The Magdalena Ridge Observatory Interferometer Fast Tip-Tilt/Narrow-field Acquisition System: Conceptual Design

CoDR_NRL_v2.3

Prepared by: Jonathan R. Andrews
Checked and validated by: Sergio R. Restaino
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Naval Research Laboratory
Remote Sensing Division, Code 7216
3550 Aberdeen SE
KAFB, NM 87117
http://rsd-www.nrl.navy.mil/7216/

Contents

Change Record

Rev.	Authors	Changes
1.1	JRA	Started rough draft
1.2	SRR	Added sections on mechanical and T/T performance
1.3	JRA	Added sections on optical and software
1.4	FSF	Finalized optics section and DP added software sections
1.5	JRA	Updated document formatting, DP added software descriptions
1.6	FSF	Updated information of optical sections
1.7	JRA	Added sections on mechanical designs from JHC
1.8	CCW	Added section on computer hardware pricing
1.9	JRA	Added sections on OAP
2.0	JRA	Added schedule and software phases
2.1	JRA	Technical editing
2.2	SRR	Technical editing and software interface sections
2.3	JRA/SRR	Final document version

Objective

The objective of this document is to specify the conceptual design for the Fast Tip-Tilt / Narrow-field Acquisition system for the Magdalena Ridge Observatory Interferometer Unit Telescope. All requirements are reviewed, the overall system design is introduced, and components are specified and described. Compliance status of the design with the requirements is listed and described. Finally, performance estimations are provided, alternative components described and interfaces listed.

Scope

This document describes the conceptual design parameters for the MROI Fast Tip-Tilt / Narrow-field Acquisition system. In particular:

- The specified functional requirements are listed
- The overall conceptual Fast Tip-Tilt/Narrow-angle Acquisition system is introduced
- The optical, camera, electrical, mechanical and software components are divided out and detailed and performance metrics for each are considered
- Interface control documents are identified

Referenced Documents

The following documents are incorporated by reference:

ICD-AAStoFTT-2009-07-06v011
(MROI)

INT-402-MIS-0034
(MROI)

INT-403-ENG-0003 rev 1.3
(MROI)

INT-403-SKT-0100 rev1.0
(MROI)

Tilt_compensation_error_calculations_for_MROI_JRA_v8
(NRL)

Andor Technologies iXon^{EM}+ 897 Data Sheet
(http://www.andor.com/pdfs/spec_sheets/L897SS.pdf)

Andor Technologies Oasis 150 Chiller Specifications
http://www.andor.com/photonics_accessories/Default.aspx?docID=223

Princeton Instruments ProEM 512B Data Sheet
(http://www.princetoninstruments.com/Uploads/Princeton/Documents/Datasheets/Princeton_Instruments_ProEM_%20512B_revM2.pdf)

Princeton Instruments CoolCube Chiller Data Sheet
http://www.princetoninstruments.com/Uploads/Princeton/Documents/Datasheets/CoolCUBE_Rev_A1.pdf

Acronyms and Definitions

AO Adaptive Optics
ADC Atmospheric Dispersion Corrector
BCA Beam Combining Area
BCF Beam Combining Facility
CPU Central Processing Unit
CCD Charge-Coupled Device
COTS Commercial Off-The-Shelf
DAC Digital-to-Analog Converter
DMA Direct Memory Access
EM Electron Multiplying
FTT Fast Tip-Tilt
FTTA Fast Tip-Tilt Actuator
FOV Field of View
FDR Final Design Review
FFOV Full Field-of-View
GB GigaByte
GUI Graphical User Interface
HFOV Half Field-of-View
ICS Interferometer Control System
MROI Magdalena Ridge Observatory Interferometer
M4 Mirror 4
NA Narrow-field Acquisition
NRL Naval Research Laboratory
OAP Off-Axis Parabola
M1 Primary Mirror
PDR Preliminary Design Review
RAM Random Access Memory
RMS Root Mean Squared
RTC JPL's Real Time Control distributed control system framework
SI Science Instrument
M2 Secondary Mirror
SNR Signal to Noise Ratio
SORL Space Optics Research Labs
SS Supervisory System
SSE Supervisory System Emulator
TBC To Be Confirmed
TEC Thermo-Electric Cooler
TIM- Technical Interchange Meeting
M3 Tertiary Mirror
UT Unit Telescope
UTC Coordinated Universal Time
WAS Wide-field Acquisition Sensor

Back-end instrument - The beam combining instrument for whose operating waveband the dispersion offset is calculated. This is normally the Science Instrument, but during initial commissioning will be the Fringe Tracker.
Nasmyth table – Defined and specified in document “INT-403-SKT-0100 rev1.0”
Science target - The object on which interferometric fringes are measured in the MROI beam combining instruments.
Tip-tilt reference object - The object which is acquired by the FTT/NA system and subsequently used to sense the tip-tilt. Usually this is the same object as the science target. However, if the science target is faint in the tip-tilt sensing waveband, it may be desirable to use a nearby bright star (if one exists) for tip-tilt sensing.
Tip-tilt zero point - A fiducial point on the FTT/NA CCD detector, corresponding to the location that the image of the science target is servoed to, in the absence of atmospheric dispersion. The zero point is determined by sending a light beam out to the Unit Telescope from the central BCF, as a start-of-night calibration task. Subsequently, the tip-tilt zero point remains fixed on the CCD until it is re-determined.

1 MROI FTT/NA System Overview of Requirements

The Magdalena Ridge Observatory Interferometer (MROI) Unit Telescope (UT) design calls for a subsystem that allows narrow-field image acquisition and correction of tip-tilt errors at a fast rate from the same camera. This subsystem has been named the MROI UT Fast Tip-Tilt/Narrow-field Acquisition (FTT/NA) system. The primary requirements of this system are: 1) to provide fast tip-tilt (FTT) correction for a large range of visual magnitude targets and 2) to switch to a narrow-field acquisition (NA) mode to allow an operator to find objects in the field of view (FOV) of the UT. Section 1.1 lists all requirements for the MROI FTT/NA system has defined in the customer supplied Top Level Requirements Document, version 1.3, MROI document number “INT-403-ENG-0003-FTTS-Top-Level-Requirements-rev1.3.”

1.1 MROI FTT/NA System Requirements

The MROI FTT/NA components as specified by the MROI will be integrated by scientists and engineers at the Naval Research Laboratory (NRL). Integration will consist of combining the components for optical bench installation and software which enable a path of integration into the overall MROI system.

The MROI have compiled a list of requirements and goals for the FTT/NA system. These requirements are listed throughout the “INT-403-ENG-0003-FTTS-Top-Level-Requirements-rev1.3” document as a list of “shalls” and are summarized in Table 1-1. In addition, several technical interchange meetings (TIMs) have resulted in additional clarifications and understanding of system operation and limitations. Specifically, the following items are important to note:

1. Current state-of-the-art limits selection of one of two cameras
2. Limited space available on Nasmyth table
3. Fixed locations of other sub-system components on the Nasmyth table
4. Optical beam height on the Nasmyth table is specified
5. Distance from Nasmyth table to electronics enclosure is specified
6. Limited space for electronic hardware
7. Power consumption limits
8. Ethernet communication and near-real-time performance implications
9. Existence of supervisory system and need for path of integration
10. Impact of various operating protocols for testing and final array operations

Table 1-1. Requirements for the MROI FTT/NA system as listed by the MROI Top Level Requirements Document and Technical Interchange Meetings.

SHALL #	Requirement
1	The system shall employ silicon detectors sensitive to 350 to 1000 nm wavelengths
2	All components (unless otherwise stated) are to be provided by the supplier

3	The system shall be able to switch between operating modes within 5 seconds
4	The system shall implement an idle mode where everything is powered but no correction is being performed
5	In idle mode, the system shall respond to a command from the ICS to verify proper initialization.
6	The system shall implement a fast tip-tilt correction mode where frames are captured at a user-selectable rate and tip-tilt corrections applied to the FTTA and the UT mount.
7	In fast tip-tilt mode, the system shall provide estimates of spatial seeing at a rate of at least 0.1 Hz.
8	The system shall implement a target acquisition mode in which it captures frames continuously at ~1Hz, feeding back acquisition/tracking correction to the UT mount only. This mode will also allow communication of corrections to the UT mount to be halted.
9	In acquisition mode, the system shall provide rough estimates of the spatial seeing.
10	The system shall implement a mode in which it capture and displays a single long exposure frame of up to 10 seconds.
11	The system shall implement a mode in which it captures a specified number of dark frames.
12	The system shall be able to transmit a system computed master dark frame to the MRO ICS and, on command, retrieve a previously transmitted master dark from the ICS using a well-defined protocol over Ethernet.
13	The system shall use the master dark frame to compensate for background signal when calculating stellar centroids.
14	The system shall implement a mode in which it captures a specified number of flat-field frames.
15	The system shall be able to transmit a system computed master flat frame to the MRO ICS and, on command, retrieve a previously transmitted master flat from the ICS using a well-defined protocol over Ethernet.
16	The system shall use the master flat frame to compensate for multiplicative gain when calculating stellar centroids.
17	The system shall perform a coordinate transform between CCD array coordinates and the tip-tilt axes of the FTTA when a customer supplied translation matrix is provided.
18	The FTT/NA sensor shall use light from all or part of the wavelength range 350-1000nm using a customer provided dichroic to split the light.
19	The system shall be compatible with a customer-specified space envelope for future upgrading the light-splitting dichroic.
20	The system shall allow a customer-specified dispersion offset to be applied to the tip-tilt zero point.
21	It shall be possible to use an off-axis object up to 30 arcsec from the science target as the tip-tilt reference object.
22	The system shall provide a facility for specifying the offset between the tip-tilt reference object and the science target in CCD coordinates.

23	New values of dispersion and off-axis offsets will be customer provided at intervals of 10 seconds and shall be applied without interrupting or disturbing closed-loop operation in fast tip-tilt mode.
24	The image centroiding algorithm shall yield centroids that vary linearly with image position within a pixel.
25	One of more graphical user interfaces (GUI) shall be implemented providing a human observer with: Control of all FTT/NA system functions and diagnostics Live display of acquisition mode frames Live display of fast tip-tilt mode frames at a reduced rate of 10Hz Live display of sequences of FTT/NA system telemetry A posteriori display of individual frames A posteriori display of sequences of FTT/NA telemetry
26	It shall be possible to display and operate the GUI from a computer in the MROI control room running the Linux operating system.
27	The system shall accept a command to disable the controls of the GUI that switch operating modes or alter parameters while leaving the image and telemetry displays functional.
28	It shall be possible to display and operate the GUI from a laptop located in the UT enclosure.
29	It shall be possible to run the GUI while streaming data to the ICS supervisory system.
30	It shall be possible to operate the FTT/NA software independently of any or all of the ICS, FTTA and UT mount.
31	The system shall be able to record sequences of frames and telemetry without communication to the ICS (called standalone mode).
32	The system shall provide at least 2GB of local storage for sequences of frames and telemetry with a posteriori display possible up to this size limit.
33	In standalone mode, the system shall be able to record sequences of detector frames in fast tip-tilt mode, acquisition mode and acquisition check mode.
34	In standalone mode, the system shall acquire frames at a user-selectable rate.
35	Telemetry items shall be recorded at the full rate which they are measured or generated in standalone mode and will include: Calibration parameters Raw centroid estimates Flux estimates Customer-supplied dispersion and off-axis offsets UT mount acquisition/tracking corrections FTTA demands Spatial seeing estimates Copies of all customer-supplied rotation matrices
36	All frames and telemetry acquired in standalone mode shall have UTC timestamps.
37	The system shall transmit detector and telemetry items to the ICS using

	well-defined protocols over Ethernet.
38	All ICS transmitted items shall have UTC timestamps.
39	Reduced data-rate frames and telemetry shall be streamed over Ethernet with a maximum latency of 0.2 sec.
40	The streamed data sent at reduced data-rate shall be derived from an evenly sampled subset of frames corresponding to a frame rate of at least 10 Hz.
41	The telemetry items sent at reduced data-rate shall be those listed in Shall #35.
42	Full data-rate frames and telemetry shall be transmitted over Ethernet with a maximum latency of 300 sec.
43	Full data-rate data shall be sent with a protocol that guarantees no data loss.
44	The telemetry items sent at full data-rate shall be those listed in Shall #35.
45	In lieu of Shall #39 and Shall #42, it is permissible to send all data to the ICS, where a maximum latency of 0.2 sec and reliable transfer of data is possible without impacting fast tip-tilt performance.
46	The field-of-view (FOV) for each frame captured in fast tip-tilt mode is at least 3 arcsec x 3 arcsec.
47	The system shall operate at user-selectable closed-loop 3dB bandwidths between 10 and 50 Hz.
48	The system shall provide the facility to apply a periodic offset to the output beam direction in fast tip-tilt mode.
49	The FOV in acquisition mode shall be at least 80 arcsec x 80 arcsec.
50	The system will automatically select the brightest object in the acquisition mode field as the tip-tilt reference object.
51	The system shall provide the facility to user-define another object as the tip-tilt reference object.
52	It shall be possible to integrate use of acquisition mode into the UT pointing and calibration sequence.
53	The system shall operate under the full range of environmental conditions given: Temperature of electronics: 10 to 40 degrees, C. Temperature of optical table: -15 to 20 degrees, C Relative humidity of optical table: 10% to 95%.
54	The system shall survive temperatures in the range -25 to -25 degrees C and relative humidity of 5% to 10% without compromising lifetime.
55	The dichroic support provided shall maintain the wavefront quality such that the overall wavefront error of the beam transmitted through the mounted optic shall not exceed 16.4nm rms.
56	Assuming the operational specifics and parameters as defined in section 7.3 of the MROI document “INT-403-ENG-0003 rev 1.3”, the limiting visual magnitude for fast tip-tilt and acquisition modes shall be V=16 for objects with V-I color bluer than +1.0 magnitudes.
57	The root-mean-squared (RMS) residual 2-axis tip-tilt error shall not exceed 0.060 arcsec for tip-tilt reference objects brighter than this limiting

	magnitude.
58	Any changes in beam direction to the BCA since the start-of-night calibration shall not exceed 0.015 arcsec on the sky for ambient temperature changes up to 5 degrees C.
59	If possible, any components that dissipate significant power shall be located in the UT electronics housing.
60	Any components on the UT Nasmyth table shall not dissipate more than 10 W of power underneath or within 30 cm of the beam path.
61	All components of the FTT/NA system shall consume no more than 100 W.
62	The system shall not require routine maintenance at intervals of less than 6 months.
63	The system shall be designed for a lifetime of 10 years.
64	All software source code shall be provided.
65	A list of interface control documents shall be provided at the Conceptual Design Review (CoDR).
TIM 1	Configuration #1 OAP angle 10.14˚, configuration #2 OAP angle is 27.5˚
TIM 2	Use provided ZEMAX design of UT
TIM 3	A CCD with 512 x 512 pixels
TIM 4	The use of reflective optics
TIM 5	Fixed dimensions on Nasmyth table
TIM 6	Fixed position of M4 on Nasmyth table
TIM 7	Beam diameter of 95 mm
TIM 8	Beam height on Nasmyth table of 150 mm
TIM 9	Fixed position of other components on Nasmyth table
TIM 10	15 degree angle on dichroic
TIM 11	Camera choice limited between Andor and Princeton EMCCD cameras
TIM 12	Acceptable to use multiple computers due to concern over Ethernet latency
TIM 13	Communication from FTT/NA to UT mount is via the Supervisory System
TIM 14	Existence of Supervisory System within the ICS for FTT/NA system
TIM 15	Supervisory System Emulator will be the intermediate step between

2 Conceptual FTT/NA System

The conceptual FTT/NA system is divided into five main areas of concentration for purposes of this document. These are: 1) The optical components, 2) the camera, 3) the electrical components, 4) mechanical components and 5) the software components. There is some overlap between these areas, for example, optical components require mechanical positioning, and the software interfaces with the electrical components, etc.

2.1 Overall System Design Constraints

The conceptual design of the FTT/NA system is based on Section 1.1 MROI FTT/NA System Requirements above. Critical to the conceptual design are:

- The camera selection and performance
- Dual performance operation (FTT and NA)
- The FOV
- Optical configurations
- Ethernet performance
- Supervisory System layer
- Power and space limitations
- Fast Tip-Tilt Actuator (FTTA) and controller performance
- Atmospheric and environmental conditions of site

Other issues include the status of other designs, development, and build components of the MROI array. These issues require consideration in iterating to the integration phase of the FTT/NA system.

Camera selection is driven by the available sensitivity, speed, low-light performance, noise and format and the trade-space between these factors. Current state-of-the-art cameras can provide low noise, large format, low light performance or speed. The challenge is to obtain all the desired features together in a commercial off-the-shelf (COTS) package. MROI has provided direction in selecting among the trade-space by specifying two cameras for use as the imaging array. What is not resolved is the difference between the existing software and firmware capabilities of both cameras which may drive final selection. The choice between the two cameras likely will be defined by the manufacturer supplied software/firmware and ease of integration.

The two cameras employ the same e2v Charge-Coupled Device (CCD) chip so there is no constraint from the camera on the FOV. Optical practice will normally lead to larger f/# optics being selected for aberration mitigation and ease of build. Downselection to the 80 x 80 arcsec FOV is required, provided the optics can be selected to meet the physical constraints of the Nasmyth table and the required beam height.

As a block diagram of all required components was included with the requirements document (shown in Figure 2.1 for clarity), components matching their performance have been selected by the NRL who will be responsible for integrating all components into the overall FTT/NA system.

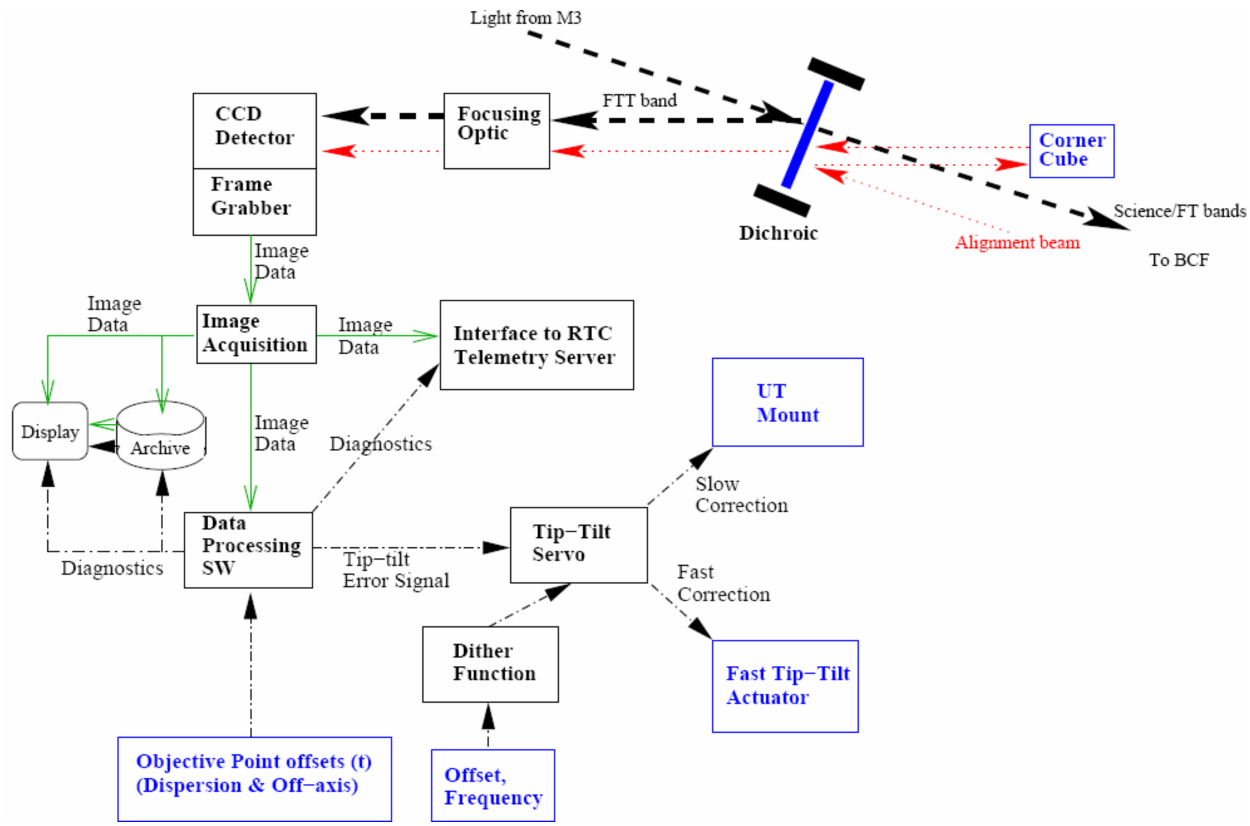


Figure 2-1. Block diagram of conceptual design provided by MROI in MROI document number “INT-403-ENG-0003-FTTS-Top-Level-Requirements-rev1.3.” Note that the interface for receiving/transmitting data to the ICS is not shown. Subsystems that are not included in the FTT/NA deliverables are shown in blue.

3 Optical Design

The optical components of the FTT/NA system, located on the Nasmyth table, receive light from the UT tertiary mirror (M3) as reflected by the dichroic. Also occupying space on the Nasmyth table are the mirror 4 (M4), the adaptive optics system upgrade and the alignment optical components which put boundaries of the locations of the components of the FTT/NA system.

Light from the dichroic entering the FTT/NA system is focused using reflective optics onto the CCD camera. This provides the signal, that when processed, is used to direct the FTTA located at the secondary of the telescope.

The CCD camera operates in a dual role as both a NA for target identification and for fast read-out mode for FTT correction using the M2 tip-tilt mirror provided by a sub-contractor to the MROI. Optically, no operational state changes are needed to support both modes.

3.1 Optical Requirements and Specifications

A summary of the requirements specific to the optical components employed in the FTT/NA system is given in this section. The requirements on the optical system are as follows:

Table 3-1. Requirements relevant to the optical components of the MROI FTT/NA system.

SHALL #	Requirement
18	The FTT/NA sensor shall use light from all or part of the wavelength range 350-1000nm using a customer provided dichroic to split the light.
19	The system shall be compatible with a customer-specified space envelope for future upgrading the light-splitting dichroic.
49	FOV for acquisition mode of 80 x 80 arcsec (120 x 120 arcsec goal)
63	The system shall be designed for a lifetime of 10 years.
TIM 1	Configuration #1 OAP angle 10.14˚, configuration #2 OAP angle is 27.5˚
TIM 2	Use provided ZEMAX design of UT
TIM 3	A CCD with 512 x 512 pixels
TIM 4	The use of reflective optics
TIM 5	Fixed dimensions on Nasmyth table
TIM 6	Fixed position of M4 on Nasmyth table
TIM 7	Beam diameter of 95 mm
TIM 8	Beam height on Nasmyth table of 150 mm
TIM 9	Fixed position of other components on Nasmyth table
TIM 10	15 degree angle on dichroic

These requirements define the specifications for component selection and placement on the Nasmyth table. These specifications will be identified in connection to the above requirements list.

Requirment #18 and TIM #4 specify the use of a protected aluminum reflective coating. Requirement #19, TIMs #1, #5, #6, #7, #8, #9 and #10 all address space constraints on the Nasmyth table to defined locations.

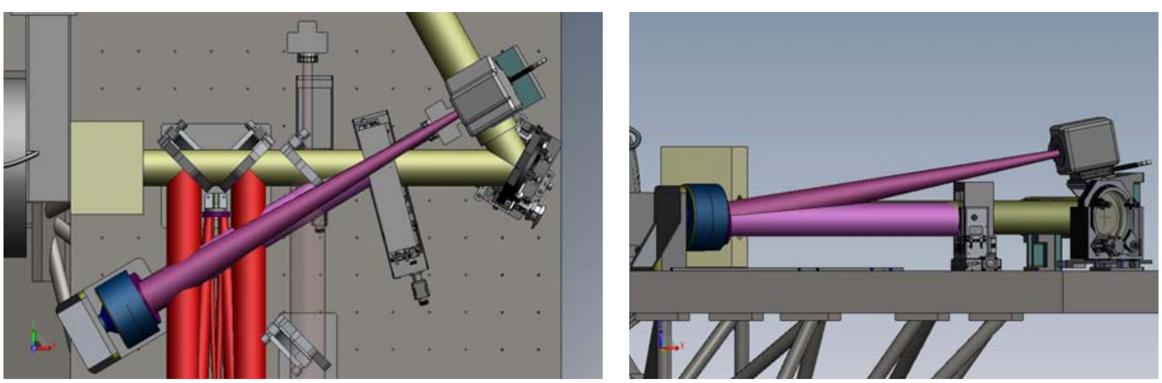
Requirement #49 and TIMs #2, #3 and #7 specify the focal length and diameter of the optics. Requirement #63 is a constraint to be included in bid packages for components.

These specifications lead to the development of the conceptual optical design.

3.2 Conceptual Optical Design

The MROI has provided two design layouts for the configuration of the components on the Nasmyth table. As a result of a TIM, the possibility of a third layout that disregards space on the Nasmyth table intended for a future upgrade with Adaptive Optics (AO) is presented. The three conceptual optical design options, labeled configurations #1, #2 and #3 are outlined in this section.

The optical design follows the specifications listed in Section 3-1. Two configurations were designed following the CAD files “INT-403-SKT-0100 rev1.0” provided by MROI, and identified as configuration #1 and configuration #2, as seen in Figure 3-1 and Figure 3-2 respectively.



Top View Side View

Figure 3-1. Configuration #1 with side view shown. Optical beam reflected out of plane.

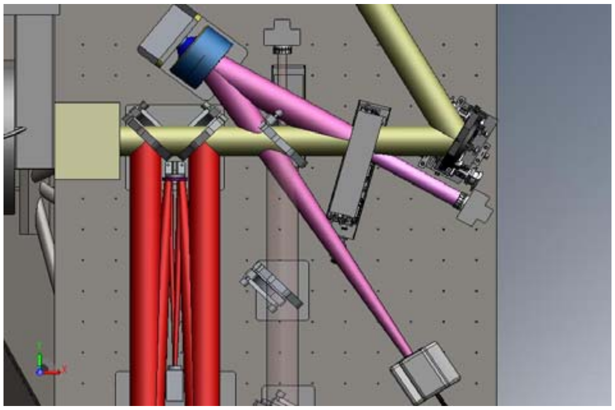


Figure 3-2. Configuration #2. Optical beam reflected in plane.

A third configuration was considered without an AO system and the addition of an optical flat on the Nasmyth table, identified as configuration #3 as shown in Figure 3-3.

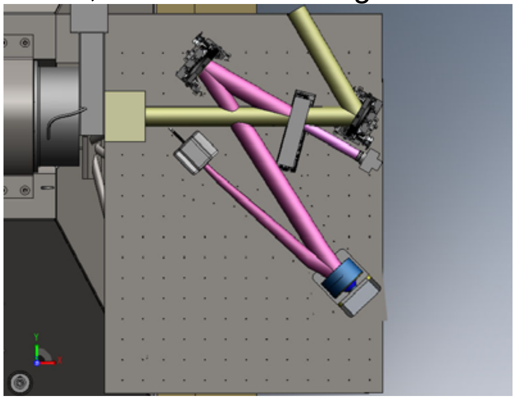


Figure 3-3. Configuration #3. Optical beam reflected in plane.

The optical design is presented in the following sections with a consideration of the optical components and the different configurations available.

3.2.1 Optical Component

Off-Axis Parabolic (OAP) Mirrors are available from several providers. One provider of high quality optics is Space Optics Research Labs (SORL), who has a reputation for providing high quality off-the-shelf and custom aspheric optical components, which is presented here for illustrative purposes.

An example of a commercially available component from SORL with descriptions and specifications is presented below:

<u>SORL Model # OAP40-035-06</u>

- 40 = 40 inch parabolic or vertex focal length
- 035 = 3.5 inch off-axis distance- specified along perpendicular from the optical axis to inner edge of mirror

- 06 = 6 inch diameter

In place of a lengthy description, the SORL model numbers will be used in the remainder of this section for comparison purposes. The specifications for the example mentioned above are:

- Focal length: 40.000" ± 0.200"
- Final Diameter: 6.000" ± 0.000" – 0.005"
- Clear Aperture: 5.900"
- Surface accuracy: λ\8 P-V over any 90% of clear aperture
- Wavelength of test: 633nm
- Material: Clear Ceram Z
- Coating: AlSiO Protected Aluminum
- Delivery: 8 weeks, 13 weeks for custom components

Using the optical design program ZEMAX, the three configurations were modeled and analyzed. Space constraints on the Nasmyth table, customer supplied designs, FOV requirements, and the desire to minimize aberrations dictated examples of OAP models that were selected for the ZEMAX models. The third configuration is an example of one of many possible configurations employing only COTS components (with an additional flat mirror) that is possible by disregarding the inclusion of the AO system. The three configurations employ the following OAP mirrors:

Configuration #1:

- OAP40-040-06: Custom OAP mirror due to the angle required to comply with the space restrictions as presented on "INT-403-SKT-0100 rev1.0" configuration 1.

Configuration #2:

- OAP40-155-06: Custom OAP mirrors due to the angle of 27.5˚ required to comply with the space restrictions as presented on "INT-403-SKT-0100 rev1.0" configuration 2.

Configuration #3:

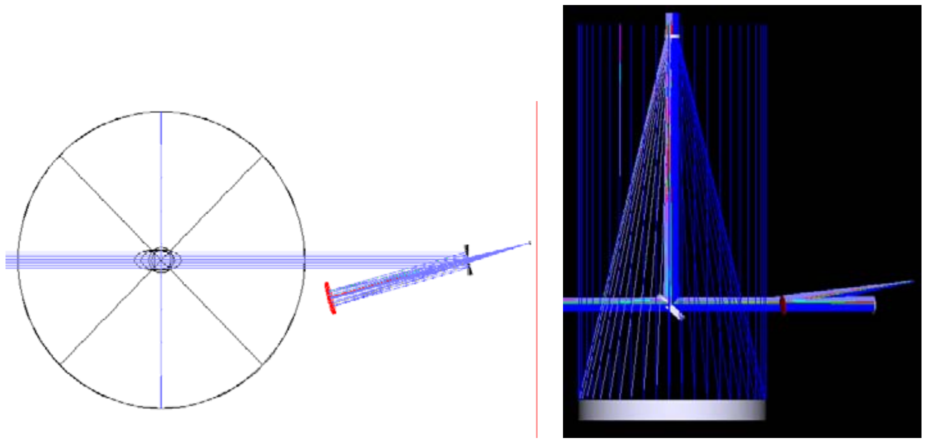
- OAP40-035-06: Off the shelf components from SORL, addition of an optical flat for folding the beam on the Nasmyth table.

Sections 3.2.2 to Section 3.2.4 present the ZEMAX analysis for the considered configurations, providing the full field spot diagram in the plane of the CCD with 512 x 512 pixels, pixel size of 16 µm, image area of 8.2 mm. Additionally, the RMS spot radius at different field angles is presented.

3.2.2 Configuration #1, SORL OAP40-040-06

Configuration #1 follows requirements on engineering drawing document "INT-403-SKT-0100 rev1.0", CONFIGURATION1. This configuration requires the use of a custom OAP, SORL model #OAP40-040-06 with the ZEMAX model layout shown in Figure 3-4.

This OAP has a focal length of 1016 mm, diameter of 152.4 mm, clear aperture of 149.86 mm and forms an angle of 10.14˚ with the optical axis, making it a custom component in order to comply with space on the Nasmyth table. The side view of Figure 3-4 shows the imaging camera out of the Nasmyth table plane as per the customer design. The OAP mirror is located at and angle of 15˚ from the output beam of the UT after the reflection from the dichroic.



Top View   Side View

Figure 3-4. ZEMAX layout for the custom OAP40-040-06.

Figure 3-5 (left) shows the full field-of-view (FFOV) spot diagram on the CCD image area of 8.2 mm, meeting the required FFOV of 80 x 80 arcsec. Figure 3-5 (right) shows the RMS spot radius at various field angles within the FFOV. The circle in each subplot is the diffraction limited spot, while the overlaid blue spot is the spot shape at that field angle.

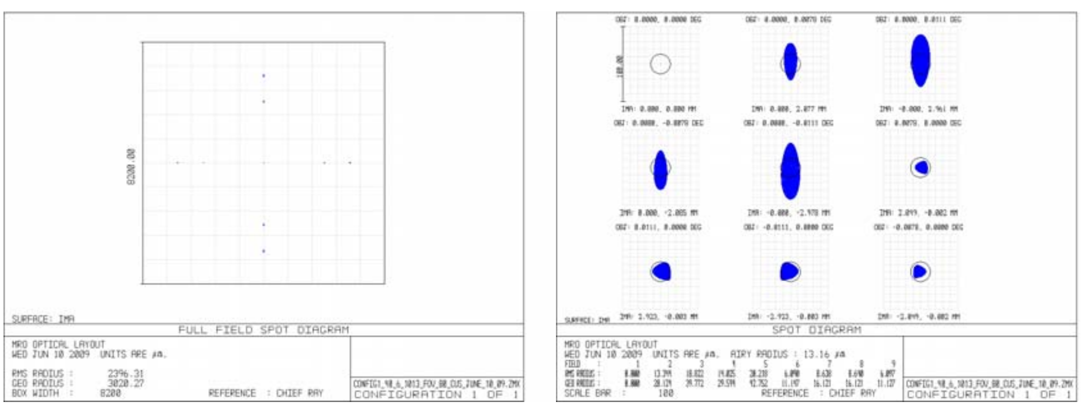


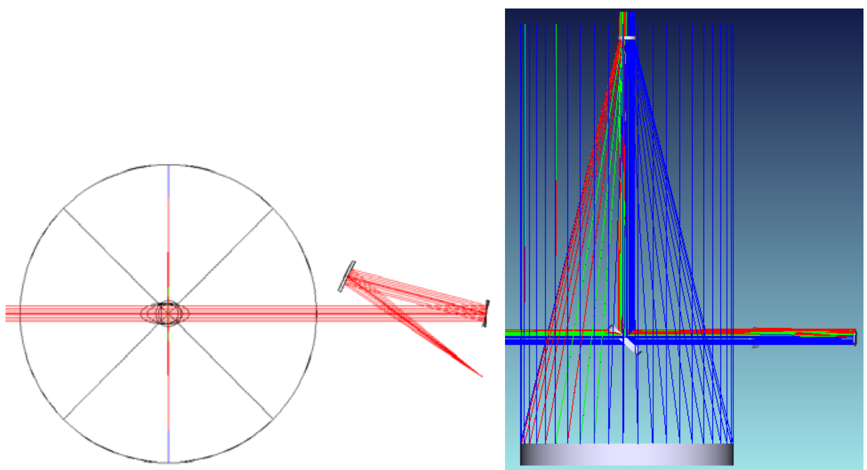
Figure 3-5. FFOV 80 x 80 arc seconds spot diagram (left). RMS spot size diagram at various field angles for OAP40-040-06 (right).

For this OAP, the maximum FFOV achievable is of 110 arcsec x 110 arcsec.

3.2.3 Configuration #2 OAP40-155-06

Configuration #2 follows requirements on engineering drawing document “INT-403-SKT-0100 rev1.0”, CONFIGURATION2. This configuration requires the use of a custom OAP, SORL model #OAP40-155-06 with the ZEMAX model layout shown in Figure 3-6.

This OAP has a focal length of 1016 mm, diameter of 152.4 mm, clear aperture of 149.86 mm and forms an angle of 27.5˚ with the optical axis, making it a custom component in order to comply with space on the Nasmyth table. The OAP mirror is located at and angle of 15˚ from the output beam of the UT after the reflection from the dichroic.



Top View Side View

Figure 3-6. ZEMAX layout for the custom OAP40-155-06.

Figure 3-7 (left) shows the full field-of-view (FFOV) spot diagram on the CCD image area of 8.2 mm, meeting the required FFOV of 80 x 80 arcsec. Figure 3-7 (right) shows the RMS spot radius at various field angles within the FFOV. The circle in each subplot is the diffraction limited spot, while the overlaid blue spot is the spot shape at that field angle.

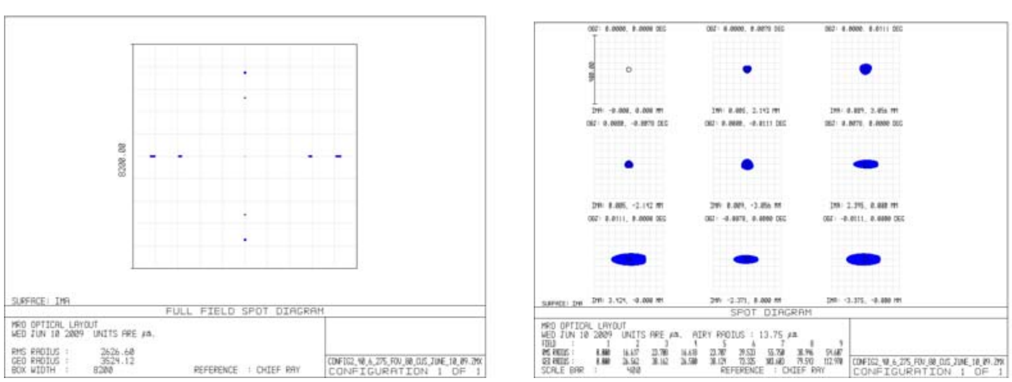


Figure 3-7. FFOV 80 x 80 arc seconds spot diagram (left). RMS spot size diagram at various field angles for OAP40-155-06 (right).

For this OAP the maximum FFOV achievable is of 93 arcsec x 93 arcsec.

3.2.4 Configuration #3 SORL OAP40-035-06

Configuration #3 is a customer requested design alternative that disregards the placement of an AO system. Using this space will allow multiple configuration options provided the addition of an optical flat is acceptable. This example configuration will employ COTS components only, which reduces the overall cost and has the added benefit of lower optical aberrations. Figure 3-8 shows the ZEMAX model layout of one possible configuration using the COTS OAP, SORL model # OAP40-035-06.

This OAP has a focal length of 1016 mm, diameter of 152.4 mm, clear aperture of 149.86 mm and forms an angle of 9.35˚ with the optical axis. This lower angle reduces optical aberrations and cost (see Section 3.4). The OAP mirror is located at and angle of 15˚ from the output beam of the UT after the reflection from the dichroic.

Figure 3-9 (left) shows the full field-of-view (FFOV) spot diagram on the CCD image area of 8.2 mm, meeting the required FFOV of 80 x 80 arcsec. Figure 3-9 (right) shows the RMS spot radius at various field angles within the FFOV. The circle in each subplot is the diffraction limited spot, while the overlaid blue spot is the spot shape at that field angle.

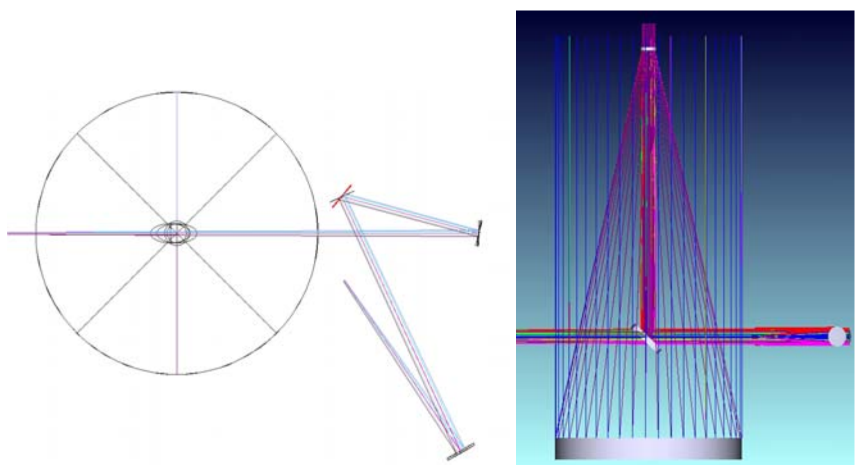


Figure 3-8. ZEMAX layout for the COTS OAP40-035-06 and flat mirror.

For this OAP the maximum FFOV achievable is of 110 arcsec x 110 arcsec.

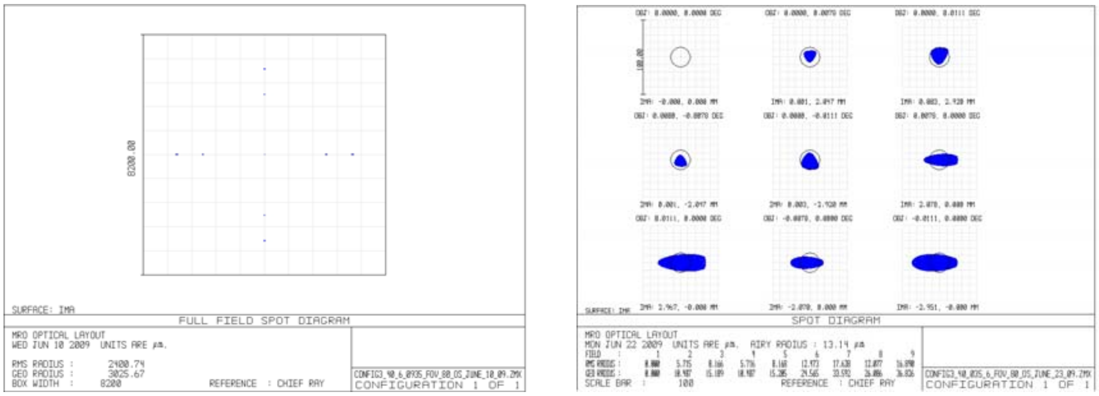


Figure 3-9. FFOV 80 x 80 arc seconds spot diagram (left). RMS spot size diagram at various field angles for OAP40-035-06 (right).

3.2.5 Configuration Summary

All three configurations meet the FFOV requirement of 80 x 80 arcsec. Configuration #2 show spot size characteristics that are worse than that of configurations #1 and #3, as can be seen in Table 3-2. The angles are identified using (± x,± y) following the Cartesian coordinate system.

Both configurations #1 and #2 rely on custom optics while configuration #3 employs an additional reflection, but maintains COTS components. The component costs are discussed in Section 3.4.

Table 3-2. RMS spot radius (in μm) for the 3 configurations for 80 x 80 arcsec FOV.

Arc seconds	0 (Airy)	28 (in y)	40 (in y)	-28 (in -y)	-40 (in -y)	28 (in x)	40 (in x)	-28 (in -x)	-40 (in -x)
OAP40-040-06	13.16	13.378	18.822	14.061	20.218	6.106	8.638	6.110	8.641
OAP40-155-06	13.75	16.660	23.708	16.661	23.707	39.626	55.750	39.045	54.607
OAP40-035-06	13.14	5.715	8.166	5.716	8.168	12.473	17.638	12.077	16.890

3.3 Compliance of Optical Components

All three optical designs comply with the specifications listed in Section 3-1 which are directly traceable to the requirements listed in Table 3-1. Implementation of the designs will require close working with the appropriate agency's procurement division and bid practices. This will directly impact Requirement #63 dictating a 10 year lifetime of all components and must be stipulated in the bidding process and documents to be met.

The conceptual design of the optical components is compliant with the requirements in Table 3-1.

3.4 Optical Component Cost Estimate

The long lead-time prior to MROI authorizing construction of the FTT/NA system precludes defining costs of the optical components. Current costs for components have been estimated and are recorded in Table 3-3 for reference use only.

Custom components increase substantially the cost of the system. Table 3-13 shows the cost of the OAPs considered for all the configurations presented in this section.

Table 3-3. Estimate cost of components considered for the optical design

Component	Cost (US $)
OAP40-040-06(Custom)	~$23,800.00
OAP40-155-06(Custom)	~$23,800.00
OAP40-035-06(COTS)	$7,615.00
Optical Flat(λ/20)	~$2,000.00

3.5 Optical Component Risk and Mitigation

Risk and mitigation management will be accomplished via on-going consultation with MROI. These consultations may include mapping MROI requirements to available technologies, extraction of engineering specifications from requirements, development of decision matrices, and cost benefit comparisons, to name a few. Many components carry detailed specifications in order to meet requirements, which must be accurately reflected in the request for purchase and procurement process. It is recommended that a technical liaison from MROI work closely with their purchasing office to ensure the specifications are satisfied. As the final integration plan for this subsystem is in early stages of development, consideration should be given to integration team selection and the mutual development of the integration plan. Care should be taken to ensure that the integration team members have the necessary scientific and engineering knowledge to appreciate and resolve the issues that arise during system integration.

4 Camera

The camera is the performance driver of the FTT/NA system and many other system performance estimates depend directly on those of the camera. Key to these are:

- Frame rate
- Sensitivity
- Noise
- Cooling

Cameras have been a topic of discussion during several TIMs between MROI and NRL which have identified two cameras as being suitable for integration in the FTT/NA system:

- Princeton Instruments ProEM 512B
- Andor iXon^{EM}+ 897

4.1 CCD Camera Requirements

A summary of the requirements specific to the CCD camera employed in the FTT/NA system is given in this section. The requirements on the camera system are as follows:

Table 4-1. Requirements applicable to the CCD camera for the MROI FTT/NA system.

SHALL #	Requirement
1	Use silicon based detectors
10	Capture up to a 10 second frame
14	Capture up to a 100 second flat field frame
18	The system shall be sensitive to all/part of 350-1000nm wavelengths
47	User selectable closed-loop bandwidths
49	Imaging detector FOV at least 80 arcsec x 80 arcsec
53	Environmental operation
54	Environmental survivability
56	Imaging detector sensitivity to V=16 magnitude
59	Electrical components that dissipate heat located in electronics housing
60	No more than 10W dissipated underneath or within 30 cm of the beam
61	Cannot consume more than 100 W total power
62	No routine maintenance for 6 months
63	10 year life span for all components
TIM 11	Camera choice limited between Andor and Princeton EMCCD cameras

Princeton Instruments ProEM 512B and Andor iXon^{EM}+ 897 electron multiplying (EM)CCD cameras use the same 512 x 512 pixel e2v CCD97 back-illuminated frame-transfer CCD.

TIM #11 requires downselection between the Andor and Princeton cameras. This allows direct comparison of the two cameras, their true manufacturer specifications, and compares them directly to the FTT/NA system top level requirements in Table 4-1. Section 4.2 lists the specifications of the two camera choices for comparison, Section 4.3 shows compliance with the requirements and Section 4.4 outlines risk and mitigation.

4.2 Camera Specifications

The two cameras are the Princeton Instruments ProEM 512B and Andor iXon^{EM}+ 897 electron multiplying (EM)CCD cameras and their specifications are listed here in Table 4-2. The cameras have many features in common and both use the 512 x 512 pixel CCD97 back-illuminated frame-transfer CCD imaging chip manufactured by e2v technologies. Noteworthy features of the two cameras are:

1. Option for liquid of air cooling
2. Electron Multiplying effectively reduces read noise to less than 1e^-
3. Both cameras include frame grabber hardware
4. Similar environmental operation

The detailed specifications of both the Princeton ProEM 512B and Andor iXon^{EM}+ 897 can be found in each manufacturer's respective data sheets, as detailed in the Referenced Documents section of this document.

Table 4-2. Summary of specifications of Princeton the ProEM 512B and Andor iXon^{EM}+ 897 EMCCD cameras.

<table>
<tr><th>Features</th><th>iXon^{EM}+ 897(back illuminated)</th><th>ProEM: 512B</th></tr>
<tr><td>Active Pixels</td><td>512 x 512</td><td>512 x 512</td></tr>
<tr><td>Pixels Size(WxH; µm)</td><td>16 x 16</td><td>16 x 16</td></tr>
<tr><td>Image Area(mm)</td><td>8.2 x 8.2</td><td>8.2 x 8.2</td></tr>
<tr><td>Active Area Pixel Well Depth(e^-)
Typical:
Maximum:</td><td>160,000
220,000</td><td>200,000</td></tr>
<tr><td>Gain register well depth(e^- typical)</td><td>800,000</td><td>800,000</td></tr>
<tr><td>Max Readout Rate (MHz)</td><td>10</td><td>10</td></tr>
<tr><td>Frame rates(frames per sec)</td><td>35 – 549</td><td>33-926</td></tr>
<tr><td>Read Noise(e^-)</td><td><table>
<tr><th>MHz</th><th>Typical</th><th>With electron Multiplication</th></tr>
<tr><td>10</td><td>49</td><td><1</td></tr>
<tr><td>5</td><td>42</td><td><1</td></tr>
<tr><td>3</td><td>32</td><td><1</td></tr>
<tr><td>1</td><td>21</td><td><1</td></tr>
</table></td><td><table>
<tr><th>MHz</th><th>Typical</th><th>With electron Multiplication</th></tr>
<tr><td>10</td><td>50</td><td><1</td></tr>
<tr><td>5</td><td>12-25</td><td><1</td></tr>
<tr><td>1</td><td>7</td><td><1</td></tr>
<tr><td>0.1</td><td>3</td><td><1</td></tr>
</table></td></tr>
<tr><td>Operating environment</td><td>0°C to 30°C ambient,</td><td>0°C to 30°C ambient,</td></tr>
</table>

	<70%(humidity, non-condensing)	<80%(relative humidity, non-condensing)
EMCCD temperature (at + 20°C ambient)	Air cooled: -85°C Water-cooled: -90°C Liquid chiller-cooled:-100°C	Liquid chiller-cooled: -70°C to -80°C
Dark current	@ -85°C(e^-/pix/sec): 0.001	@ -70°C(e-/pix/sec): 0.005
Power Requirements	0.6A @ +12V 0.3A @ -12V 3.0A @ +5V	80 W

It is important to note that some specifications in Table 4-2 are dependant upon modes of operation and not all best-case performance metrics can be achieved in each mode of operation. The maximum frame rates are dependant upon the binning of the pixels and proximity of the region of interest (ROI) to the readout buffer of the camera. The dark current of each camera is specified at different cooling temperatures and the lowest available cooling temperature is dependant upon the type of cooler provided by each camera manufacturer, the length of tubing for the camera chillers and ambient temperature.

Both cameras are based on the e2v chip, and will have similar quantum efficiencies, format, pixel size, etc., defined by their respective datasheets. CCD chips can be ordered with different windows and coatings which can affect spectral performance. Care must be taken when ordering to specify wavelength range of the CCD chips to 350nm to 1000nm.

4.3 Camera Compliance

Final selection of the FTT/NA system camera is based on a decision matrix which compares individual camera specifications with their compliance to the requirements stated in Table 4-3.

Table 4-3. Camera compliance, C is compliant, C# is labeled, NC is not compliant.

SHALL #	Requirement	Andor	Princeton
1	Use silicon based detectors	C	C
10	Capture up to a 10 second frame	C	C
14	Capture up to a 100 second flat field frame	C1	C1
18	The system shall be sensitive to all/part of 350-1000nm wavelengths	C2	C2
47	User selectable closed-loop bandwidths	C3	C3
49	Imaging detector FOV at least 80 arcsec x 80 arcsec	C	C
53	Environmental operation	NC	NC
54	Environmental survivability	NC	NC
56	Imaging detector sensitivity to V=16 magnitude	NC	NC

59	Electrical components that dissipate heat located in electronics housing	C	C
60	No more than 10W dissipated underneath or within 30 cm of the beam	NC	NC
61	Cannot consume more than 100 W total power	NC	NC
62	No routine maintenance for 6 months	C	C
63	10 year life span for all components	NC	NC
TIM 11	Camera choice limited between Andor and Princeton EMCCD cameras	C	C

C1- Camera is compliant with up to 100 second exposures, communication with camera manufacturers indicates exposure times up to 10 minutes are possible. Suitability for particular applications is not guaranteed by the manufacturer.

C2- The CCD chip is sensitive over the specified range, CCDs can be ordered with different coatings and cover glass. Correct coating and cover glass must be specified when ordering to achieve compliance.

C3- Maximum camera frame and data rates are specified by the camera manufacturer and cannot be selected outside of that range. Camera is compliant provided user selected closed-loop bandwidth does not exceed the maximum frame rate of the camera. See section 4.4.2 and Appendix B.

Selection of either the Andor or the Princeton camera is compliant with the requirement specified by TIM #11. Based on manufacturer's specifications, both cameras are non-compliant to shall #53, #54, #56, #60, #61 and #63. Therefore requirements set out in TIM #11 and shalls #53, #54, #56, #60, #61 and #63 are mutually exclusive. Clarification is requested as to the acceptability of satisfying TIM #11 over shalls #53, #54, #56, #61 and #63 from the MROI.

Shall #56 specifies operation of the camera at V=16 magnitude. The two specified cameras define the sensitivity of the system.

4.4 Camera Risk and Mitigation

Risk and mitigation management will be accomplished via on-going consultation with MROI. These consultations may include mapping MROI requirements to available technologies, extraction of engineering specifications from requirements, development of decision matrices, and cost benefit comparisons, to name a few. Many components carry detailed specifications in order to meet requirements, which must be accurately reflected in the request for purchase and procurement process. It is recommended that a technical liaison from MROI work closely with their purchasing office to ensure the specifications are satisfied. As the final integration plan for this subsystem is in early stages of development, consideration should be given to integration team selection and the mutual development of the integration plan. Care should be taken to ensure that the integration team members have the necessary scientific and engineering knowledge to appreciate and resolve the issues that arise during system integration.

The Princeton ProEM 512B and Andor iXon^{EM}+ 897 EMCCD cameras have manufacturer specified environmental operation and survivability, sensitivity, power consumption (with chiller), lifetime and frame rates that are contradictory to the requirements specified in the MROI Top Level Requirements Document. The camera choices represent the state-of-the-art in low noise, fast frame rate and high sensitivity imaging arrays operating in the visible wavelengths. A possible mitigation plan for meeting the system requirements is to incorporate a different camera in the future as the technology becomes available.

The remainder of this section deals with specific information from the camera vendors that has been identified as a risk and outlines possible mitigation, where applicable.

4.4.1 Environmental Operation and Maintenance

The requirements in shall #53 and #54 require both operation and survivability under environmental conditions in excess of those specified by the camera manufacturer. As these two camera choices implement the same underlying CCD technology and represent the state-of-the-art in low noise and high frame rate cameras, there are no alternative technologies available. Therefore, the FTT/NA system will not be compliant with the environmental operation and survivability requirements.

Additionally, shall #63 requires a 10 year lifespan for all components of the FTT/NA system. Neither of the manufacturers guarantee their components for 10 years. Both cameras will have a 1 year manufacturer's warranty that will not be voided unless the camera operates above the range of environmental conditions listed in Table 4-2.

Should environmental operation and survivability in excess of the ranges specified by the camera manufacturers be required, this may be included in the bid package to the camera vendors. The requirement for a 10 year lifespan of the camera should also be included in the bid package to the camera vendors.

4.4.2 Frame Rates

The camera frame transfer rate is the performance driver of the FTT/NA system. There are many operating modes for CCD cameras which provide a wide range of frame rates, both transferred and buffered. The operating mode of the camera must be chosen based on the functional requirements of the system, of which sustainable operation via frame transfer into computer memory is key for near-real-time operation of the FTT/NA system. Based on the current choice of cameras, frame transfer rates in the range of 770 to 555 fps are achievable as a best-case scenario. Details of camera operation that lead to this conclusion are outlined in Appendix B.

4.4.3 Camera Chiller

Both the Princeton ProEM 512B and Andor iXon^{EM}+ 897 camera heads rely on thermo-electric cooling (TEC) to help reduce dark current of the camera to within the range specified in Table 4-2. This relies on dissipating a large amount of heat (between 75 and 100 W) directly from the camera by means of a fan, which is non-compliant to shall #60. Some relief may be obtained by using liquid cooling, but the heat dissipation near the camera head may still be in excess of 10W.

Both cameras offer an option to disable the fan through software, allowing the fan cooling of the TEC to be replaced by remote liquid camera cooler. As the liquid cooler will dissipate more than 10W, it will need to be located in the electronics cabinet, which is located within approximately 5 meters (to be determined by MROI) away from the Nasmyth table. The two camera manufacturers provide an option for a liquid cooler with their respective cameras, but neither will guarantee full functionality of the cooler with tubing in excess of 10 to 12 feet. The coolers will still function, but at a reduced cooling rate as the flow rate of the liquid drops as the tubing length increases. This will increase the camera dark noise to levels exceeding those shown in Table 4-2, as those numbers are best-case scenarios where both the cooling fan and liquid cooling options are employed.

Both camera manufacturers' chillers draw approximately 100W of power which will not be compliant with shall #61. Additionally, they both weigh approximately 6 pounds, have dimensions of roughly 7" x 7" x 6", and employ similar tubing connectors, so care must be taken in integrating and interfacing these chillers with the electronics enclosure.

5 Electrical and Electronic Components

The electrical and electronic components required, as part of the FTT/NA system are identified in Figure 1 of “INT-403-ENG-0003 rev 1.3” and Figure 2-1 of this document and include a computer for image acquisition, processing, FTTA control, archiving, receiving commands, and sending/receiving telemetry

In addition, other electrical components have been identified in TIMs between MROI and NRL and include:

- optical stage actuators and controllers
- a second computer
- communication cards for the two computers

The electrical and electronic components fit into three categories, those related to:

- the optical/mechanical stages
- computers
- computer peripherals

5.1 Electrical and Electronic Component Requirements

A summary of the requirements specific to the electrical components employed in the FTT/NA system is given in this section. The requirements on the electrical system are as follows:

Table 5-1. Requirements applicable to the electrical components of the MROI FTT/NA system.

SHALL #	Requirement
12	Transmit/receive master darks from ICS via Ethernet
15	Transmit/receive master flats from ICS via Ethernet
23	Offsets provided and applied without interrupting closed loop operations
26	Operate and display GUI from computer in MROI control room
27	System accepts commands to disable controls on GUI
28	Operate and display GUI from laptop in the UT enclosure
32	Provide 2GB of storage for local telemetry storage during standalone mode
36	UTC timestamp put on all frames and telemetry acquired in standalone mode
37	Transmit frames and telemetry to ICS via Ethernet
38	UTC timestamp put on all items transmitted to ICS
48	User-specified dither function support
51	Allow user override brightest object auto-selection
53	Environmental operation
54	Environmental survivability
59	Electrical components that dissipate heat located in electronics housing
60	No more than 10W dissipated underneath or within 30 cm of the beam

61	Cannot consume more than 100 W total power
62	No routine maintenance for 6 months
63	10 year life span for all components
TIM 12	Acceptable to use multiple computers due to concern over Ethernet latency
TIM 13	Analog communication to FTTA

5.1.1 Meeting Electrical and Electronic Component Requirements

This section covers many different components which, as a group, contribute to meeting the requirements above. These are addressed by grouping the linked requirements together and showing how they are satisfied by selection of a specific electrical or electronic component.

Many of the requirements enumerated in Table 5-1 focus on communication, user selectability and transmission/receiving of data and commands. Many of the requirements are met through selection of Ethernet, the preferred communications network of the MROI. In particular, shalls #12, #15, #23, #26, #27, #28, #36, #37, #38, #48, #51 and TIM #12 are addressed by providing the specification that two Ethernet ports are available on the buffer computer (per TIM #12 which allows for more than one computer).

The system will interface via Ethernet to synchronize the computer clock with the MROI clock to satisfy #36 and #38 using timestamps delivered from the Supervisory System. Accuracy of the timestamps resides with the Supervisory System.

TIM #13 requires a specification of an Input/Output (I/O) computer peripheral card for communication to the FTTA. In addition to the peripheral card, communication to opto-mechanical stages (in support of shall #62) requires an RS-232 port be available to support COTS actuator drives.

Power requirements for electronic components are addressed in shalls #59, #60 and #61, and lead to the specifications for placement and power consumption of the components. All computers will be located in the electronics enclosure and the combined power of all computers is specified to be less than 100W. The opto-mechanical controllers will be installed in the electronics cabinet and will be specified to draw less than 100W of power. However, COTS computers, controllers, etc., that have been identified to date draw more combined power than the 100W specified in shall #61.

Computers will be specified to support 4GB of RAM so that 2GB will be available for archiving detector frames and telemetry in support of shall #32.

Environmental operation and maintenance is addressed in shalls #53, #54 and #62 and require that the bid package for these COTS items include the specifics to be met. As a specification for the bid package, cleaning and maintenance of the rack-mounted components filter replacements need to be addressed by the vendor. Operationally, routine alignment will be provided by remotely controllable opto-mechanical stages.

Requirement #63 is a constraint to be included in bid packages for components.

5.2 Computers

The near-real-time operating requirements of the FTT/NA system necessitate careful handling of the transfer and reception of information via Ethernet. This can be accomplished by dedicating one computer to communication (called the buffer computer) while another is dedicated to camera frame acquisition, near-real-time processing of information and direct control of the FTTA.

The near-real-time operating requirements of the FTT/NA system and the volume of information from the camera and processing needed requires a state-of-the-art CPU optimized for numerical processing with a large amount of RAM.

The near-real-time computer (hereafter called the FTT/NA primary computer) performance requirements dictate Pentium Xeon-class CPU, with associated power requirements (including hard-drive) which are beyond 100W. The required computer peripherals, the two PCI-bus I/O cards and camera frame acquisition card, each require ~5W to ~7W of power. The processing requirements of the buffer computer are not as intensive and require less processing power and overall power consumption.

The buffer computer will support communications through Ethernet, and there will be two dedicated Ethernet ports on the buffer computer for this purpose.

The two computers outlined in this section for the FTT/NA system are shown in Figure 5-1.

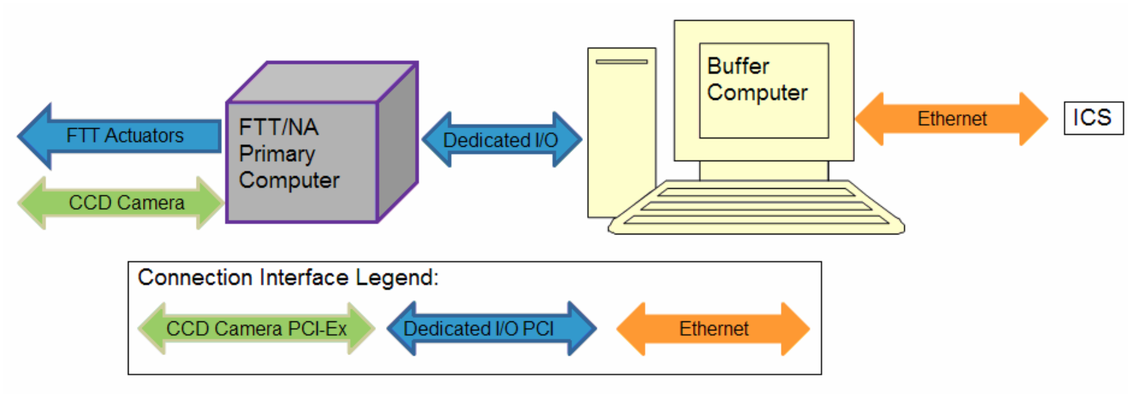


Figure 5-1. Block diagram description of the proposed system.

The long lead-time prior to MROI authorizing construction of the FTT/NA system precludes defining future costs of the computer components. Current costs for the two suitable computers have been estimated and are recorded in Table 5-2 and 5-3 for reference use only.

Table 5-2. Specifications, estimated cost and estimated power consumption for FTT/NA primary computer.

Processor	Intel Xeon Quad-Core E5450 3.0GHz w/ 12MB Cache
RAM	8 GB DDR2
Hard Drive	Kingston 128GB Solid-State Drive
Expansion Peripherals	PCI-Express Expansion slot for the Camera PCI-based I/O card PCI-based digital to analog converter card
Physical Dimensions	2U Rack mount
Power Requirements	160 Watts + power of peripherals
Cost	$4,000 + peripherals

Table 5-3. Specifications, estimated cost and estimated power consumption for buffer computer.

Processor	Intel Celeron D347 3.06GHz w/ 512kB Cache
RAM	4 GB DDR2
Hard Drive	Kingston 128GB Solid-State Drive
Expansion Peripherals	PCI-based I/O card
Physical Dimensions	1U Rack mount
Power Requirements	120 Watts + power of peripherals
Cost	$2,000 + peripherals

The total power requirements and total cost using today's available components approach 300 Watts and $6,000. Peripherals are extra and discussed in Section 5.2.1, below.

5.2.1 Computer Peripherals

The long lead-time prior to construction of the FTT/NA system precludes defining costs and availability of the computer peripheral components. Current costs for suitable components are shown in this section.

High speed communication and bus-mastering capabilities between the FTT/NA primary computer and the buffer computer requires dedicated I/O cards. Suitable cards available for this purpose are manufactured by NuDAQ. Other manufacturers are available for this purpose, but the PCI-7300A is listed here as an example. This card provides up to 80MB/s transfer rate on a bus-mastered PCI card with a 16kB buffer and is suitable for this application. The power consumption is 5 Watts maximum per card with a current cost of $1,100 per card.

In addition, the FTTA will be presented with an analog signal from a PCI card that employs analog-to-digital converters (DACs). AccessIO is one manufacturer that provides several suitable cards, which consume roughly 7.5 Watts of power and cost around $800.

5.3 Optical Stage Actuators and Controllers

Remote actuation of optical stages is accomplished with COTS actuators and controllers. These components are available from a variety of vendors. The FTT/NA system requires four (4) remotely controllable actuators in addition to the other degrees of freedom of the optical stages adjusted with thumbscrews as outlined in Section 6. Current cost estimates and manufacturer specified power consumption for a suitable component line are recorded in Table 5-4.

Table 5-4. Sample actuators and controllers for remote control of optical stages.

Newport Model	Key Specifications	Price (ea)
PZA12 Actuator	Axial Load: 50N Travel: 12.5 mm / 0.03 μm	$950.00
PZC 200 Controller	USB or Serial Interface (w/ external hardware)	$500.00
PZC-SB Switchbox	Single input, 8 output channels	$950.00
NSC-PS25 Power Supply	Input: 90-246 VAC Output:15 VDC, 4.6 A	$90.00

5.4 Electronics Risk and Mitigation

Risk and mitigation management will be accomplished via on-going consultation with MROI. These consultations may include mapping MROI requirements to available technologies, extraction of engineering specifications from requirements, development of decision matrices, and cost benefit comparisons, to name a few. Many components carry detailed specifications in order to meet requirements, which must be accurately reflected in the request for purchase and procurement process. It is recommended that a technical liaison from MROI work closely with their purchasing office to ensure the specifications are satisfied. As the final integration plan for this subsystem is in early stages of development, consideration should be given to integration team selection and the mutual development of the integration plan. Care should be taken to ensure that the integration team members have the necessary scientific and engineering knowledge to appreciate and resolve the issues that arise during system integration.

6 Mechanical Design Components

The mechanical mounts and stages required are those related to positioning and alignment of the OAP, the CCD Camera, the MROI provided dichroic and the MROI provided corner cube. Use of off-the-shelf mounts is limited by various constraints which are discussed within the appropriate sections.

6.1 Mechanical Design Requirements

A summary of the requirements specific to the mechanical components employed in the FTT/NA system is given in this section. The requirements on the mechanical system are as follows:

Table 6-1. Requirements applicable to the mechanical components of the MROI FTT/NA system.

SHALL #	Requirement
19	Compatible with a customer-specified space envelope for dichroic upgrade
53	Operate under environmental conditions listed in requirements document
54	Survive under environmental conditions listed in requirements document
55	Maintain wavefront quality
58	Beam changes not to exceed 0.015 arcsec for temperature changes of 5ºC
62	No routine maintenance for 6 months
63	10 year life span for all components
TIM 6	Fixed position of M4 on Nasmyth table
TIM 8	Beam height on Nasmyth table of 150 mm

These requirements define the specifications for component selection and design for mechanical stages and mounts on the Nasmyth table. These specifications will be identified in connection to the above requirements list.

Requirment #19 and TIMs #6 and #8 address space constraints and beam height on the Nasmyth table to defined locations and specify dimensions of mechanical stages and mounts and their placement into one of the three configurations.

Requirements #53 and #54 specify selection of materials for design that can operate and survive under the range of environmental conditions specified in the MROI Top-Level Requirements document. The environmental range of operation and survivability is a constraint that must be specified in the bid package of COTS mechanical stages and mounts.

Requirements #55 and #58 specify design choices and materials to minimize distortion on the optical components and maximize thermal stability. The thermal stability is a constraint that must be specified in the bid package of the COTS mechanical stages and mounts.

Requirement #62 specifies both COTS and custom designed stages and mounts to be compatible with remotely controllable actuators for remote alignment.

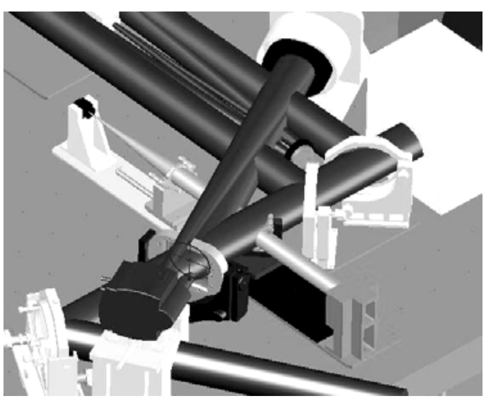
Requirement #63 is a constraint to be included in bid packages for COTS components and needs to be address in the design of custom components.

These specifications lead to the development of the conceptual mechanical designs or COTS selection for the dichroic mount, the OAP mount, corner cube mount and camera mount.

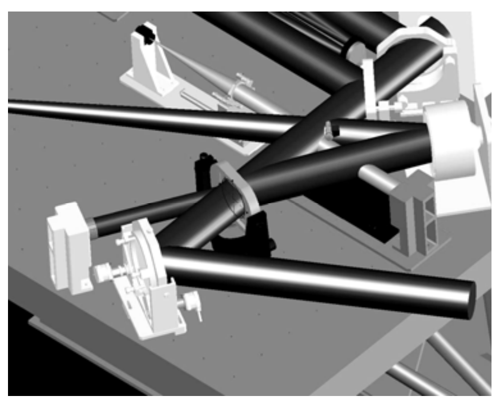
6.2 Dichroic Mount

MROI has specified and will provide a dichroic for splitting the light from the telescope for use in the FTT/NA system. The cuboid dichroic is composed of Infrasil 301 material and measures 125mm wide by 120mm high by 15mm thick. The NRL designed mount must fit in the space requirements of the Nasmyth table, must account for beam height and the design should demonstrate the ability to maintain wavefront quality and thermal stability to comply with shalls #19, #55 and #58 and TIMs #6 and #8. Additionally, it should have a lifetime of 10 years and should function and survive across the environmental conditions detailed in shalls #53, #54 and #63. The design will be compatible with remotely controllable actuators for remote alignment to comply with shall #62.

The design implements a 4-degree of freedom (x-y translation in the breadboard plane plus tip/tilt with respect to the optical axis) mount to hold the cuboid dichroic. This has been designed using a modified COTS gimbal mount. See the illustration in Figure 6-1 showing the modified commercial gimbal mount in the two customer specified configurations. The same gimbal mount can also be used in configuration #3.



Configuration #1



Configuration #2

Fig 6-1. Modified commercial gimbal mount in two configurations.

The mount holds a single dichroic and remains stationary once located on the breadboard. The main modification to the mount is the optics cell, which gently holds the dichroic in a stable manner with best effort to comply with shall #55. The overall height of the modified COTS gimbal is 223mm, which meets the requirement of fitting within the space envelope with a maximum height of 400mm above the Nasmyth table, as described in shall #19.

6.2.1 Dichroic Mount Performance

Due to the tolerance of 16.4 nanometer deformation of the dichroic due to its mounting, a design approach was used that softly and uniformly applies a continuous closed-circuit path line-pressure to both front and back surfaces of the optics. This maintains the optics in the fore and aft position relative to the cell. This positioning technique is accomplished by using two Teflon® coated Hollow Core Elastomer low durometer O-rings located directly across from each other and outside the clear aperture of the dichroic. The line-pressure is accomplished from a predetermined and preset squeeze between the fore and aft components of the cell. Two polymer rods spaced along the bottom edge of the cell maintain the vertical position of the dichroic. See Figure 6-2 for a close up illustration of the modified gimbal mount and Figure 6-3 for a visual of the aft component of the custom cell.

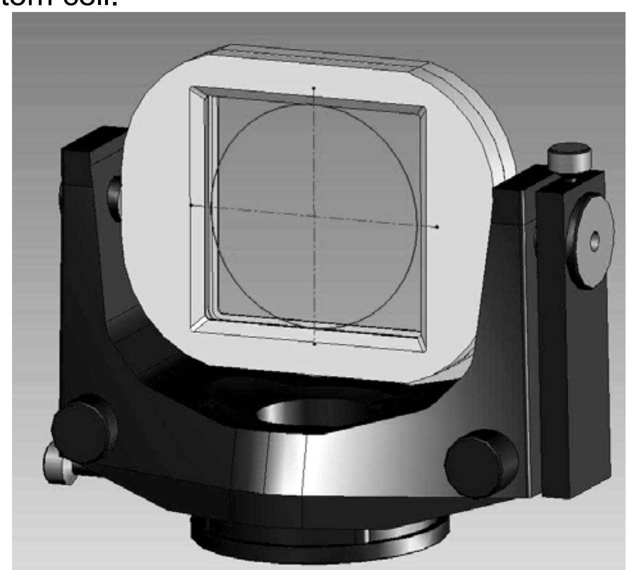


Figure 6-2. Modified commercial gimbal mount.

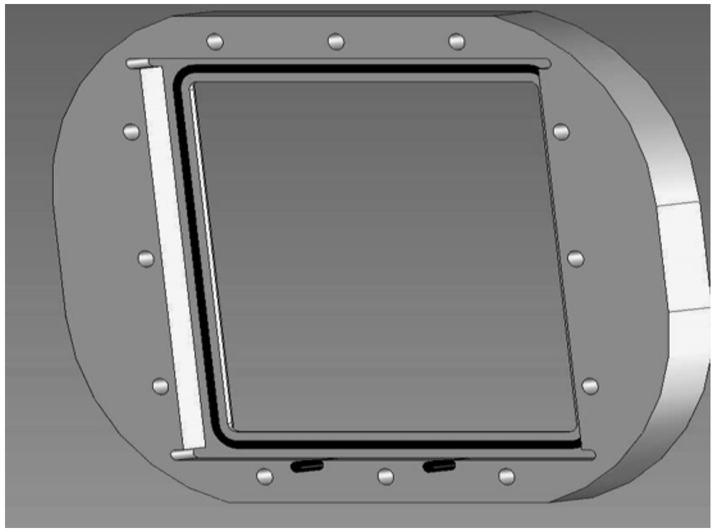


Figure 6-3. Aft component of the custom cell.

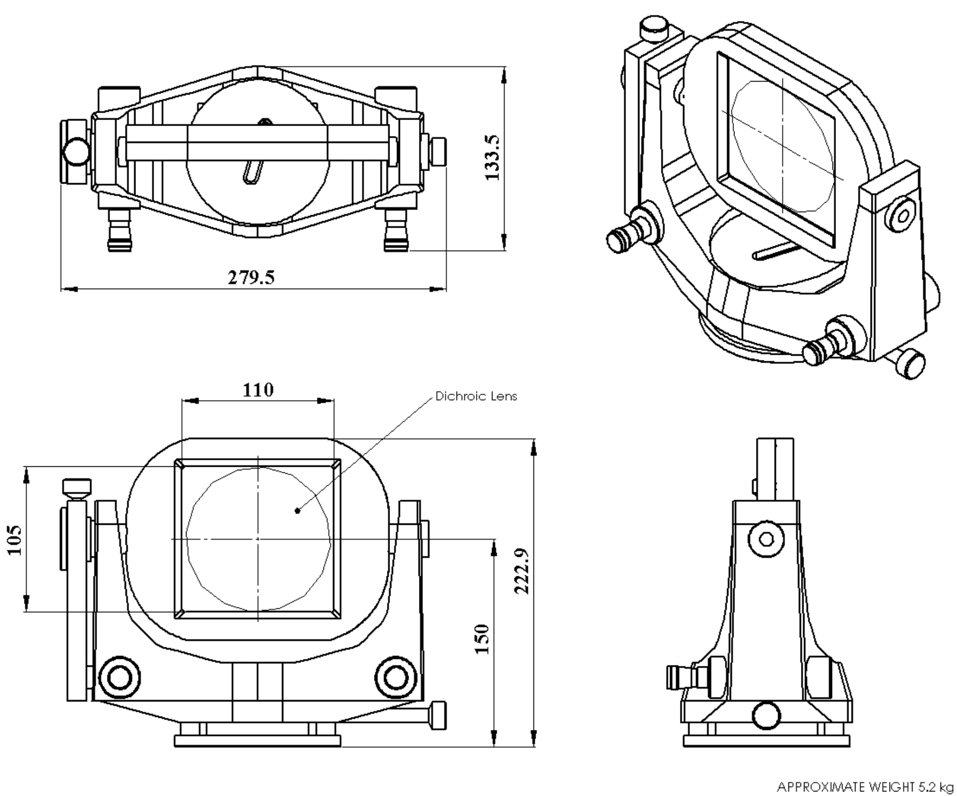


Figure 6-4. Mechanical drawing of modified commercial gimbal mount.

The clear aperture of the cell is a rectangle 105mm tall by 110mm wide centered at 150mm above the breadboard. By choosing the Newport SL-15A Series Clear-base Precision Gimbal Mount the front surface of the dichroic is located at the intersection of the tip/tilt axes of the mount, easing the overall alignment task. The tip/tilt has an unlimited course angle setting and a fine angle range of +/- 2 degrees. The tip/tilt control can be actuated remotely using suitable actuators. The breadboard plane x-y translation has a range of +/- 18mm and a fine setting of no worse than +/- 0.5mm depending on dexterity. The weight of the assembled mount, including the dichroic, is on the order of 5.2kg. See Figure 6-4 for drawing details with dimensions.

The approach used to clamp the dichroic in the cell is straight forward and simple, and in general generates low bending and compression stresses and corresponding surface deformations. A finite element analysis (FEA) will help greatly in determining the Shore durometer and squeeze parameters required. Calibration of the elastic “spring” modulus of the Hollow Core Elastomer O-rings is required prior to the final design dimensions. In order to simplify assembly of the mount and increase stability over the environmental range, fairly tight tolerances on dimensions and flatness are expected on the custom cell. The thickness dimension of the dichroic is expected to be held within +/- 0.025mm. Although this adds to the upfront cost, it will assure that deformations are held to a minimum as well as errors due to the human component. All materials used are rated at least from -23C to 150C. The particular COTS mount chosen has been used extensively by NRL/NPOI and drift tests show excellent mechanical and thermal stability. By modifying a commercial off the shelf gimbal mount, costs and design time are greatly reduced. The estimated cost of the modified commercial mount is on the order of $3.2k.

6.3 OAP Mount

The mount for the OAP must fit in the space requirements of the Nasmyth table, must account for beam height and the design should demonstrate the ability to maintain wavefront quality and thermal stability to comply with shalls #55 and #58 and TIMs #6 and #8. Additionally, it should have a lifetime of 10 years and should function and survive across the environmental conditions detailed in shalls #53, #54 and #63. The design will be compatible with remotely controllable actuators for remote alignment to comply with shall #62.

The wavefront quality of the example OAPs introduced in Section 3 are guaranteed by the manufacturer only when used with mirror mounts (MM) provided by the same manufacturer. Shown in Figure 6-5 is the mechanical drawing of a COTS MM provided by SORL. The optical axis height exceeds that specified by TIM #8 necessitating a custom MM development by SORL to ensure wavefront quality.

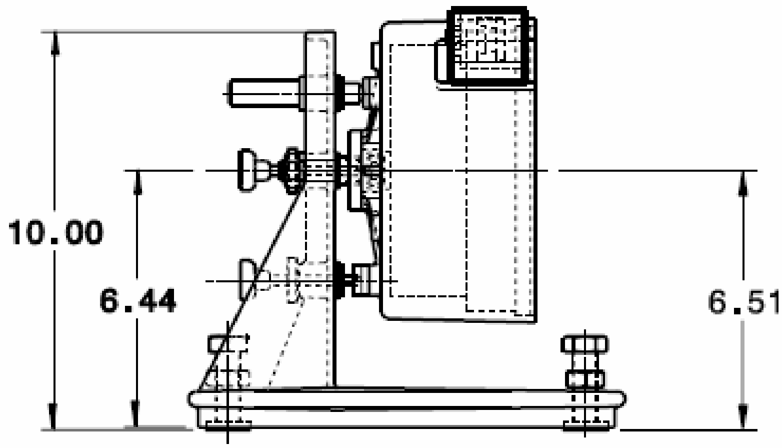


Figure 6-5. COTS mount drawing for a 6 inch OAP from SORL (inches).

The long lead-time prior to MROI authorizing construction of the FTT/NA system precludes defining costs of the MMs. Table 6-2 summarizes the current cost estimates for the COTS SORL MMs both with (MMOA-6) and without (MMO-6) alignment flats. Table 6-2 also shows the current estimated cost of a custom MM provided by SORL and an optical flat mount, should configuration #3 be chosen. All mounts can use provided thumbscrews for alignment or can be upgraded to remote actuators such those presented in Section 5.3.

Table 6-2. Cost of COTS and custom mounts for the OAP and optical flat

MM (Custom)	$4,800.00
SORL MMOA-6(COTS)	$3,675.00
SORL MMA-6(COTS)	$2,785.00
Optical Flat mount	~$800.00

The OAP mount designed by SORL will be compatible with the space envelope of the Nasmyth table in compliance with TIMs #6 and #8. The mechanical stability and environmental operation and survivability as specified in shalls #53, #54, #58 and #63 are determined by the vendor and need to be addressed in the bid package to ensure compliance.

6.4 Corner Cube Mount

Ongoing discussions with MROI are continuing to determine NRL involvement in the design/selection of the corner cube mount. Depending on the optical configuration chosen, the corner cube mount will either be co-located in the camera mount (as described in Section 6.5) or be a separate COTS component. As described in MROI document ICD-AAStoFFT-2009-07-06v011, the corner cube selected is the PLX Innovative Optical Systems HM-25-5.

Should optical configuration #2 or #3 be chosen, the COTS component KS1 from Thorlabs would be a suitable choice for mounting the corner cube.

Should optical configuration #1 be selected, the camera mount will need to include the corner cube mount. This could use a modified COTS component as part of the design.

6.5 Camera Mount

The final design of the camera mount is dependant upon selection of one of the three optical configurations on the Nasmyth table. Depending on the configuration chosen, the camera will be mounted in one of two ways. For optical configuration #2 or #3 we envision the use of a three axis COTS positioning system like the Newport 462-XYZ-M. For this position system we suggest the use of manual thumbscrews for the lateral position axis and a remotely controllable actuator for the "focusing" axis. This solution, with two thumbscrews (such as the Newport HR-13) and one piezo-electric micro-stepping motor actuator (like the Newport PZA-12) will have an approximate cost of $2,600.

For configuration #1 a custom mount will have to be designed and developed around the COTS camera mount listed above. The camera mount will also house the corner cube mount. This design has not been fully explored at this time, however it is expected that this option will cost in excess of $5,000.

6.6 Compliance of Mechanical Designs

All four mechanical mount components comply with the specifications listed in Section 3-1 which are directly traceable to the requirements listed in Table 6-1, except for shalls #55 and #58, which are not measurable. Care has been taken in the design to maintain mechanical stability.

Implementation of the designs will require close working with the appropriate agency's procurement division and bid practices. This will directly impact Requirement #63 dictating a 10 year lifetime of all components and must be stipulated in the bidding process and documents to be met.

6.7 Mechanical Designs Risk and Mitigation

Risk and mitigation management will be accomplished via on-going consultation with MROI. These consultations may include mapping MROI requirements to available technologies, extraction of engineering specifications from requirements, development of decision matrices, and cost benefit comparisons, to name a few. Many components carry detailed specifications in order to meet requirements, which must be accurately reflected in the request for purchase and procurement process. It is recommended that a technical liaison from MROI work closely with their purchasing office to ensure the specifications are satisfied. As the final integration plan for this subsystem is in early stages of development, consideration should be given to integration team selection and the mutual development of the integration plan. Care should be taken to ensure that the integration team members have the necessary scientific and engineering knowledge to appreciate and resolve the issues that arise during system integration.

7 Software Design Components

The operational status of the FTT/NA system is to be commanded by the Supervisory System (SS) to provide control of the FTT and be commanded by the same SS to provide NA system functionality. In addition, FTT/NA system status and telemetry is communicated to the SS by request. The FTT/NA system is composed of two computers and supporting I/O communication cards. Communications with external computers and/or the SS is handled exclusively through the buffer computer. To provide stand-alone diagnostics and control, a Supervisory System Emulator (SSE) will be provided, commanded by a graphical user interface (GUI).

The FTT/NA performs its functional requirements, reports status, and provides data via a command driven interface.

Functionally, the software components of the FTT/NA system consist of: 1) a set of routines for reading the camera, calculating tilt errors and applying correction to the FTTA, 2) routines for communication to remote computers for display, archiving and remote controllability, and 3) a graphical user interface for control and display of FTT/NA system performance.

7.1 Software Design Requirements

A summary of the requirements specific to the software components employed in the FTT/NA system is given in this section. The requirements on the software system are as follows:

Table 7-1. Requirements applicable to the software components of the MROI FTT/NA system.

SHALL #	Requirement
3	Switch between operating Modes in less than 5 second
4	The system will have an Idle Mode that will serve as an initialization mode
5	While in Idle Mode, system capable of receiving/responding to commands
6	The system will have an FTT Mode with user/supervisor specified correction and provide low-frequency correction to the UT mount via the SS or SSE
7	While in FTT Mode the system will provide estimates of spatial seeing
8	The system will have an Acquisition Mode that provides full camera frames at a rate of ~1Hz
9	In Acquisition Mode the system will provide spatial seeing estimates
10	The system will have an Acquisition Check Mode that provides for long exposures for looking for objects in the field
11	The system will have a Dark Frame Mode
12	The system will provide the master dark frame to the SS
13	This dark frame will be considered the system wide dark frame
14	The system will have a Flatfield Mode providing exposures up 100 sec via

	image summation if necessary
15	The system will provide this master flatfield frame to the SS
16	This flatfield frame will be considered the system wide flat field
17	The system will perform coordinate transformations with the appropriate rotation matrix provided by the SS or SSE
20	The system will apply dispersion and off-axis offsets provided by the SS to the tip-tilt zero point
22	The system will be able to perform tip-tilt correction on an off-axis object
23	The system will have the ability to receive offset corrections at ten-second intervals while the FTT loop is closed
24	The system will calculate centroids that vary linearly within one pixel
25	GUIs will be provided to control all system Modes
26	These GUIs will run on a Linux based computer located remotely with respect to the FTT/NA system
27	The system will accept a command to disable controls from the GUI while still displaying images and telemetry on the GUI
28	The GUIs will run on a laptop situated in the UT enclosure
29	It will be possible to run the GUIs while data is streaming to the ICS
30	It will be possible to operate the system independently of the ICS, FTTA, and UT mount
31	The system will be able to record frames and diagnostic telemetry without the MRO ICS
32	The system will be able to record all system and image data up to 2GB while the loop is closed and be retrieved after the loop is opened for diagnostics
33	The system will be able to record detector frames in the various Modes
34	The rate of recording of these frames will be selectable
35	Telemetry data (non-image data) will recordable
36	All recorded detector frames and telemetry will be UTC timestamped
37	Detector frames and telemetry from the various Modes will be transmittable to the MRO ICS via Ethernet
38	Detector frames and telemetry from the various Modes will be transmitted to the MRO ICS via Ethernet and will be UTC stamped
39	Reduced-data-rate detector frames and telemetry will be streamed from the system via Ethernet with a maximum .2 sec latency capture to transmission
40	The reduced-date-rate will be an evenly sampled frames corresponding to a transmitted frame rate of at least 10Hz
41	The telemetry streams will calibration parameters, raw centroid estimates, flux estimates, dispersion and off-axis offsets, UT mount acquisition /tracking corrections, FTTA demands, spatial seeing estimates and copies of all rotation matrices used
42	Data recorded on the FTT/NA will be transmitted via Ethernet with a maximum latency of 300 seconds
43	There will be no data loss on this transfer
44	The telemetry items will be calibration parameters, raw centroid estimates, flux estimates, dispersion and off-axis offsets, UT mount acquisition /tracking

	corrections, FTTA demands, spatial seeing estimates, and copies of all rotation matrices used
45	If possible the data will be transmitted a single realization at a time with a maximum latency of .2 second from recording
47	The system shall support selectable closed loop 3dB bandwidths of a range of 10-50 Hz
48	The system will provide a facility to apply periodic offsets to the FTT zero point with specified direction, amplitude, and frequency
50	The system by default will select the brightest object in the Acquisition Mode file as the tip-tilt reference object
51	They system will provide the ability to select an override of the brightest object in the field
52	The system will provide the possibility to use the Acquisition Mode during UT pointing and calibration
64	All software source code shall be provided
TIM 13	Communication from FTT/NA to UT mount is via the SS
TIM 14	Existence of Supervisory System within the ICS for FTT/NA system
TIM 15	Supervisory System Emulator will be the intermediate step between

Shall #3 specifies transition between the FTT and NA Modes in less than 5 seconds. These two systems use the camera in different ways and provided atomic camera operations, such as a long exposure, is not occurring, this can be met.

Shalls #4, #5, #6, #8, #10, #11 and #14 specify different operation modes as discussed in detail in Section 7.2 Conceptual Software Architecture. Shall #6 also requires communication to the UT mount. This is facilitated by communicating these offsets to the SS in compliance with TIM #13.

Shalls #7 and #9 specify providing estimates of the spatial seeing based on a customer provided algorithm.

Shalls #12, #13, #15 and #16 specify transmitting and receiving flat and dark frames and using them for image correction.

Shalls #17 and #20 specify application of coordinate transform and dispersion offset information as provided by the SS.

Shall #22 specifies providing functionality to use a SS or SSE defined offset between the tip-tilt reference object and the science target.

Shalls #23 and #24 specify receiving dispersion and off-axis corrections and applying them to the system properly.

Shalls #25, #26, #28 and #29 specify using a GUI that will run on Linux for SSE using MROI provided java shell.

Shall #27 specifies a passive display such that commands from the GUI do not affect system state. Additionally, shall #30 specifies operation of the FTT/NA system independently of any or all of the ICS, FTTA and UT mount for testing and integration.

Shalls #31, #32, #33, #34, #35 and #36 specify a stand-alone mode of operation including full functionality and recording telemetry items for local storage with UTC timestamps while the SS is not issuing commands.

Shalls #37 and #38 specify data transmission in all operational modes with UTC timestamps to the SS.

Shalls #39, #41, #42, #43, #44 and #45 specify the use of Ethernet communications between the FTT/NA system and the SS. This specifies recording all telemetry items for up to 300 seconds (or at the end of the 2GB of available RAM) and then transmitting it with no loss of data. Additionally, a subset of frames and telemetry will be transmitted at a 10 Hz rate for intermediate display.

Shall #47 specifies system functionality for the user to select a closed-loop bandwidth. Available range will be specified by the hardware specification for the selected camera.

Shall #48 specifies the inclusion of a dither function where the system will accept direction, amplitude and frequency from SS and apply this during FTT mode.

Shall #50 and #51 specify automatic software selection of brightest object in Acquisition Mode with the functionality for the user to override this selection.

Shall #52 specifies updating the UT mount corrections while in Acquisition Mode.

Shall #64 specifies ALL software source code be included in the system delivery.

7.2 Conceptual Software Architecture

The FTT/NA system communicates with the outside world through the buffer computer to either the SS, remotely located in the ICS, or to the SSE. Control of the FTT/NA system is available remotely in the ICS or in the dome through the buffer computer to a standalone laptop or another computer.

The FTT/NA system operates the camera in the frame transfer mode. The frame transfer mode, which provides the highest speed operation of the camera, shifts the entire frame behind a non-illuminated area to be read by the read-out buffer.

The FTT mode and NA modes provide two separate functions of the system. One updates the FTTA controller based on subframes of camera data, while the other reads and passes full frames of data. While it appears that the FTT mode and the NA mode are completely separate, there is significant data handshaking and sharing between the two modes, for example the need for dark/flat frames to be used in data reduction in both modes.

In the following sections, the conceptual timing and data flow is described for the FTT and the four NA Modes, while the data interaction between the two modes is shown separately for emphasis. The driving philosophy is to provide a command driven interface capable of operating the FTT and NA from the SS using the same basic tools and functions.

Data from the FTT/NA system (detector frames, telemetry, and status) is presented to the SS or the SSE for retrieval. A simple GUI or set of GUIs will be provided at the SSE level to control the system and examine recorded and streaming data.

7.2.1 Physical Layout and Interfaces

The physical implementation of the FTT/NAS will consist of a primary computer, which directly interfaces to the FTTA controller and the camera. This FTT/NA primary computer also connects to a buffer computer via a set of high-speed Digital Input-Output (DIO) cards. The use of two computers allows the FTT/NA system primary computer to operate closed-loop at the highest rate possible, while the buffer computer provides communications with the SS or SSE. A top-level diagram of the system is shown in Figure 7-1.

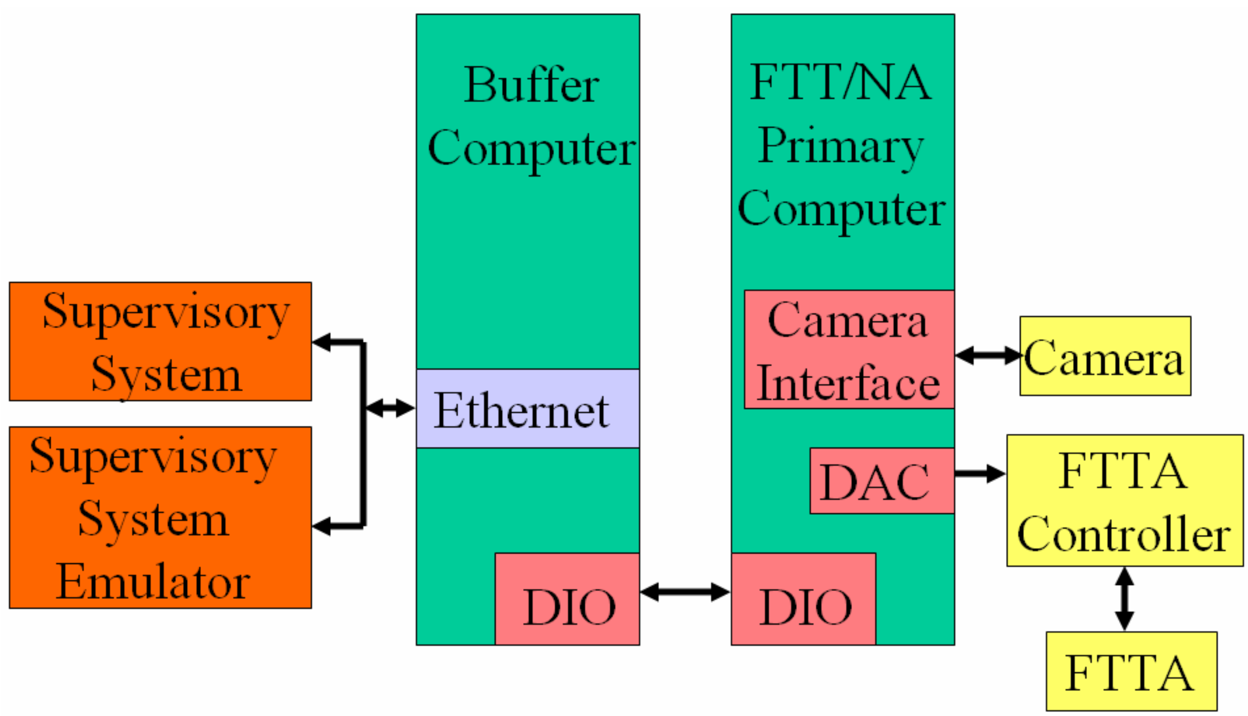


Figure 7-1. Top-level diagram of FTT/NA system, illustrating the four interfaces, two communications protocols and FTT/NA primary and buffer computers. Arrows indicate flow of data or commands.

7.2.2 Ethernet Interface

The Ethernet Interface will carry Commands and Data Objects from the FTT/NA system to/from the SSE and SS via the buffer computer. The Command Object and Data Object formats will be well defined and described as part of the documentation of the system. Commands Objects will be of three types:

1. FTT/NA state changes such as closing/opening the FTT control loop or putting the system in various Modes
2. Status report requests that command the FTT/NA to report its current status including any error conditions due to autonomous state changes due to error conditions
3. Detector/telemetry report requests

Data Objects will be either status reports, detector reports, or telemetry reports.

7.2.3 Digital I/O Interface

The DIO Interface will be realized with DIO card residing on both the FTT/NA primary computer and the buffer computer. The DIO cards will have an interrupt capability to provide for Interrupt Service Routines running on both computers. The protocol will be defined so that the FTT/NA primary computer is the Master interrupting the operations of the buffer computer. When the interrupt is serviced, Data Objects are placed on the buffer computer and any state changes in the System State Database are updated on the FTT/NA primary computer. A parameter table will be maintained on the buffer computer that contains current intended status and parameter values for the primary computer.

The primary computer, as the Master, will not interrupt and pole these values for a to-be-determined amount of time. This prevents any indeterminate states from developing and minimizes chances of a race condition developing in the system between the FTT/NA primary computer and buffer computer for the critical control data in the System State Database.

The buffer computer will never interrupt the operations of the FTT/NA primary computer except for an emergency shutdown condition. Data will flow directly or in burst mode if provided by the DIO driver software. Any error condition arising from a DIO exchange or lack of an expected one will place the primary computer in Idle Mode with the mirror parked to its nominal position.

7.2.4 Camera Interface

The Camera Interface will be provided by the manufacture of the camera. This will include all hardware and software drivers and libraries for implementation of this interface. The Camera Interface must be capable of operating in a master interrupt spawning mode. This provides the highest speed operation possible for the camera. New frames of data are placed continuously in the primary computer memory and an interrupt is generated to present data for operations. The Camera Interface must also allow for the setting of the control parameters of the camera including exposure, camera gains, frame/sub-frame definitions. To minimize operational latencies the Camera Interface must move data via Direct-Memory-Access (DMA).

7.2.5 FTT Controller Interface

The FTTA Controller Interface will consist of a DAC card that translates a digital value stored by the primary computer on the DAC card to an analog voltage in the range expected by the tip-tilt controller. The primary computer will update this digital value as demanded by the operational mode of the FTT. There is no handshake for these values with the FTTA controller. The sampling of these values will be determined by the FTTA controller as determined by its performance requirements. It assumed that the FTTA controller will provide a specifically accurate and repeatable positioning of the FTTA from the same voltage presented to it by the DAC.

7.3 Software Flow

The FTT Mode is a demanding near-real-time mode of operation, as the system must be ready for the next frame. This is a timing issue requiring that the primary computer has completed all of its calculations, updated the FTTA and transmited/received to the SS or the SSE via the buffer computer before the next DMA flag from the camera. The FTT/NA system begins processing camera data when an interrupt indicating completion of DMA from the camera frame to memory is complete. This is illustrated in Figure 7-2 showing the conceptual timing relationship.

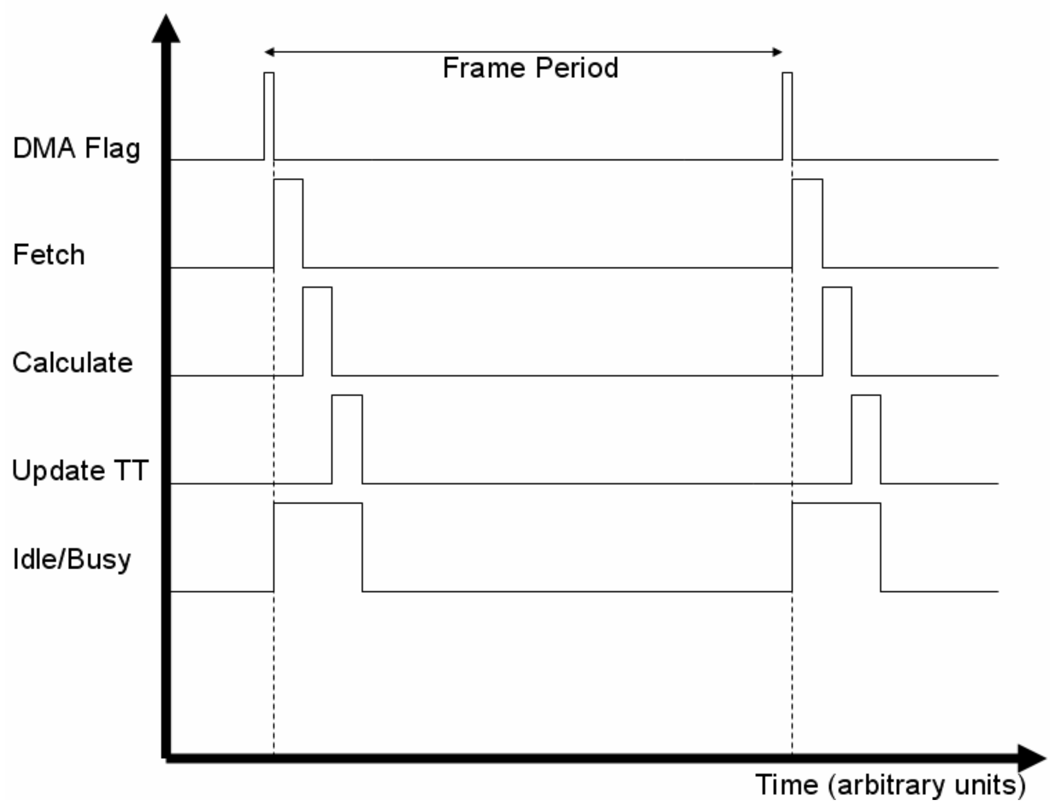


Figure 7-2. Conceptual timing diagram for processing camera frames. Idle time in this diagram is time available for updating the buffer computer and state changes of FTT/NA primary computer.

The Idle/Busy trace in Figure 7-2 is the period under which the most demanding FTT processing takes place. In slower Acquisition processes, this represents the period available to complete computational and communications tasks before the next frame is available.

The entry into the software system begins with an initialization of the FTT/NA system, including the computers, camera, and peripherals. Control of the FTT/NA system is handled through state changes in System State Database, copies of which exist on the FTT/NA primary computer, buffer computer and either the SS or SSE. Changes to the State Database located on the primary computer are seen as a state change and select the desired operating mode. The five operating Modes, FTT, Acquisition, Acquisition Check, Flatfield and Dark Frame Modes are represented in three flow charts with overlaps identified. Figure 7-3 shows the software initialization routine prior to entering one of the five operating Modes.

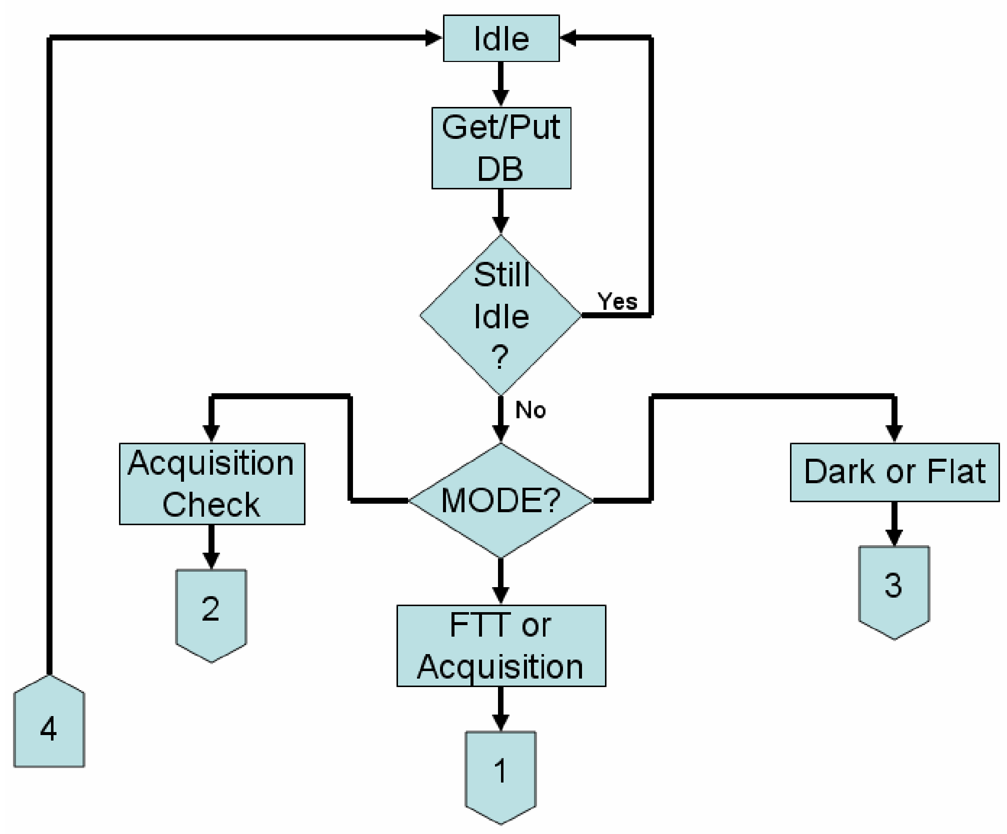


Figure 7-3. Software initialization and breakout flow chart.

On power up, the software enters the Idle Mode. During Idle Mode, a check is made for state changes in the State Database and updates of system initialization status is recorded in the State Database and put on the buffer computer. Upon receipt of a state change, the desired Mode is entered, as shown in Figure 7-3 as either the breakouts 1, 2 or 3. The following Figures show a software flow through those Modes and control is returned to the Idle Mode through breakout 4.

The FTT and Acquisition Modes are identified in Figure 7-3 as breakout 1 and are detailed in Figure 7-4. These two Modes tie together because they require continuous frame acquisitions. In the FTT/Acquisition Modes, the availability of a data frame is signaled by a DMA flag. This initiates grabbing the data frame from memory and reducing that data using the information retrieved from the State Database (such as the dark frames, flatfield frames, rotation matrices, etc.). In the FTT Mode, the State Database includes the information for subframe size and location, which is set in the camera firmware. In Acquisition Mode, a full frame is captured. In both Modes, centroids, spatial seeing estimates, etc., are calculated. In the Acquisition Mode, the State Database is updated and control is returned to an idle state within the loop (not to be confused with the Idle Mode) awaiting the next DMA flag. In the FTT Mode, a position error signal is generated and used to correct the position of the FTTA and the State Database is updated before returning to an idle state awaiting the next DMA flag. The information in the State Database contains all telemetry items for use by the SS or SSE. The SS or SSE will use this information to update the UT mount.

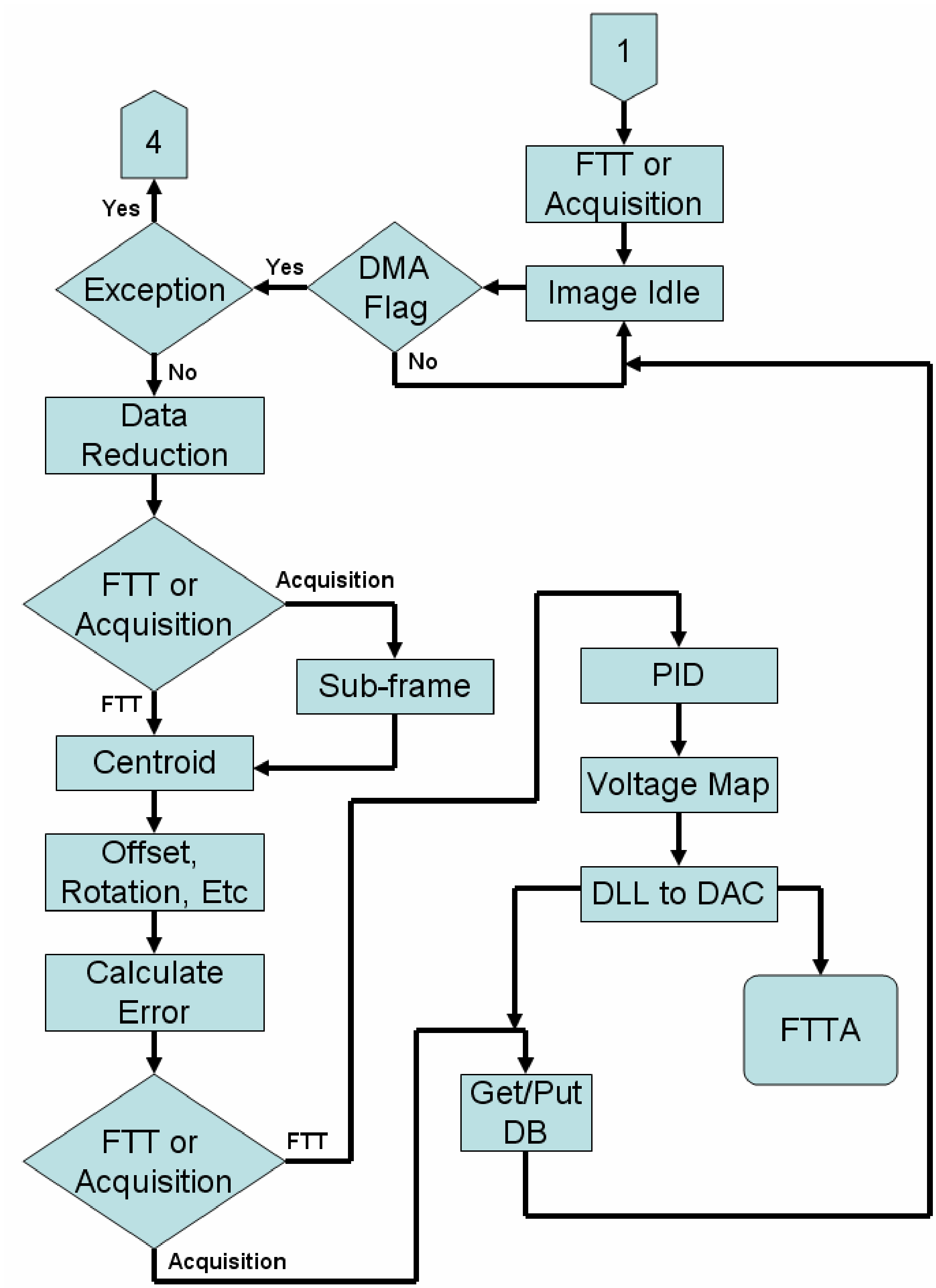


Figure 7-4. Operational flow chart during FTT and Acquisition Modes.

The Acquisition Check Mode is identified in Figure 7-3 as breakout 2 and is detailed in Figure 7-5. In Acquisition Check Mode, when the DMA flag goes high, a frame is available to be grabbed and data reduced before being placed in the State Database and returns to the Idle Mode.

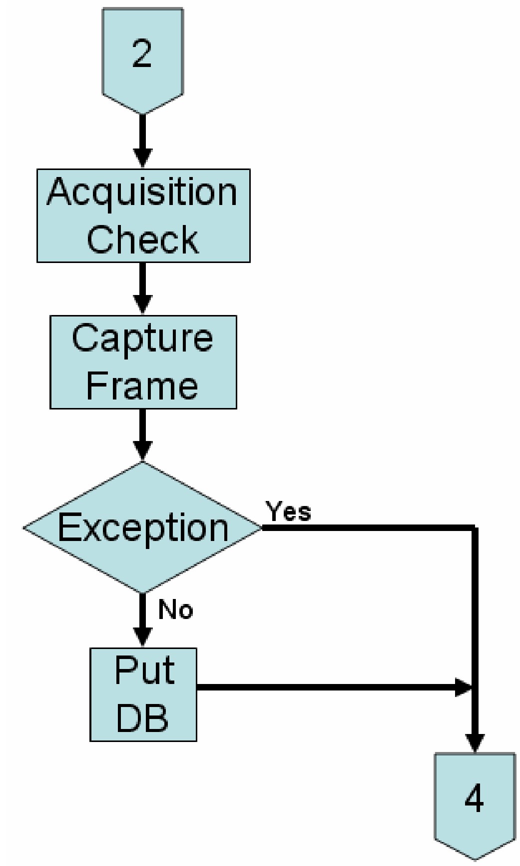


Figure 7-5. Operational flow chart during Acquisition Check Mode.

The Dark Frame and Flatfield Frame Modes are identified in Figure 7-3 as breakout 3 and are detailed in Figure 7-6. Based on the number of frames requested as recorded in the State Database, camera frames are captured and data reduced. Once all frames are captured, the frames are combined into a master dark or master flatfield frame and the State Database is updated.

If at any point in any of the Modes, it is desired to exit early, and exception handler is available to escape the loop so that undue delays are not introduced in operation, allowing switching Modes as rapidly as possible.

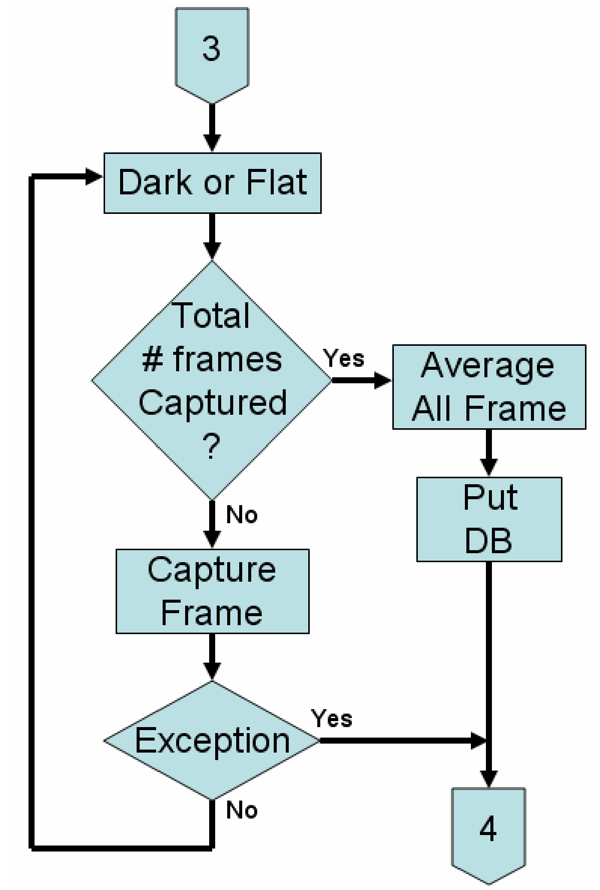


Figure 7-6. Operational flow chart during Dark and Flat Modes.

7.4 Software Compliance

Software compliance is based on the final second phase developed software as outlined in Section 8. The specifications listed in Section 7.1 are derived from the requirements in Table 7-1. The compliance of the requirements are shown in Table 7-2 followed by a description of discussing non-compliant components.

Table 7-2. Software compliance, C is compliant, C# is labeled, NC is not compliant.

SHALL #	Requirement	Compliance
3	Switch between operating Modes in less than 5 second	C
4	The system will have an Idle Mode that will serve as an initialization mode	C
5	While in Idle Mode, system capable of receiving/responding to commands	C
6	The system will have an FTT Mode with user/supervisor specified correction and provide low-frequency correction to the UT mount via the SS or SSE	C
7	While in FTT Mode the system will provide estimates of	C

	spatial seeing	
8	The system will have an Acquisition Mode that provides full camera frames at a rate of ~1Hz	C
9	In Acquisition Mode the system will provide spatial seeing estimates	C
10	The system will have an Acquisition Check Mode that provides for long exposures for looking for objects in the field	C
11	The system will have a Dark Frame Mode	C
12	The system will provide the master dark frame to the SS	C
13	This dark frame will be considered the system wide dark frame	C
14	The system will have a Flatfield Mode providing exposures up 100 sec via image summation if necessary	C
15	The system will provide this master flatfield frame to the SS	C
16	This flatfield frame will be considered the system wide flat field	C
17	The system will perform coordinate transformations with the appropriate rotation matrix provided by the SS or SSE	C
20	The system will apply a dispersion and off-axis offset provided by the SS to the tip-tilt zero point.	C
22	The system will be able to perform tip-tilt correction on an off-axis object	C
23	The system will have the ability to receive offset corrections at ten-second intervals while the FTT loop is closed	C
24	The system will calculate centroids that vary linearly within one pixel	NC
25	GUIs will be provided to control all system Modes	C
26	These GUIs will run on a Linux based computer located remotely with respect to the FTT/NA system	C
27	The system will accept a command to disable controls from the GUI while still displaying images and telemetry on the GUI.	C
28	The GUIs will run on a laptop situated in the UT enclosure	C
29	It will be possible to run the GUIs while data is streaming to the ICS	C
30	It will be possible to operate the system independently of the ICS, FTTA, and UT mount	C
31	The system will be able to record frames and diagnostic telemetry without the MRO ICS	C
32	The system will be able to record all system and image data up to 2GB while the loop is closed and be retrieved after the loop is opened for diagnostics	C
33	The system will be able to record detector frames in the various Modes	C
34	The rate of recording of these frames will be selectable	C

35	Telemetry data (non-image data) will recordable	C
36	All recorded detector frames and telemetry will be UTC timestamped	C1
37	Detector frames and telemetry from the various Modes will be transmittable to the MRO ICS via Ethernet	C
38	Detector frames and telemetry from the various Modes will be transmitted to the MRO ICS via Ethernet and will be UTC stamped	C1
39	Reduced-data-rate detector frames and telemetry will be streamed from the system via Ethernet with a maximum .2 sec latency capture to transmission	NC
40	The reduced-date-rate will be an evenly sampled frames corresponding to a transmitted frame rate of at least 10Hz	C2
41	The telemetry streams will calibration parameters, raw centroid estimates, flux estimates, dispersion and off-axis offsets, UT mount acquisition /tracking corrections, FTTA demands, spatial seeing estimates and copies of all rotation matrices used	C2
42	Data recorded on the FTT/NA will be transmitted via Ethernet with a maximum latency of 300 seconds	C
43	There will be no data loss on this transfer	NC
44	The telemetry items will be calibration parameters, raw centroid estimates, flux estimates, dispersion and off-axis offsets, UT mount acquisition /tracking corrections, FTTA demands, spatial seeing estimates, and copies of all rotation matrices used	C
45	If possible the data will be transmitted a single realization at a time with a maximum latency of .2 second from recording	NC
47	The system shall support selectable closed loop 3dB bandwidths of a range of 10-50 Hz	C3
48	The system will provide a facility to apply periodic offsets to the FTT zero point with specified direction, amplitude, and frequency	C
50	The system by default will select the brightest object in the Acquisition Mode file as the tip-tilt reference object.	C
51	They system will provide the ability to select an override of the brightest object in the field.	C
52	The system will provide the possibility to use the Acquisition Mode during UT pointing and calibration.	C
64	ALL software source code shall be provided.	NC
TIM 13	Communication from FTT/NA to UT mount is via the Supervisory System	C
TIM 14	Existence of Supervisory System (ICS) for system	C
TIM 15	Supervisory System Emulator will be the intermediate step between	C

C1- The time clock on the FTT/NA system will be updated by the Supervisory System. Data will be timestamped using the FTT/NA system clock. Accuracy of the timestamps resides with the Supervisory System.

C2- Data provided on the buffer computer for extraction by the SSE or SS.

C3- Maximum camera frame and data rates are specified by the camera manufacturer and cannot be selected outside of that range. Software is compliant provided user selected closed-loop bandwidth does not exceed the maximum frame rate of the camera.

Shall #24 requires further clarification.

Shall #39 and #45 are non-compliant because data is provided in the buffer computer and is available on request. Ethernet latency is not guaranteed.

Shall #42 dictates that an MROI provided TCP/IP protocol will be used. No effort is made to ensure zero data loss, i.e., cyclic redundancy checking or other error-checking schemes are not implemented.

Shall #64 is non-compliant. There are several software vendors. It is up to MROI to negotiate receipt of software source code separately.

7.5 Software Risk and Mitigation

Risk and mitigation management will be accomplished via on-going consultation with MROI. These consultations may include mapping MROI requirements to available technologies, extraction of engineering specifications from requirements, development of decision matrices, and cost benefit comparisons, to name a few. Many components carry detailed specifications in order to meet requirements, which must be accurately reflected in the request for purchase and procurement process. It is recommended that a technical liaison from MROI work closely with their purchasing office to ensure the specifications are satisfied. As the final integration plan for this subsystem is in early stages of development, consideration should be given to integration team selection and the mutual development of the integration plan. Care should be taken to ensure that the integration team members have the necessary scientific and engineering knowledge to appreciate and resolve the issues that arise during system integration.

8 Proposed FTT/NA System

The following provides a description of the overall proposed FTT/NA system to be developed in support of the MROI Top Level Requirements document. Compliance with the specific requirements and TIMs is described in Sections 3 through 7 of this document.

Discussions on the implementation of UTs on the site suggest that the complete enclosure package for the UT may not be available for telescope commissioning. However, some TT functionality and data recording capabilities may be desirable during this period. This is incorporated into a phased development plan for the FTT/NA system. The following discusses a proposed development path that will provide near-term functionality required for commissioning and the long-term functionality outlined in the MROI Top-Level Requirements document. The timeline describing this implementation is provided in Section 9. The hardware and software components are described within these two phases as follows in Section 8.1 and 8.2.

The COTS hardware related to the FTT/NA system consists of components to be purchased by the customer. Care must be taken during the acquisition process to ensure that vendor specific performance meets requirements, specified in MROI Top-Level Requirements document and as outlined in Section 2. It is anticipated that the hardware related to the FTT/NA system as described in this document will be purchased by the customer and will be available for the development of the laboratory demonstration as outlined in the schedule.

In the first phase, basic functional performance of the FTT/NA system will be provided. This will consist of obtaining the optical, opto-mechanical and opto-electronic components to be integrated onto the Nasmyth table, subject to MROI downselecting to an optical configuration. Based on Section 3 of this document, configuration #1 is the leading candidate based on optical performance, while configuration #2 has lower cost and is simpler to commission. In addition, NRL will be developing a dichroic mount which will be integrated on the Nasmyth table.

The selection of the camera to be integrated has direct impact on the software developed for the FTT/NA system. While the two proposed cameras are very similar in performance, NRL has extensive experience in the development of software related to the Princeton brand of cameras. NRL's experience in developing similar systems using the Princeton platform evolved from the maturity of the software/firmware provided by the manufacturer, simplifying integration and application development. Similar advantages can be obtained in this project by continuing work with the Princeton camera.

The software provided for the first phase will provide basic FTT stabilization and data logging capabilities.

The second phase will provide the software functionality as described in the requirements document and compliance listed in this document subject to the availability of site hardware.

The close of each phase of the project will be marked by submission of a report outlining progress and status. The aggressive timeline for this project development does not provide sufficient time for the development of extensive reporting. Should a greater level of effort on reporting be required, a third party technical writing sub-contractor will be required out of customer's expense.

8.1 First Phase Sample Software

For first light, software is provided to allow for basic boot and testing of the camera and FTT controller. This software will provide functionality for a stand-alone lab demonstration and commissioning at the MROI site. A sample GUI demonstrating many of the features of the software is shown in Figure 8-1. It is envisioned that this software will run on the FTT/NA primary computer directly connected to the camera and FTTA.

Figure 8-1. Sample GUI with real-time feedback of mirror position, camera image and other telemetry items. GUI also displays control buttons with graphical feedback for control of system parameters.

Through this software, control of the FTTA and camera and minimal reporting functionality is available. Live camera display, subframing, voltage bounding for the FTTA, exposure control and other basic FTTA controls are provided.

8.2 Second Phase Software

Phase two software is not at the same level of development as phase one. A basic overview of the software is provided in Figure 8-2.

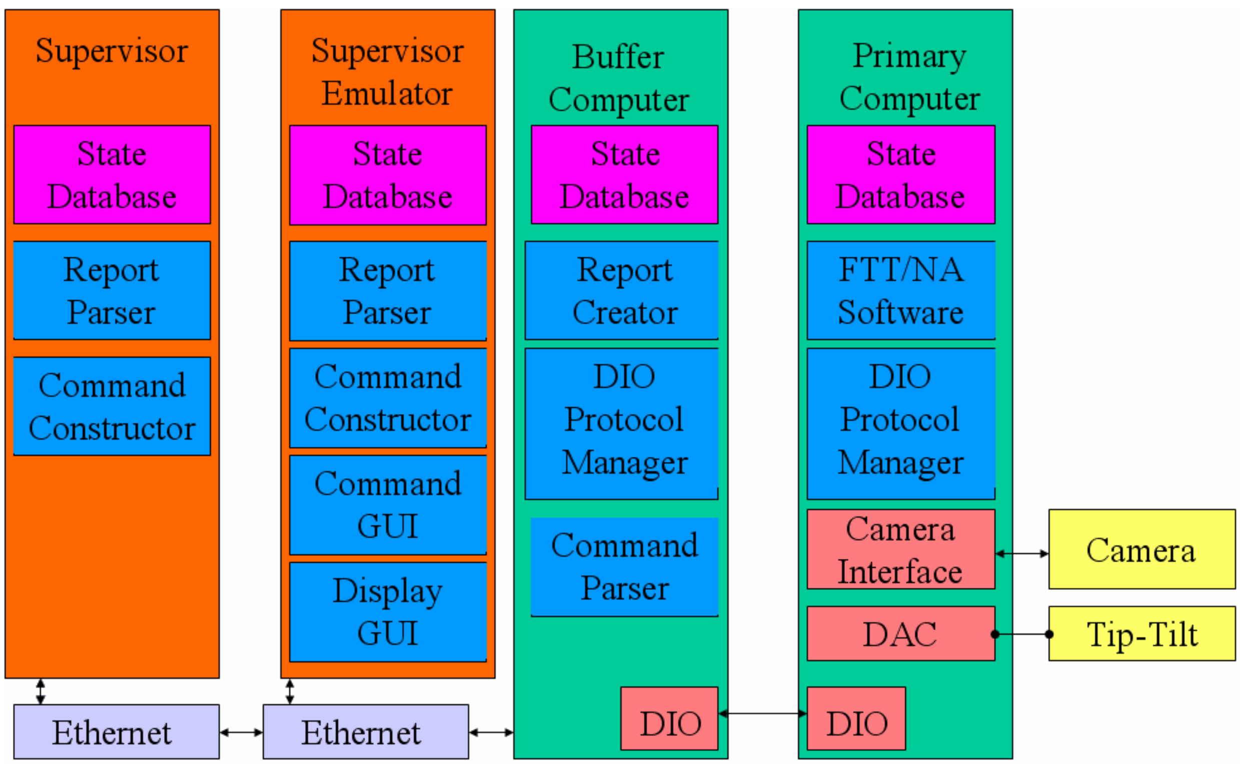


Figure 8-2. Component breakdown of software capabilities and responsibilities for second phase.

The software is driven by a SS layer which communicated directly to the buffer computer to read the State Database. This database can also be accessed by a standalone emulator (the SSE) which provides demonstration of command construction for control and report parsing for display. The second phase also introduces the buffer computer which provides accommodation for streaming data from the FTT/NA primary computer back to the SSE and/or SS. An integral component of this development cycle is the creation of the standalone SSE which is derived from the SS design.

Final functionality available in the second phase is compliant with the Top-Level Requirements Document subject to non-compliance outlined in Section 7.

9 Schedule and Milestones

The schedule and milestones for this project are illustrated in Figure 9-1. The entire timeline is on a relative scale from the t=0 time that will be jointly agreed upon. The timeline for purchasing is based on interfacing with numerous vendors.

Hardware acquisition for MROI will be in compliance with NMT/MROI purchasing processes, outside of the purview of NRL. These processes will have a direct impact of the final timeline/schedule, as such a detailed timeline cannot be established at this point. MROI is responsible for acceptance and testing of NMT/MROI purchased hardware and demonstration of compliance with the requirements.

To provide a framework for development of the FTT/NA system, the first milestone has been placed approximately seven months after hardware delivery and is identified as a Laboratory Test (LT). This milestone will consist of a demonstration of the FTT closed loop capabilities based on NRL owned Physik Instrumente tip-tilt stage, MROI acquired CCD camera, necessary optical components and NRL/Narrascape control software.

Following the successful completion of the LT, there will be a Site Integration Test (SIT) in 6 months. During this phase all hardware will be installed and tested. The hardware installation is predicated on the availability of the MROI infrastructure. The control software for this stage will be compatible with the available level of the SS, and with the commissioning requirements of the first UT. Upon completion of this milestone, work will start to deliver the final system, phase two. The final site integration (FIT) will happen approximately one year after the SIT.

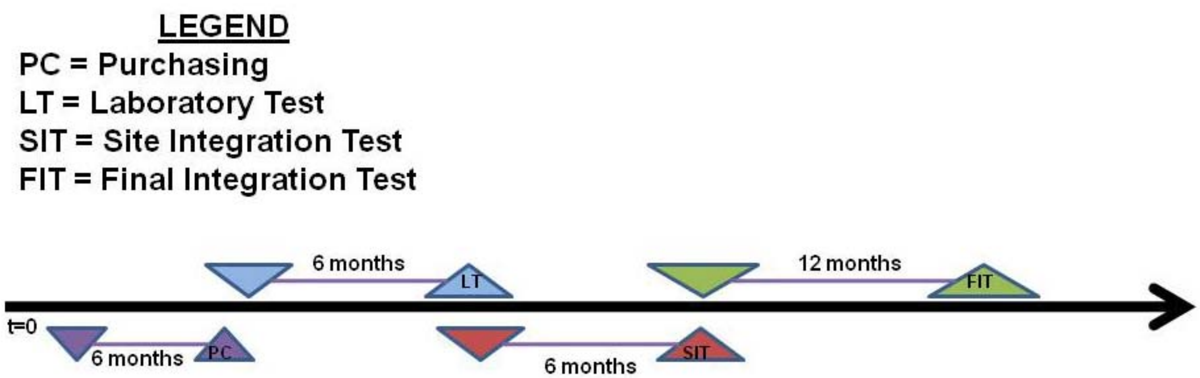


Figure 9-1. Milestones and timeline for FTT/NA system.

10 Budget

Not applicable.

Appendix A: Idealized Model of Visual Magnitude and Tip-Tilt Performance

Shall #56 specifies that the FTT/NA system, specifically the camera, be sensitive to 16 magnitude stars after the light has propagated through the MROI provided optical train. The camera sensitivity is listed by the manufacturer as capable of detecting single photons, provided the signal is above the background noise. The background noise varies with the operating parameters of the camera as described in Section 4 and Appendix B. The following calculation compares the astronomy and engineering units, as requested by MROI and was developed using the assumptions in the MROI document "INT-402-MIS-0034", restated below. This calculation does not attempt to endorse the suitability of the camera for any particular application or the validity of the MROI assumptions.

MROI Provided Requirements and Assumptions

D, diameter of the entrance pupil of unit telescope = 1.4 m
r_0, atmospheric coherence diameter, or Fried's parameter > 0.1 m at λ=0.55 μm
v, turbulent layer maximum wind speed = 10 m/s
λ, central operational wavelength = 0.675 μm
σ_{tot} , rms residual two-axis error not to exceed 0.06 arcsec
$\sigma_{totx}= \sigma_{toty}$ single axis rms error not to exceed 0.0425 arcsec ~ 0.2 μrad

Simplified Model

The main sources of one axis root mean squared (RMS) errors for tilt can be expressed as:

$$\sigma^2_{totx}= \sigma^2_{toty}= \sigma^2_{SNR}+ \sigma^2_{BW}+ \sigma^2_{TA}+ \sigma^2_{CA} \qquad \text{[A-1]}$$

Where σ^2_{SNR} represents the RMS error due to the finite SNR of the sensor; σ^2_{BW} is the RMS error due to the finite bandwidth of the system; σ^2_{TA} is the RMS error due to tilt anisoplanatism, and finally σ^2_{CA} is the RMS error due to the presence of higher order aberrations.

Calculation of σ_{SNR}

The accurate calculations will model the SNR in function of the brightness of the target object in terms of visual magnitude etc. The expression for σ_{SNR} is given by:

$$\sigma_{SNR} = \frac{3\pi}{16}\frac{1}{SNR}\frac{\lambda_C}{r_0}\chi \qquad \text{[A-2]}$$

Where the expression for the SNR per pixel is given by:

$$SNR = \frac{\gamma SQt}{\sqrt{\left((\gamma S + B)Qt + Ct + R^2\right)}} \qquad \text{[A-3]}$$

Where *S* is the signal collected by a telescope of aperture diameter *D* within a spectral band $\Delta\lambda$ and this can be expressed as:

$$S = \Gamma_0 \tau 0.7 D^2 \Delta\lambda 10^{-0.4m} \qquad \text{[A-4]}$$

Where Γ_0 is given by:

$$\Gamma_0 = \frac{F_0}{hc/\lambda_T}\left(\frac{\lambda_V}{\lambda_T}\right)^5 \left[\exp\left(\frac{hc}{\lambda_V k T_{eff}}\right) - 1\right]\left[\exp\left(\frac{hc}{\lambda_T k T_{eff}}\right) - 1\right]^{-1} \qquad \text{[A-5]}$$

Where $F_0 = 3.45 \cdot 10^{-8}\ J\ s^{-1} m^{-2} \mu m^{-1}$ is the monochromatic flux of a star with 0 apparent magnitude, λ_V is the central wavelength of the V band, λ_T is the operational wavelength, *h* is the Planck's constant, *k* is Boltzman's constant and *c* is the speed of light in vacuum.

The other parameters in Equation A-4 are: τ is the atmospheric transmittance and *m* is the apparent magnitude of the object observed. The other quantities in Equation A-3 are *Q* the quantum efficiency of the detector; *t* the exposure time; B the background photon flux given by $B = \Gamma_0 \tau 0.7 D^2 \Delta\lambda 10^{-0.4m'} \phi$ where m' is the sky brightness in magnitudes per arc-seconds squared and Φ is the detector area projected on the sky in arc-seconds squared; *C* the dark current counts per second and finally *R* is the RMS read-out noise. In table A-1 are the specific parameters for the E2V CCD chip that were used for the analytic model.

Table A-1. Assumptions for model used.

Quantum Efficiency	Dark Current Counts	RMS Read Out Noise
95% (@λ= 0.67 μm)	0.03 e^-/pixel/sec	1 e^-

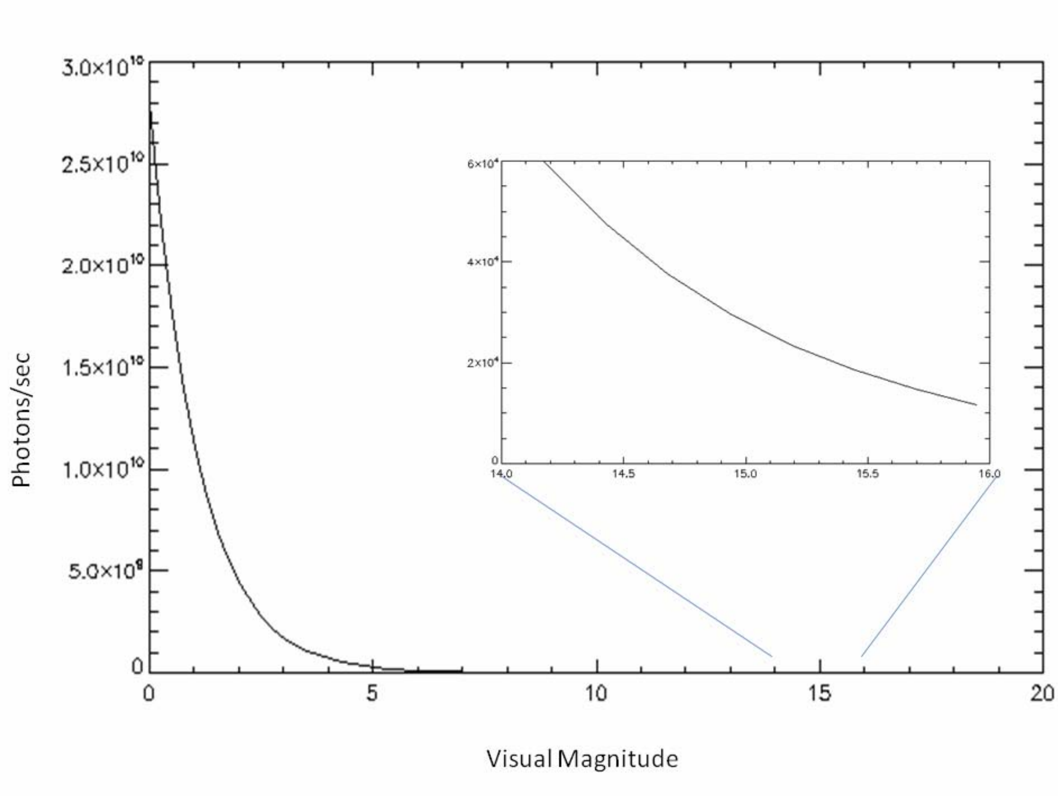


Figure A-1: Calculated photon flux collected by a 1.4 m telescope.

The photon flux shown in Figure A-1, obtained by using the assumptions provided by MROI, is consistent with their results as reported in MROI document "INT-402-MIS-0034". With the assumptions presented in the MROI document "INT-402-MIS-0034", we obtain a value for the σ_{SNR} 1.5 nrad of residual error for a single axis and 2 nrad for the two axis residual error for m_V=16.

Calculation of σ_{BW}

The calculation of σ_{BW} is based on Equation A-6:

$$\sigma_{BW} = \frac{f_T}{f_c}\frac{\lambda}{D} \quad \text{[A-6]}$$

Where f_T is the Tyler frequency and f_c is the closed loop bandwidth. Using the assumptions in MROI document "INT-402-MIS-0034", the residual error due to the bandwidth in one axis is 50 nrad and the residual on both axes is 70 nrad.

The other contributions in Equation A-1 are considered negligible as reported in the NRL document "Tilt_compensation_error_calculations_for_MROI_JRA_v8".

Appendix B: Camera Frame Rate

The discussion that follows refers only to the manufacturer provided frame rates due to hardware latency for given exposure times. Manufacturer's specifications sheets show each camera provides similar maximum frame rates. The Andor offers a "Cropped Mode" of operation where frames can be streamed from a small region of the detector at very high rates (~4k frames per second), however this buffered mode is not sustainable over time. The maximum usable frame rates for the FTT/NA system derived from manufacturer specification sheets and discussions with Andor is summarized in Table B-1.

Using the maximum readout rate of 10 MHz as defined by the CCD manufacturer, the maximum frame rates is defined by the size of the region of interest (ROI) and the proximity to the read-out buffer. After an exposure, the frame is transferred to the frame-transfer region of the CCD chip with a vertical row shift speed of 0.9us. Once in this frame transfer region, a new exposure can begin while the previous frame is read out from the frame transfer region.

Both camera manufacturers engineering specifications sheets show similar performance, noise characteristics and maximum frame rates. It is important to note that neither of these cameras were designed for low-noise, near-real-time operation.

Table B-1. Sample frame readout time for Andor iXon^{EM}+ 897 EMCCD camera using 10 x 10 area of unbinned pixels in lower left, center and upper right regions of CCD at different exposure times.

Vertical shift speed 0.9us			
10x10 sub-area with no binning.			
	Cycle time in seconds (exposure)		
Minimum Exposure (10us)	Non-frame transfer	Frame Transfer	Cropped mode
Lower Left	0.00233 (10us)	0.0013 (820us)	0.0001776 (165us)
Center	0.00261 (10us)	0.00156 (1090us)	-
Upper right	0.00284 (10us)	0.00180 (1330us)	-
Exposure 250us	Non-frame transfer	Frame Transfer	Cropped mode
Lower Left	0.00256 (250us)	0.0013 (820us)	0.0002668 (250us)
Center	0.00284 (250us)	0.00156 (1090us)	-
Upper right	0.00307 (250us)	0.00180 (1330us)	-
Exposure 500us	Non-frame transfer	Frame Transfer	Cropped mode
Lower Left	0.00281 (500us)	0.0013 (820us)	0.0005168 (500us)
Center	0.00309 (500us)	0.00156 (1090us)	-
Upper right	0.00332 (500us)	0.00180 (1330us)	-
Exposure 1000us	Non-frame transfer	Frame Transfer	Cropped mode
Lower Left	0.00331 (1ms)	0.00147 (1ms)	0.0010168 (1ms)

Center	0.00359 (1ms)	0.00156 (1090us)	-
Upper right	0.00382 (1ms)	0.00180 (1330us)	-

Highest speed operation is obtained by using the frame-transfer mode with the minimum exposure time, which corresponds to a 10 x 10 array of unbinned pixels in the lower left region of the CCD array with a period of 1.3ms, which corresponds to a rate of 770 fps. However, there is no guarantee that this quadrant will be used. The worst case is for the same size of a ROI in the upper right corner with a period of 1.8ms, corresponding to a rate of 555 fps. This worst-case frame rate degrades further as exposure time is increased.

Appendix C: List of Identified Interfaces

In compliance with shall #65, NRL has identified the following list of interfaces. Depending on design choices that are TBD, some interfaces may disappear or others created. The final list of interface documents will be determined in the future, at which point the documents will be named ICD-##, where the number corresponds to the order in which the documents are developed. The current list of documents, subject to change, is shown below:

- ICD-1. Supervisory System to Buffer computer via Ethernet
- ICD-2. Mechanical mounts to Nasmyth table via ¼” x 20 screws
- ICD-3. Computers to power via internal rack mounted power supply
- ICD-4. Computers to rack mount via screws
- ICD-5. Camera cooler to rack mount via screws
- ICD-6. Optical signal from telescope via dichroic
- ICD-7. Optical signal from automated alignment system/corner cube to FTT mounts
- ICD-8. FTT/NA primary computer to buffer computer via digital I/O cards
- ICD-9. FTT/NA primary computer to FTTA via analog I/O card
- ICD-10. FTT/NA primary computer to camera via PCI/PCI-X
- ICD-11. Camera cooler to camera via flex tubing/liquid coolant
- ICD-12. Remote actuators/actuator controller via RS-232
- ICD-13. Remote actuators/actuator controller power via rack mounted power supply
- ICD-14. Remote actuator controller to rack mount via screws
- ICD-15. Remote actuator to mechanical stages
- ICD-16. Camera cooler power via rack mounted power supply
- ICD-17. Camera to rack mounted power supply