EH
Optics Actuators	10W	OT
Optics Actuator Controllers	50W	EH

Maximum Estimated Heat Dissipation: ~250W
Typical Estimated Heat Dissipation: ~100-120W
Typical Estimated Heat Dissipation on the Optical Table: ~10W or less.

*EH = Electronics Housing
**OT = Optical Table

This does not account for any heat budget allocated to the WAS which can offset a portion of the FTT Server heat budget.

If the heat dissipation target of 100W is a hard target, it is recommended that the chilled glycol loop that is being considered be sized so that the UT Enclosure electronics housing is actively cooled during observation, allowing higher heat dissipation for the FTT system components in the UTE electronics housing.

The UT enclosure team will be working on a heat budget for all components in the UT enclosure. It is possible that the target heat budget for the FTT system will change once this budget is developed.

5.2. Environment

The temperature, relative humidity and wind at the site present a significant challenge to the design and specification of the components exposed to the elements. The effects of wind shake on the FTT optics as well as debris accumulation must be accommodated. The extreme temperatures and relative humidity may also affect the performance of the electrical components. The environmental conditions will be a driving factor in the preliminary design and early prototyping may involve environmental tests at the site.

The most significant environmental challenge is ensuring system operation in the 0C to -15C temperature range. Most electronics components are not rated for operation below 0C, and identifying COTS equipment that will function in this temperature range and survive temperatures of -25C is proving challenging.

5.2.1. Relocation Shock Loads

The possible shock loads during relocation are currently undefined. It is likely that the system will require re-alignment as part of the relocation process, but the impact of the shock loads will not be considered until the preliminary design.

5.3. Work Package Interfaces & Dependencies

The number of work package interfaces presents a design challenge. The FTT is dependent on other sub-systems as follows:

- The Nasmyth table position defines the configuration of the mounts for the FTT. The table position is defined by the UT Vendor. The UT Vendor also specify the FTTA and FTTA controller, which are necessary for the operation of the FTT subsystem.
- The UT enclosure electronics housing placement is limited by the maximum distance between the detector and server. Height of the UT enclosure is also a factor as well as the wind reduction at the optical table.
- The alignment system work package and the FTT work package share hardware and the systems are highly inter-related in their function since an inadequate alignment procedure can cause the FTT system to function outside of specifications and incorrect mount tolerances provided by the FTT team could render alignment impossible.
- Multiple work packages occupy the same space as discussed in section 5.3.1 below.

Careful coordination between these teams will be required. The ICDs will be especially detailed to address the work package overlap and interfaces. The ICDs will also establish communication and documentation procedures for any changes that occur at these interfaces.

5.3.1. Space

There is limited space on the Nasmyth table. In addition to the FTT hardware, there are the following external work packages sharing space on the optical table:

- Atmospheric Dispersion Corrector
- Adaptive Optics System
- Alignment System
- Beam Relay System (Turning Mirror)

An internal risk is also the focal length of the focusing optic, which is longer than a table axis and certain system components may push the boundaries of the table.

In an effort to coordinate the space allocations on the Nasmyth table, the FTT team has been assigned ownership of the table. A three-dimensional model of the table and all sub-systems occupying the table will be developed as part of the preliminary design and maintained through the final design stages for all associated work packages. Interfaces and obstructions will be resolved through the ICDs outlined in section 4.9.

5.4. Sub-System Alignment

Alignment of the FTT system is critical since it will provide the narrow-angle tracking corrections to the UT. The distances between some of the components also increases the effect of temperature fluctuations and other variables that will promote optical creep. Care must be taken in the choice of materials as well as the specifications of the mounts so that there is minimal change in the alignment of the system as the environment changes throughout the night.

The proposed alignment procedure shall use a light source from within the BCF. This light source is collimated and allows us to determine the nominal pointing center for the system. The center of this light source becomes the alignment target for star light. Should this center deviate from the center of the detector, this is acceptable so long as the position will allow the minimum required field of view.

If we provide actuators on the focusing optic, the software routine can adjust the position of the focusing optic to center the beam on the CCD camera using a number of short exposures to calibrate the system.

The sub-system alignment process shall be automated so that it can be performed every night. The system shall be designed to be stable over the course of a night's observation. Alignment after relocation will involve manual adjustment to fixed elements of the system.

A detailed alignment procedure will be developed as part of the preliminary design. Since this sub-system will also use hardware provided by the Alignment System work package, it must also be documented in an ICD.

Any additional optics required for the alignment process will be documented in the preliminary design stage. In addition, the specifications for the mounts will be developed as part of the preliminary and final design.

6. Commissioning Plan

Sections 2 and 3 describe the system in its fully functional state. However, it is our intention to phase the deployment of the FTT system for the first UT. This section attempts to present each step in the commissioning, development and testing of the FTT system and the relative performance verification milestones (PVMs) these stages relate to.

Stage I

The first stage in system commissioning will simply connect the detector to the server. This allows the software team to begin development of the drivers and software routines. This level of development will take place in the Workman lab using an existing optical table.

Light sources and optics available in the lab may be used to project an image onto the detector to test the image acquisition system.

Stage II

The second phase will use a fixed mirror to replace the dichroic and our focusing optic. The major components will be mounted in their intended locations but the system is simplified in the following ways:

- The dichroic is simply a mirror. No slide is implemented.
- The FTTA and FTTA Controller are not available to test the closed-loop performance of the system.

While still implemented in the lab, this level of development would allow us to reach PVM1.

Stage III

The third phase requires closed loop operation of the FTT system. However, testing the system in a closed-loop without using the FTTA and FTTA controller is a challenge. We may have to build a mirror mount with piezoelectric actuators that can be used to mimic the performance of the FTTA. We could subject our light source to harmonics in the 1Hz to 50Hz range using a similar actuator to determine the effective F3db point of the system.

While implemented in the lab, this level of development would allow us to reach PVM2. The cost of this test system has not been tabulated and may be eliminated if more development time is available after UT delivery. By using the FTTA and FTTA controller, we can eliminate the cost of the prototyping equipment at the expense of more development time after UT delivery.

Stage IV

Stage IV is integration with the UT. The test system will be reassembled on the ridge to complete PVMs 1 & 2. Once complete, the dichroic will be implemented with its slide to move towards the next PVMs.

This commissioning plan is very preliminary and it will be expanded and refined as part of the preliminary design.

Schedule

The project shall adhere to the following milestone schedule developed as part of the FY2008H1 baseline exercise:

WBS	Task Name	Date	Notes
FTT	CDR and Software Inception Results	31-Oct-07	IDT
FTT	Camera Prototype	15-Dec-07	Demonstration in lab
FTT	PDR and Software Elaboration Results	31-Mar-08	IDT
FTT	Final Design Review	15-Aug-08	IDT
FTT	Feedback Control Loop Prototype	15-Dec-08	Demonstration in Lab
FTT	FTT1 Sub-system Acceptance	9-Feb-09	In Lab
FTT	T01 Integration: Ready for PVM1	30-Jul-09	
PVM	PVM1: First star light on detector	1-Aug-09	
FTT	T01 Integration: Ready for PVM2	20-Aug-09	
PVM2	PVM2: Closed loop operation of the FTT	1-Sep-09	
FTT	FTT2 Subsystem Acceptance	7-Jan-10	In Lab
FTT	T02 Integration: Final Acceptance	7-Feb-10	Final Acceptance T02: 7-jan-10
FTT	FTT3 Subsystem Acceptance	8-Apr-10	In Lab
FTT	T03 Integration: Final Acceptance	8-May-10	Final Acceptance T03: 8-apr-10
FTT	FTT4 Subsystem Acceptance	8-Aug-10	In Lab
FTT	T04 Integration: Final Acceptance	8-Sep-10	Final Acceptance T04: 9-jul-10
FTT	FTT5 Subsystem Acceptance	28-Dec-10	In Lab
FTT	T05 Integration: Final Acceptance	28-Jan-11	Final Acceptance T05: 7-jan-11
FTT	FTT6 Subsystem Acceptance	30-Apr-11	In Lab
FTT	T06 Integration: Final Acceptance	30-May-11	Final Acceptance T06: 9-may-11

A detailed Gantt chart showing the detailed tasks and dependencies is attached as Appendix C.

7. Budget & Equipment List

The following budget was prepared as part of the FY2008H1 baseline exercise:

Resource	Standard Rate	Units Required	Total Cost
		WTC	CTC
Dichroic Mirrors (Glass and Coating)	9500	6	$57,000.00
Off-Axis Parabola	5000	6	$30,000.00
2-Position Slide	10000	6	$60,000.00
Motorized Tilt/Mount	3000	6	$18,000.00
Camera Feed Optic/Mount	2000	6	$12,000.00
Acquisition Camera	34000	6	$204,000.00
Miscellaneous Mechanical Items	2000	6	$12,000.00
M2 Interface	5000	6	$30,000.00
Computer Equipment	5000	6	$30,000.00
Chillers	3000	6	$18,000.00
Travel (1 Socorro Engineer to AMOS)	3000	3	$9,000.00
TOTAL			**$450,000.00**
Cost Per UT:			**$75,000.00**

The following list represents the known components of the system with representative part numbers and costs if applicable. The part numbers shown are for costing only. They may not reflect the final detailed design. The cost of some items is poorly defined, and they are noted below.

Note that the quantities specified are for a single system (for a single UT). A six-element interferometer would have six times the quantity listed in this chart.

Equipment	Typical Part #	Estimated Unit Cost	Qty. Reqd.	Total	Notes
Dichroic – Mirror (Phase I)	Custom 4" Dichroic	$9500	1	$9500	Price is a guess.
Dichroic – Mirror (Phase II)	Custom 4" Dichroic	$9500	1	$9500	Price is a guess.
Dichroic – Mounts	ThorLabs KS4	$234	2	$468	+ Tax & Shipping.
Dichroic – Mount Slide	Nanomotion FB100-300	$4250	1	$4250	+ Tax & Shipping.
Dichroic – Slide Actuator Controller	Nanomotion AB2 Series	$845	1	$845	+ Tax & Shipping. May need something with a different interface.
AB2 to Server Interface	Unknown	?	1	?	Can hopefully be eliminated.
Focusing Optic – OAP	SORL OAP44-06-06Q	$13000	1	$13000	Model number isn't perfect, may need custom.

Focusing Optic – Rotary Mount	ThorLabs NR360S	$2550	1	$2550	+ Tax & Shipping.
Focusing Optic – Goniometer Mount	ThorLabs GNL18	$445	1	$445	+ Tax & Shipping. May be too small.
Focusing Optic – Mount Controller	ThorLabs TDC001	$637	2	$1275	+ Tax & Shipping. USB controller
Focusing Optic – Controller PSU	ThorLabs TPS001	$25.50	2	$51	+ Tax & Shipping.
Focusing Optic – Optic Holder	ThorLabs KS4	$234	1	$234	
CCD Detector - Slide & Mount	ThorLabs LNR50S	$2548	1	$2548	+ Tax & Shipping.
CCD Detector- Slide Controller	ThorLabs TDC001	$637	1	$637	+ Tax & Ship.
CCD Detector- Slide Controller PSU	ThorLabs TSP001	$25.50	1	$25.50	+ Tax & Ship. May purchase multiple unit PSU for economy.
CCD Detector – Camera	Andor DU-897	$30,980	1	$30,980	+ Tax & Ship. Includes PCI card, Air-Cooled Chiller & SDK
CCD Detector - Fixed Mount	N/A.	$500	1	$500	Custom by R&ED Machine Shop. Price is a guess.
CCD Detector – C-Mount Lens		?		?	Have not yet found suitable lens.
Server - CPU	AMD Athlon64 X2 6400	$240	1	$240	+ Tax & Ship.
Server – PCI Timing Card	Symmetricom BC635-BC637	$795	1	$795	+ Tax & Ship.
Server – Motherboard	MSI K9NBPM2	$80	1	$80	+ Tax & Ship. May not be suitable, more PCI chipset research required.
Server - RAM	Corsair XMS2 2GB	$85	1	$85	+ Tax & Ship.
Server - HD	Seagate Baracuda, 160GB	$55	1	$55	+ Tax & Ship.
Server – Case	5U Rackmount Case	$150	1	$150	+ Tax & Ship.
Server – PSU	Seasonic S12	$80	1	$80	+ Tax & Ship.
Server – Disk Drive	DVD-RW	$40	1	$40	+ Tax & Ship.
Server – Display & Input Devices	N/A	$0	1	$0	Surplus Equipment from Office
Misc. Mount Adapters, mounting plates & hardware	N/A	$500	1	$500	Price is a guess. Items largely unknown at this

					point.
Closed Loop Chiller	10C water supply	$3000	1	$3000	Price is a guess. May not be required.
Misc – Cables from Controllers to Actuators	ThorLabs PAA613	$85	4	$340	+ Tax & Ship. Dichroic Slide will require an equivalent cable.
Misc – FTT Retroreflector	Edmund Optics NT46-187	$975	1	$975	+ Tax & Ship. May be part of Alignment System Work Package
Misc – FTT Retroreflector Cover	Unknown	$500	1	$500	May be custom by R&ED machine shop
Misc – Light Sources for Testing	NA	$0		$0	Will use items available in WC Lab.
Travel to AMOS	NA	$5000	1	$5000	System testing with FTTA closed loop. May not be required.

The total estimated cost of the FTT sub-system for the first UT is $79,148 for Phase I and $84,148 for Phase II. The cost for each additional UT is estimated at $74,148 for Phase I, and $83,648 for Phase II.

Total cost for six Phase I UTs is estimated at $449,891 which is just below our 2008H1 budget projection. Total cost for six Phase II systems is estimated at $506,891. An updated budget will be developed for the preliminary design review.

8. Personnel Resources

In an effort to complete the project within the schedule and budget shows in Sections 0 & 7, the following personnel resources will be required. Note that this is for the hardware system only.

Skill Set	Tasks	Man Month Estimate	Possible Individual	Notes
Work Package Leader	Budgeting, Scheduling, etc.	2	Tatiana Paz	
Hardware Engineer	Hardware design, procurement, commissioning & testing.	12	Rob Selina	
Machinist	Fabrication of adapters and CCD mount.	1	R&ED Machine Shop	
Optics Engineer	Design of optics & mounts.	4	Colby Jurgenson	
Procurement & Contracts	Procurement of parts & contract management.	1	Lorraine Archuleta & Darrell Brown	

In addition, the systems architects have been providing design guidance. Their continued review of proposed specifications and system configuration is desirable.

Appendix A – COTS CCD Detector Analysis

CCD Detector	Andor iXon DU-897	Princeton PhotonMax 512B	Hamamatsu C9100-13	QImaging Rolera MGi
Array Size	512x512	512x512	512x512	512x512
Pixel Size	16x16 um	16x16 um	16x16 um	16x16 um
16x16 Readout Rate	617Hz or 4338Hz	563Hz	315Hz	<300Hz
Latency	Low (no Buffering)	Low (PCI & Fiber)	Unknown	Unknown
Sensitivity for 350-1000nm	QE ~95% @ 550nm	QE ~ 95% @ 550nm	QE ~93% @ 550nm	QE ~92% @ 550nm
Readout Noise	<1e- , 0.06e- @ 1000 gain	<1 e- (no gain chart)	<1 e- (no gain chart)	<1 e- (no gain chart)
Dark Current	0.001 e-/pix/sec	0.005 e-/pix/sec	0.001 e-/pix/sec	0.5 e-/pix/sec
Linux SDK	Yes	Unknown	Unknown	Unknown
Re-window capability	Yes	Unknown	Unknown	Unknown
Operational Life	~8 yrs	Unknown	Unknown	Unknown
Min Operating Temp.	0C Operating, -25C Storage. Has been operated in the 0C to -15C range.	0C Operating	0C Operating, -10C Storage	0C Operating, -20C Storage
Power Dissipation	22W + chiller	70W	~85W	96W

Appendix B – Andor DU-897 Specifications

(See attached PDF.)

Appendix C – Project Gantt Chart

Task Name	Duration	Start	Finish
FTT Hardware System (1st UT)	**519 days**	**Wed 10/31/07**	**Mon 10/26/09**
Conceptual Design	**5 days**	**Wed 10/31/07**	**Tue 11/6/07**
Conceptual Design Review	0 days	Wed 10/31/07	Wed 10/31/07
CDR Document Revisions	5 days	Wed 10/31/07	Tue 11/6/07
Issue Final CDR Document	0 days	Tue 11/6/07	Tue 11/6/07
Preliminary Design	**103 days**	**Wed 11/7/07**	**Mon 3/31/08**
Detector Acquisition	20 days	Wed 11/7/07	Tue 12/4/07
Final Server Specification	5 days	Wed 11/7/07	Tue 11/13/07
Server Parts Acquisition	7 days	Wed 11/14/07	Thu 11/22/07
Server Assembly	1 day	Fri 11/23/07	Fri 11/23/07
Detector Setup in Lab	1 day	Wed 12/5/07	Wed 12/5/07
Camera Prototype Demonstration	0 days	Fri 12/14/07	Fri 12/14/07
Preliminary Design Documentation	100 days	Wed 11/7/07	Tue 3/25/08
ICD preparation	100 days	Wed 11/7/07	Tue 3/25/08
Preliminary Design Review	0 days	Mon 3/31/08	Mon 3/31/08
Final Design	**99 days**	**Mon 3/31/08**	**Fri 8/15/08**
Final Design Documentation	98 days	Mon 3/31/08	Wed 8/13/08
ICD Revisions	98 days	Mon 3/31/08	Wed 8/13/08
Final Design Review	0 days	Fri 8/15/08	Fri 8/15/08
Prototyping	**86 days**	**Fri 8/15/08**	**Mon 12/15/08**
Optics Procurement	30 days	Fri 8/15/08	Thu 9/25/08
Optics Coating	30 days	Fri 9/26/08	Thu 11/6/08
Mount & Actuator Procurement	40 days	Fri 8/15/08	Thu 10/9/08
CCD Mount Fabrication	20 days	Fri 8/15/08	Thu 9/11/08
Lab Test Bench Setup	25 days	Fri 11/7/08	Thu 12/11/08
Feedback Control Loop Prototype	0 days	Mon 12/15/08	Mon 12/15/08
Acceptance Testing (Lab)	**40 days**	**Mon 12/15/08**	**Mon 2/9/09**
Lab Testing	39 days	Mon 12/15/08	Thu 2/5/09
Final Acceptance	0 days	Mon 2/9/09	Mon 2/9/09
Site Installation & Testing	**63 days**	**Thu 7/30/09**	**Mon 10/26/09**
UT Acceptance (External)	0 days	Thu 7/30/09	Thu 7/30/09
Integration with UT	3 days	Thu 7/30/09	Mon 8/3/09
Pass PVM1	0 days	Mon 8/3/09	Mon 8/3/09
Testing PVM2	60 days	Tue 8/4/09	Mon 10/26/09
Pass PVM2	0 days	Mon 10/26/09	Mon 10/26/09
Software Development (TP)	500 days	Mon 11/26/07	Fri 10/23/09