# Technical Requirements

# Fast Tip-Tilt/Narrow-field Acquisition System

INT-403-ENG-0003 rev 2.2

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# Change Record

| Revision | Date | Authors | Changes |
|---|---|---|---|
| 2.0 | 2009-11-29 | MRO | Version for RFP |
| 2.1 | 2010-05-04 | JSY | Corrected summary of tip-tilt residual requirement in table |
| 2.2 | 2010-05-20 | JSY | Corrected target flux ratios in Sec. 6.3 |

# Objective

To specify the technical requirements for the MROI Fast Tip-Tilt/Narrow-field Acquisition systems.

# Scope

This document specifies the technical requirements for the MROI Fast Tip-Tilt/Narrow-field Acquisition (FTT/NA) systems, in particular:

- Functional requirements: *what* the system must do
- Performance requirements: *how well*, and *under what conditions* the system must perform its functions
- Initial identification of interfaces

The specifications listed in this document are the minimum allowable.

The superscripts following each "shall" requirement in this document refer to the draft acceptance verification plan in Sec. 8 (which is to be revised at PDR and FDR).

# Referenced Documents

The following documents are incorporated by reference:

**INT-403-TSP-0003** rev 1.3 "Technical Requirements: Unit Telescopes for the MRO Interferometer"

**INT-403-TSP-0002** rev 8 "Requirements for the Unit Telescope Optics for the MRO Interferometer"

**INT-404-TSP-0003** rev 2.5 "Technical Requirements: Unit Telescope Enclosures and Relocation System for the MRO Interferometer"

**INT-403-DWG-0100** issue 1 "CAD model of the space allocation on the Nasmyth optical table"

**MRO-ICD-AMO-6000-025** issue 3 "Unit Telescope Electrical ICD"

# Acronyms used in this document

**AAS** Automated Alignment System

**ADC** Atmospheric Dispersion Corrector

**AO** Adaptive Optics

**BCA** Beam Combining Area

**BCF** Beam Combining Facility

**CCD** Charge-Coupled Device

**FTT** Fast Tip-Tilt

**FTTA** Fast Tip-Tilt Actuator

**FDR** Final Design Review

**FWHM** Full Width at Half Maximum

**GUI** Graphical User Interface

**ISS** Interferometer Supervisory System

**NA** Narrow-field Acquisition

**NTP** Network Time Protocol

**PDR** Preliminary Design Review

**SI** Science Instrument

**TBC** To Be Confirmed

**UT** Unit Telescope

**UTM** Unit Telescope Mount

# 1 Assumptions and Constraints

This document is predicated on the following decisions about the conceptual design of MROI and the FTT/NA system. These decisions have previously been made by the system architects and adopted by the MROI project.

- That there will be one Fast Tip-Tilt/Narrow Acquisition (FTT/NA) system installed at each of the six Unit Telescopes.
- That the starlight arriving at each Unit Telescope will be split by color so as to be delivered and used separately for tip-tilt sensing, fringe tracking, and interferometric science.
- That some of the space on the Nasmyth table of each Unit Telescope must be reserved for MRO-provided systems, for example, hardware associated with the interferometer alignment system. Please refer to Sec. 3 for more details.

The number of detectors (or cameras) to be used to satisfy the requirements is to be selected by the Vendor. The MROI Project Office *does not* preclude the use of multiple cameras — for example, one for fast guiding and the other for acquisition — but has a strong preference, based on long-term maintenance and support issues, for FTT/NA designs that utilise a single camera.

# 2 Definitions

**User-specified:** Parameter value to be specified by either a human observer (via the supplied Graphical User Interface) or the MRO ISS (via the supplied FTT/NA command interface), chosen from within a permitted range.

**User-selectable:** Choice from several permitted possibilities, specified by either a human observer or the MRO ISS.

**Live display:** A display that is continuously updated as new data (such as CCD images or diagnostic quantities) becomes available, with a maximum latency of 0.2 sec.

**Science target:** The object on which interferometric fringes are measured in the MROI beam combining instruments.

**Tip-tilt reference:** The object which is acquired by the FTT/NA system and subsequently used to sense the tip-tilt error. 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 for tip-tilt sensing.

**Tip-tilt zero point:** A fiducial point on the fast tip tilt 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 Beam Combining Facility (BCF), as a start-of-night calibration task (refer to Sec A.1 for a full description of the procedure). Subsequently, the tip-tilt zero point remains fixed on the detector until it is re-determined.

**Objective point:** The location on the fast tip tilt detector that the *tip-tilt reference object* is servoed to. The location of the objective point is given by applying (time-variable) offsets to the tip-tilt zero point to account for atmospheric dispersion and (when applicable) use of an off-axis tip-tilt reference object.

**Back-end instrument:** The beam combining instrument for whose operating waveband the dispersion offset (Sec. 5.3) is calculated. This is normally the Science Instrument (SI), but during initial commissioning will be the Fringe Tracker system.

All angles in this document are angles referred to the sky.

# 3 Context for the FTT/NA system

The purpose of this section is to provide the Vendor with a description of the context of the FTT/NA system within the MRO interferometer as a whole, and to identify the components and functions of a conceptual implementation.

*The description in this section is schematic only: it is not intended to indicate a preference for any particular detailed design or implementation of the FTT/NA system, only the conceptual layout of one type of implementation.*

A block diagram of a conceptual FTT/NA system, utilising a single detector for acquisition and fast tip-tilt sensing, is shown in Figure 1. An outline description of each component in the figure follows, but only a level that is sufficient to help understand this rest of the document.

- Dichroic mount: supports a vendor-supplied dichroic mirror which reflects the colours of light to be fed to the FTT/NA detector while transmitting the colours used for fringe tracking and interferometric science;
- Focusing optic: forms an image of the sky on the detector used for acquisition and tip-tilt sensing;
- Detector system, including detector head, cooling system, readout electronics, power supply: captures images of the source used for acquisition and tip-tilt sensing;
- FTT/NA control system (hardware & software): executes real-time image analysis, image archiving, diagnostic telemetry data streaming, live display and GUI. Also implements the real-time tip-tilt servo (see Sec. A.4 of INT-403-TSP-0003);

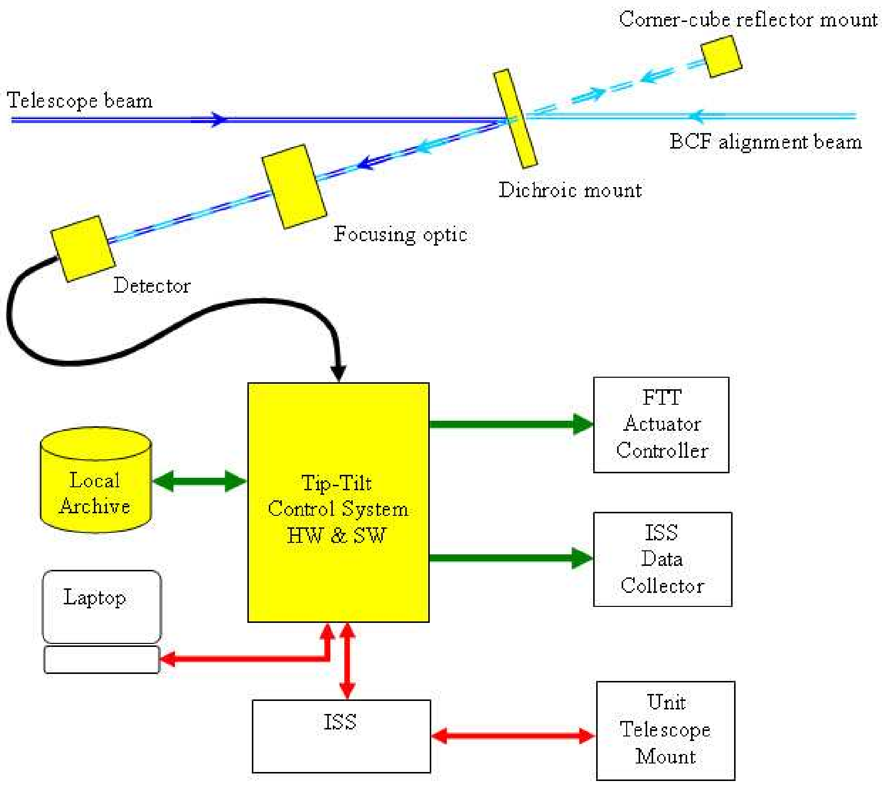


Figure 1: A block data-flow diagram of a conceptual FTT/NA system (colored in yellow) that uses a single detector for acquisition and tip-tilt sensing. Mandatory data flow paths are show as green arrows, control paths from the ISS and a laptop as red arrows, and the light paths from the UT and BCF as dark and light blue arrows respectively. Black lines identify other dataflow paths specific to this example conceptual design. The functions of the various components are described below. The interfaces needed to receive/transmit commands and signals are not shown explicitly, nor are any of the dataflows associated with mechanical actuators and/or stages that might be needed to meet the requirements. Note that it is not the intention to control the system from the ISS and customer-supplied laptop at the same time.

- Corner cube retro-reflector mount: holds a customer-supplied corner-cube reflector used in the start-of-night determination of the tip-tilt zero point (see Sec. 2) to retro-reflect an alignment beam originating from the BCF so that it is imaged onto the FTT/NA detector.

The following components shown in Figure 1 will also be needed for the FTT/NA system to function correctly, and will be delivered by AMOS as part of the UT contract (see INT-403-TSP-0003):

- Unit Telescope Mount, with interface for mount offset data sent from the ISS.

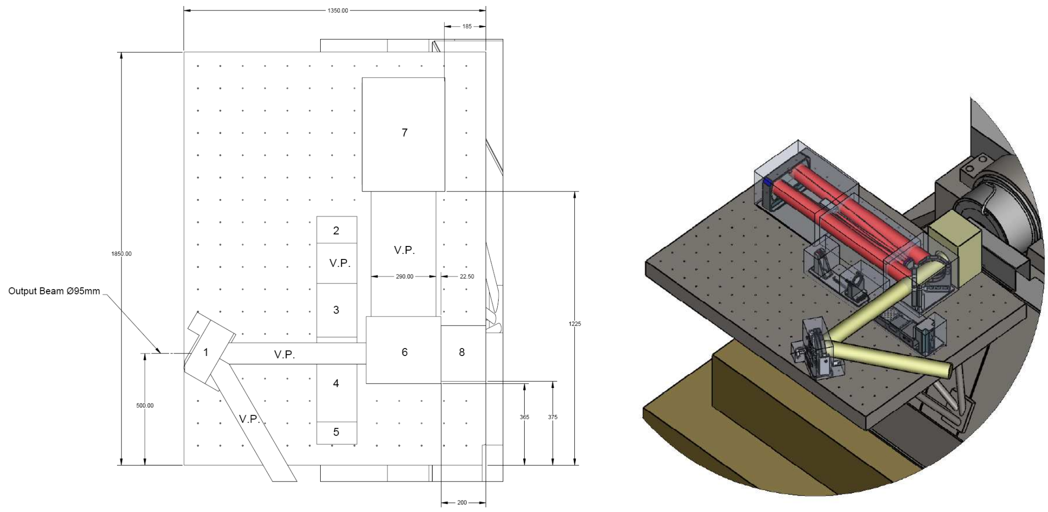


Figure 2: Plan view of the Unit Telescope Nasmyth optical table (left panel), showing one possible set of footprints for the MRO-provided components to be located there (this includes anticipated future upgrades). Volumes occupied by light beams are labelled "V.P." and would permit the passage of other light beams through the same space. The AAS component footprints are labelled 2–5, while the footprints reserved for AO components are labelled 6 and 7 and that for the ADC is labelled 8. In this layout, components 2–5 are in a line that may be translated to the left, subject to them not interfering with the exiting output beam, while components 2 and 3 may be translated vertically in the figure (maintaining their separation) without compromising the performance of the AAS so to allow clear passage of a light beam. This diagram is for information only: the latest provisional information on these footprints is to be found in drawing INT-403-DWG-0100. The right panel is an isometric view showing the optical components that would occupy these footprints in schematic form.

- Fast Tip-Tilt Actuator (FTTA) and controller, with $\pm 10$ volt analogue interface for mirror tip and tilt control signals sent from the FTT/NA system.

Also present, and to be delivered by the MROI Project Office, will be the Interferometer Supervisory System which will include interfaces to (a) receive detector image frames and diagnostic telemetry data and (b) to control and provide information (e.g. dispersion offsets) to the FTT/NA system.

As mentioned in Sec. 1 the FTT/NA system is to be located on the Nasmyth optical table of each Unit Telescope. A fraction of this table will be populated with certain MRO-provided hardware associated with other interferometer systems — for example an interferometer Automated Alignment System (AAS); space will also need to be reserved for future MRO-provided hardware, such as an Atmospheric Dispersion Corrector (ADC). The design of the FTT/NA system will need to accomodate this sharing of the table. Figure 2 shows one possible layout for the MRO-provided hardware to give some context for the reader. The components enumerated in this figure include footprints for a future adaptive optics system, a future ADC and the AAS. The vendor should note that in the layout, the AAS footprints identified as "2" and "3" may be translated vertically in the figure (maintaining their separation) to allow the passge of a light beam without compromising the performance of the AAS. Furthermore, there may be clear space *within* the footprints of the AAS components through which a light beam may pass unobstructed. The vendor will thus be expected to work with the customer to identify the optimum layout for the FTT/NA system compatible with the MRO-provided hardware (see Sec 7).

The following sections describe the requirements for the FTT/NA system under four separate categories:

**Operating modes:** defines the six modes of operation the system must implement, and the timescale for changing between these modes;

**Functional requirements:** defines the specific functions that the system must carry out;

**Performance requirements:** defines how well the system must perform;

**Interface requirements:** defines certain interface requirements.

For the purposes of clarity, the remainder of this document has been written assuming an implementation using the same camera for narrow-field (routine) acquisition and fast tip-tilt sensing, fed with a fixed focal-length focusing optic.

*Should the Vendor desire to utilise separate cameras for these two functions, or, for example, use interchangeable optical elements to change the image-plane scale, they are requested to contact the MROI Point of Contact as soon as possible so that the requirements drafted herein can be translated where necessary to the equivalent requirements for a multi-camera/multi-optical-feed implementation.*

# 4 Requirements: Operating Modes

## 4.1 Switching between modes

The FTT/NA system shall[1] be able to switch between any two of the operating modes defined below within 5 seconds (goal 1 second). The functional requirements for each mode are detailed in Sec. 5.

## 4.2 Idle Mode

The system shall[2] implement an idle mode, in which the FTT/NA system detector has been powered on but is not being read out: the system must enter this mode after being initialised.

In this mode the system shall[3] respond to a command from the MRO ISS to indicate whether it has initialised successfully.

## 4.3 Fast Tip-Tilt Mode

The system shall[4] implement a fast tip-tilt correction mode, in which image data are captured at a user-selectable rate (to comply with the requirement in Sec. 5.11 that the closed-loop bandwidth be user-selectable), high-frequency tip-tilt corrections are supplied to the FTTA, and low-frequency pointing corrections are supplied to the ISS for transmission to the UT mount.

In this mode, the system shall[5] provide quantitative estimates of the image FWHM (or equivalent image smear) at a rate of at least 0.1 Hz

It is a goal for the system to provide quantitative estimates of the atmospheric coherence time, $t_0$.

## 4.4 Acquisition Mode

The system shall[6] implement a target acquisition mode in which it captures image data continuously at $\sim$1 Hz, feeding back acquisition/tracking corrections to the ISS for transmission to the UT mount.

In this mode, the system shall[7] provide rough quantitative estimates of the image FWHM (or equivalent image smear), for use in choosing initial operational (e.g. bandwidth) and calibration (e.g. centroid calibration) parameters for the fast tip-tilt Mode.

## 4.5 Acquisition Check Mode

The system shall[8] implement a mode which captures and makes available for display a single long-exposure (up to 10 sec) acquisition image. It is permissible to sum multiple exposures in order to obtain a total integration time equal to the user-specified time. This mode will be used by a human observer to check what objects are in the field.

### 4.6 Dark Frame Mode

The system shall[9] implement a mode which captures a specified number of dark frames, using a detector readout scheme (sub-framing, integration time etc.) identical to that employed for a specified mode from those listed above.

The system shall[10] be able to transmit the master dark frame (i.e. the average of the captured frames) to the MRO ISS and, on command, retrieve a previously transmitted master dark frame from the ISS, using a well-defined protocol over Ethernet.

A master dark frame will be obtained typically once per night, with the UT pointing at an empty patch of nighttime sky. The system shall[11] use the master dark frame to partially or fully compensate for additive background signal when calculating stellar centroids.

### 4.7 Flatfield Mode

The system shall[12] implement a mode which captures a specified number of flatfield frames, using a detector readout scheme identical to that employed for a specified mode from those listed above, but with a user-specified integration time (up to 100 sec). It is permissible to sum multiple exposures in order to obtain a total integration time equal to the user-specified time.

The system shall[13] be able to transmit the master flatfield frame (i.e. the sum of the captured frames) to the MRO ISS and, on command, retrieve a previously transmitted master flatfield frame from the ISS, using a well-defined protocol over Ethernet.

A master flatfield frame will be obtained typically once per week, with the UT pointing at an empty patch of twilight sky. The system shall[14] use the master flatfield frame to compensate for variations in multiplicative gain between detector pixels when calculating target centroids.

## 5 Functional Requirements

The requirements in this section should be read in conjunction with the definitions in Sec. 2.

### 5.1 Coordinate transformations

The system shall[15] perform the appropriate transformations when converting between coordinates on the detector array and the tip and tilt axes of the fast tip-tilt actuator. The Customer will be able to supply appropriate rotation matrices as a function of pointing direction through communication with the ISS.

## 5.2 Spectral bandwidth

The FTT/NA sensor shall[16] be sensitive to light in the wavelength range 350–1000 nm; the astronomical J, H, and K bands will be transmitted to the Beam Combining Facility. This wavelength separation will be performed by a vendor-supplied dichroic. The performance specifications for this dichroic are presented in Section 6.

A future upgrade to visible-wavelength science will require that the 600–1000 nm band plus the H and K bands be transmitted to the BCF when the visible science instrument is being used. To facilitate this upgrade, the FTT/NA optical layout shall[17] be compatible with a customer-specified space envelope which may be used in future by MRO to accommodate a slide for switching between two dichroics (replacing the mount for a single dichroic supplied as part of the FTT/NA system).

## 5.3 Dispersion-offset guiding

In both acquisition and fast tip-tilt modes, the system must account for the difference between the apparent sky coordinates of the tip-tilt reference object in the tip-tilt sensing band and the back-end instrument band arising from atmospheric dispersion, by applying an ISS-delivered dispersion offset expressed in detector coordinates. The design of the FTT/NA system shall[18] allow for this offset to be applied to the tip-tilt zero-point (in addition to any off-axis offset – see Sec. 5.4) to determine the objective point.

## 5.4 Off-axis tip-tilt sensing

It shall[19] be possible to use an off-axis object up to 10 arcsec from the science target as the tip-tilt reference object.

For the purposes of implementing this offset fast guiding capability the FTT/NA system design shall[20] provide a facility for accepting an ISS-delivered offset between the tip-tilt reference object and the science target, expressed in CCD coordinates. These "off-axis" offsets are to be applied in addition to the dispersion offset described in Sec. 5.3 when determining the objective point.

## 5.5 Time-variability of offsets

New values of the dispersion and off-axis offsets will be made available to the FTT/NA system by the ISS at ten-second intervals and whenever the reference object is changed. Changes to these offsets shall[21] not interrupt or disturb closed-loop operation when the system is running in fast tip-tilt mode.

Each offset change will typically be much less than one pixel, hence the image centroiding algorithm(s) shall[22] yield centroids that vary linearly with image position within a pixel.

## 5.6 ISS command interface

The vendor shall[23] provide and document an Applications Programming Interface (API) which permits the MRO to command the FTT/NA system with the ISS.

The API shall[24] provide control of all system functions through a simple, robust, and well documented TCP/IP protocol over Ethernet.

## 5.7 Graphical user interfaces

As well as a command interface to the ISS, one or more Graphical User Interfaces (GUIs) shall[25] be implemented, providing a human observer with:

- Control of all FTT/NA system functions, including diagnostic functions;
- Live display of captured acquisition mode image data frames, at the full frame rate;
- Live display of captured fast tip-tilt mode image data frames, at a reduced frame rate of $\sim$10 Hz;
- Live display of sequences (i.e. graphs) of FTT/NA system telemetry data (see Sec. 5.9.1 for telemetry data items);
- When using the stand-alone recording capability (see Sec. 5.9):
  - A posteriori display of individual image data frames (captured in any of the FTT/NA modes);
  - A posteriori display of sequences (i.e. graphs) of FTT/NA system telemetry data.

It shall[26] be possible to display and operate the graphical user interface(s) from a customer-supplied computer located in the MROI control room that runs the Linux operating system. Note that in this context "operate" means that it must be possible for a human observer to control all FTT/NA system functions (i.e. switch operating mode) and alter all user-specified/user-selectable parameters from the control room. The vendor is not expected to provide network connection to the control room.

The system shall[27] accept a command to disable the controls on the GUI(s) that switch modes or alter parameters, while leaving the image and telemetry displays active. This will be used when the FTT/NA system is under ISS control, but observers in the control room wish to use the the supplied display capabilities.

It shall[28] also be possible to display and operate the graphical user interface(s) from a laptop computer situated inside the Unit Telescope enclosure.

It shall[29] be possible to run the graphical user interface(s) while data streaming to the ISS data collector (Sec. 5.10.1) is active.

## 5.8 Stand-alone operation

It shall[30] be possible to operate the FTT/NA software independently of any or all of the ISS, FTTA, and UT mount for testing purposes, with appropriate reductions in functionality being permitted.

## 5.9 Stand-alone archiving capability

The FTT/NA system shall[31] be able to record sequences of detector image data and diagnostic telemetry (captured in fast tip-tilt mode, acquisition mode, and acquisition check mode) without using the MRO ISS data collector. This capability will be used during commissioning and integration in order to diagnose problems with the FTT/NA system and/or the MROI sub-systems that it interacts with.

It shall[32] be possible to record multiple datasets and later display the data from any of these datasets (using the GUI stipulated in Sec. 5.7).

The FTT/NA system shall[33] provide at least 2GB of storage for recorded sequences of detector image data and telemetry data.

When archiving without the ISS data collector, image data frames shall[34] be recorded at a user-selectable rate, up to and including the rate at which they are acquired by the FTT/NA detector system.

The telemetry data to be saved shall[35] consist of the items listed in Sec. 5.9.1 (plus any other data that the FTT/NA supplier anticipates will be useful for diagnostic purposes) recorded at the full rate at which they are measured or generated within the FTT/NA control system.

All recorded detector frames and telemetry data shall[36] have accompanying UTC time-stamps which are accurate to 1 ms. MRO can supply an IRIG-B time signal if required, but the reader should note that NTP is sufficient to ensure 1 ms accuracy.

### 5.9.1 Telemetry data items

- All calibration parameters;

- Raw centroid estimates;
- Flux estimates;
- Dispersion and off-axis offsets;
- UT mount acquisition/tracking corrections;
- FTTA demands;
- Spatial and temporal (goal) seeing estimates;
- Copies of all rotation matrices used by the FTT/NA system.

## 5.10 Data transmission to MRO ISS data collector

In fast tip-tilt mode, acquisition mode, and acquisition check mode, the FTT/NA system shall[37] transmit detector frames and telemetry data to the MRO ISS data collector using well-defined protocols over Ethernet. The requirements on transmitted telemetry data items, data rates, latency, and reliability are listed in the following sub-sections.

All transmitted detector frames and telemetry data shall[38] have accompanying UTC time-stamps which are accurate to 1 ms. MRO can supply an IRIG-B time signal if required, but the reader should note that NTP is sufficient to ensure 1 ms accuracy.

### 5.10.1 Data streaming to the ISS for "user diagnostics"

Reduced-data-rate detector frames and telemetry data shall[39] be streamed over Ethernet with a maximum latency of 0.2 sec between capture/measurement by the FTT/NA system and *transmission* to Ethernet. Note: this is not a requirement on when these data transmitted over Ethernet must arrive.

The streamed data shall[40] be derived from an evenly-sampled subset of the detector frames, corresponding to a frame rate of at least 10 Hz (or the original frame rate if this is lower, e.g. in acquisition mode). These data will be used for display and decision-making, hence it is permissible for a small fraction (~1%) of the data to be lost.

The telemetry data items streamed shall[41] be those listed in Sec. 5.9.1 together with any other data that the FTT/NA supplier anticipates will be useful for diagnostic purposes.

#### 5.10.2 Data streaming to the ISS for archiving

Full-data-rate detector frames and telemetry data shall[42] be transmitted over Ethernet with a maximum latency of 300 sec. Note: 300 s is the maximum amount of time the system is expected to run uninterrupted in fast tip-tilt mode.

A protocol that guarantees no data loss (such as TCP/IP) shall[43] be used for this purpose.

The telemetry data items transmitted shall[44] be those listed in Sec. 5.9.1 together with any other data that the FTT/NA supplier anticipates will be useful for diagnostic purposes.

#### 5.10.3 Alternative: Dual-purpose data transmission to ISS

The MROI Project Office has decided that is preferable to transmit a single copy of the data to the ISS in order to satisfy both the "user diagnostics" (Sec. 5.10.1) and archiving (Sec. 5.10.2) requirements rather than transmit two separate streams.

In this case full-data-rate detector frames and telemetry data shall[45] be transmitted with a maximum latency of 0.2 sec using a reliable protocol.

In the subsections that follow, we specify functional requirements specific to certain of the operational modes defined in Sec. 4.

### 5.11 Fast Tip-tilt Mode

The field-of-view of each captured image data frame in fast tip-tilt mode shall[46] be at least 3 arcsec $\times$ 3 arcsec.

The system shall[47] be capable of operating with a user-selectable closed-loop 3dB bandwidth in the range 10–40 Hz (this facility will be used to accommodate a range of target brightnesses and seeing conditions). It is a goal that the system be capable of operating with a closed-loop 3dB bandwidth in the range 1–50 Hz, to allow observations of both very faint and very bright targets.

#### 5.11.1 Dither function

When in fast tip-tilt mode, the system shall[48] provide a facility to apply a periodic sinusoidal offset to the output beam direction of up to $2''$ peak-to-peak, at integer frequencies up to 10 Hz. The offset direction, amplitude and frequency will be specified by the ISS.

The zero-phase starting point of the sinusoid shall[49] be co-incident with a UTC second with a maximum latency of 1 ms.

## 5.12 Acquisition Mode

The field-of-view of each captured image frame in acquisition mode shall[50] be at least 60 arcsec × 60 arcsec, with a goal of 100 arcsec × 100 arcsec.

The system shall[51] by default automatically select the brightest object in the acquisition mode field as the tip-tilt reference object.

The system shall[52] provide a facility for the user to override this choice (both via the GUI and via the ISS command interface). Note that the default behaviour will almost always achieve the desired result, because (a) given the small size of the acquisition mode field, it is most likely that the brightest object in the field will be the science target; (b) in the rare cases when the science target appears faint and hence an off-axis tip-tilt reference is needed, then if such a reference exists it will likely be the brightest object in the field.

## 5.13 Relocation of Unit Telescopes

The Unit Telescopes will be relocated between array stations at intervals of approximately 3–6 months. The vendor shall[53] design and document a procedure (which need not be automated) whereby the FTT/NA system can be secured for relocation, and a corresponding procedure for readying the system for normal operations after relocation.

The vendor shall[54] supply all clamps and other equipment required to protect delicate parts of the FTT/NA system (such as optics and mechanisms) during relocation.

The FTT/NA system shall[55] be designed to withstand shock accelerations $\pm 0.4\,\mathrm{m\,s^{-2}}$ horizontally (TBC) and $\pm 0.2\,\mathrm{m\,s^{-2}}$ vertically (TBC) during relocation of a Unit Telescope.

The total time required to enter relocation mode and, subsequent to relocation, return to readiness for normal operation shall[56] be no more than 2 hours.

# 6 Performance Requirements

## 6.1 Environment

The FTT/NA system shall[57] be operable under the full range of environmental conditions given in Table 1. It is a *goal* that the FTT system be operable *beyond* the ranges

Table 1: Environmental conditions under which the FTT/NA system must be able to operate. The conditions on the optical table are assumed to be identical to the ambient night-time conditions.

| Parameter | Range |
|---|---|
| | **Electronics Housing** |
| Temperature | 10 to +40°C |
| | **Optical Table** |
| Temperature | -5 to +20°C |
| Relative humidity | 10% to 70% |

given in Table 1: to ambient temperatures extending down to minus 10°C and/or relative humidity extending up to 90%.

The FTT/NA system shall[58] survive being exposed to temperatures in the range minus 25°C to plus 40°C and/or relative humidity in the range 5% to 95% without compromising its lifetime (Sec. 6.6), but is not required to operate under these conditions.

## 6.2 Dichroic requirements

The clear aperture of the dichroic over which the following four specifications need to be met shall[59] be any 95mm-diameter circle wholly contained within a 110mm-diameter circle centered on the nominal exit beam of the Unit Telescope.

The beam transmitted through the dichroic shall[60] have an average throughput of $> 97\%$, over each of the following three wavelength bandpasses: 1.17 to 1.33 microns, $1.49 - 1.78$ microns, and $1.95 - 2.45$ microns. (The quality and amount of light reflected by the dichroic to the FTT/NA detector is a derived requirement for the vendor to establish.)

The diattenuation of the beam transmitted through the dichroic shall[61] have an average diattenuation of $< 1\%$, over each of the following three wavelength bandpasses: 1.17 to 1.33 microns, $1.49 - 1.78$ microns, and $1.95 - 2.45$ microns.)

The surface quality (i.e. scratch:dig) of the dichroic substrate prior to coating shall[62] be at least as good as 60:40.

The wavefront error of a beam transmitted through the mounted dichroic shall[63] not exceed 16.4 nm rms, assuming an input beam with zero aberrations.

## 6.3 Limiting magnitude & fast tip-tilt performance

For the purpose of demonstrating compliance with the requirements in this section, the supplier should assume:

1. The wavefront error delivered by the UT as specified in Sec. 5 of INT-403-TSP-0002;
2. The photon throughput of the UT as inferred from the coating specifications in Sec. 6 of INT-403-TSP-0002;
3. The response of the UT mount as specified in Sec. 2.6.3 of INT-403-TSP-0003;
4. An FTT actuator that meets the range, resolution and bandwidth specifications in Sec. 4.4 of INT-403-TSP-0003;
5. A bandpass limited in wavelength between 600 nm and 1000 nm reflected towards the tip-tilt sensor;
6. Seeing conditions with Fried parameter $r_0 \geq 14$ cm and turbulent layer wind speeds not exceeding 10 m/s;
7. Observations at the zenith, that is, no effects due to atmospheric dispersion need be considered;
8. That the target has a detected flux (W $m^{-2}$ $m^{-1}$) at 640 nm, 790 nm, 900 nm and 1000 nm that is lower than in the $V$ band (i.e. at 550 nm) by factors of 0.93, 0.83, 0.78, and 0.74 respectively. These factors correspond to a spectral index of $-0.5$, which approximates the spectral energy distribution of a typical Type 1 AGN. Note that this distribution is appreciably redder than that of Vega, for which the flux (W $m^{-2}$ $m^{-1}$) at 790 nm is 0.34 of that at 550 nm.

Given assumptions 1–8, the limiting magnitude in acquisition mode shall[64] be $V = 16$.

Given assumptions 1–8, the rms residual two-axis tip-tilt (i.e. the quadrature sum of the tip and tilt residuals for the tip-tilt reference object) when the system is operating in tip-tilt mode shall[65] not exceed 0.060 arcsec for tip-tilt reference objects brighter than $V = 16$. The residual referred to here is total residual of the atmospheric disturbances, the Unit Telescope mount errors and the wind shake errors (see Sec. 2.6.3 of INT-403-TSP-0003).

## 6.4 Stability of tip-tilt zero point

Any changes in the beam direction in the BCA that corresponds to the tip-tilt zero-point (e.g. due to tilt or position drifts of optical components on the UT Nasymth table) since start-of-night calibration shall[66] not exceed 0.015 arcsec , for changes in ambient temperature up to 5°C. In assessing compliance with this requirement, the FTT/NA supplier should assume that the UT Nasmyth table is perfectly stable, and that the maximum rate-of-change of temperature is no greater than 1.5° C per hour.

## 6.5 Power dissipation and consumption

Wherever possible, electronic components of the FTT/NA system that dissipate significant power shall[67] be located in the UT electronics housing (see INT-404-TSP-0003).

The external surface of any of the components of the FTT/NA system located on the UT optical table shall[68] be within 2° C of the ambient air temperature during nighttime observing conditions.

The FTT/NA system (excluding the UT mount and FTTA) shall[69] consume no more than 250 W total.

## 6.6 Lifetime and maintenance requirements

The system shall[70] not require routine maintenance (defined to mean any procedure that requires personnel to enter the UT enclosure, including alignment or cleaning) at intervals of less than 3 months. Note that this requirement precludes the use of cryogenic cooling for the CCD camera.

The system shall[71] be designed for a lifetime of 10 years (excluding the coatings on the optical components, and low-cost components such as cables).

A plan for maintenance of the FTT/NA control system software and hardware over the 10 year lifetime of the system shall[72] be provided. This plan may take the form of:

1. providing all developed source code together with object libraries for operating system dependencies, device-drivers for cameras, etc. or

2. a fee structure (annual or hourly fee) for supporting and maintaining the system.

The nature of such a plan, including its cost, will be taken into account in selecting a supplier.

It is a goal that the FTT/NA control system software run under the Xenomai real-time variant of the Linux operating system.

# 7 Interface Requirements

As part of the preparation for the Conceptual Design Review, the vendor shall[73] provide a document enumerating the interface control documents (ICDs) applicable to the FTT/NA system and the party provisionally responsible for writing each document.

The following is a preliminary list of interfaces which should be used as a basis for determining the list of ICDs.

- Optical interface to unit telescope (e.g. input beam size, location, orientation)
- Optical interface with customer-supplied Automated Alignment System
- Mechanical interface to unit telescope Nasmyth optical table (e.g. physical envelope) — see INT-403-DWG-0100 for current provisional information
- Utilities interface (power, cooling, network, timing signals)
- Controls interface to AMOS-provided fast tip-tilt actuator controller (current information in MRO-ICD-AMO-6000-025)
- Interface to Interferometer Supervisory System: This ICD should specify a list of high-level commands for controlling the system and configuring the transmission of detector frames and diagnostic data to the supervisory system. MRO will supply interface software, available in both Java and C versions for incorporation into the FTT/NA systems, that runs under Linux and that implements a TCP/IP-based Ethernet messaging protocol for receiving commands and transmitting data. Included in this MRO-provided software will be methods for transmitting faults and alerts, saving log messages to a local file, and saving and retrieving configuration data.

The vendor shall[74] ensure their designs are compatible with the space envelope for the FTT/NA system on the Nasmyth optical table that is agreed between vendor and customer during the design process.

# 8 Requirements Verification

Verification that the requirements in this document have been met will be made by a combination of reviewing design documents and drawings, inspection of hardware as-built, and a series of Factory Acceptance Tests and Site Acceptance Tests, as described below.

Detailed acceptance testing shall be performed in accordance with the Factory and Site Acceptance Test Plans developed by the supplier and approved by the customer. All tests and their results shall be documented by the supplier. These tests shall demonstrate that the FTT/NA system performs in accordance with the specifications in this document.

Preliminary acceptance will be based on Factory Acceptance Tests (FATs) to occur at the supplier's facility. Final acceptance will occur at the Magdalena Ridge facility after installation based on the results of a series of Site Acceptance Tests (SATs). The supplier is expected to have or obtain all and any other special test equipment necessary to demonstrate compliance with the system requirements and interfaces.

What follows are a number of tables of references from each "shall" requirement in this specification document. These tables will serve as a checklist for product acceptance. Each entry lists first the reference number, then a summary field which describes the kind of verification associated with the given specification. This is followed by a brief description of the requirement being referred to (the requirement in the main text is to take precedence over the summary description in all cases) and a comment clarifying, e.g. the type of verification the MROI Project Office is expecting.

This summary field consists of 5 sub-fields denoted by the letters 'D', 'A', 'I', 'F', and 'S', denoting the main methods by which the customer will verify whether the requirement has been satisfactorily met by the supplier. These methods are as follows:

**D: "design"** Inspection of drawings and other documents (including ICDs) showing proposed designs, methods, or procedures. In many cases these documents are part of design review documentation.

**A: "analysis"** Inspection of documents which verify by computational methods (e.g. analytical calculations or Finite Element Analysis results) that a proposed design, method, or procedure, meets the given requirements.

**I: "inspection"** Visually inspecting, measuring, activating or other actions on as-built components to determine proper form, fit or function of the supplier's solution to the given requirement. Inspections do not in general rely on any specialized test equipment.

**F: "factory acceptance tests" (FATs)** Tests performed on the as-built system or subsystem at the supplier's facility which measure the performance of the system as a whole or of some subsystem.

**S: "site acceptance tests" (SATs)** Tests performed upon delivery and installation of each system at the Magdalena Ridge.

## 8.1 Operating mode & functional requirements checklist

| No. | Description | D | A | I | F | S | Comments |
|---|---|---|---|---|---|---|---|
| 1 | Mode switching time $< 5\,\mathrm{s}$ | x | | | x | x | Goal 1 s |
| 2 | Provision of idle mode | x | | | x | x | |
| 3 | Command response (idle mode) | x | | | | x | |
| 4 | Provision of fast tip-tilt mode | x | | | x | x | |
| 5 | Estimate image FWHM in fast tip-tilt mode at $\geq 0.1\,\mathrm{Hz}$ | x | x | | | x | Goal to estimate $t_0$ |
| 6 | Provision of acquisition mode | x | | | x | x | Offsets delivered at $\sim 1\,\mathrm{Hz}$ |
| 7 | Estimate of image FWHM in acquisition mode | x | x | | | x | |
| 8 | Provision of acquisition check mode (Exp. time $\leq 10\,\mathrm{s}$) | x | | | x | x | Multiple exposures permissible |
| 9 | Provision of dark frame mode | x | | | x | x | |
| 10 | Master dark frame transmission and retrieval | x | | | | x | |
| 11 | Use of dark frame | x | | | x | x | |
| 12 | Provision of flatfield mode (Exp. time $\leq 100\,\mathrm{s}$) | x | | | x | x | Multiple exposures permissible |
| 13 | Master flatfield frame transmission and retrieval | x | | | | x | |
| 14 | Use of flatfield | x | | | x | x | |
| 15 | Coordinate transformations | x | x | | | x | |
| 16 | Sensor spectral bandwidth: 350–1000 nm | x | | | | | |
| 17 | Space for future dichroic slide | x | | | x | | |
| 18 | Application of dispersion offset | x | | | x | x | |
| 19 | Off-axis tip-tilt sensing distance $\leq$ 10 arcseconds | x | | | x | x | |
| 20 | Facility for accepting & using off-axis offsets | x | | | x | x | |
| 21 | Continuous tracking through offset changes | x | | | x | x | |
| 22 | Linearity of centroiding | x | x | | x | | |
| 46 | Fast tip-tilt mode FOV $\geq 3'' \times 3''$ | x | x | | | | |
| 47 | Closed-loop 3dB bandwidth: 10–40 Hz | x | x | | x | x | Goal 1–50 Hz |
| 48 | Sinusoidal dither facility: $\leq 2''$ at up to 10 Hz | x | x | | x | x | |
| 49 | Latency of dither function $\leq 1\,\mathrm{ms}$ | x | x | | x | | |
| 50 | Acquisition mode FOV $\geq 60'' \times 60''$ | x | x | | | x | Goal $100'' \times 100''$ |
| 51 | Selection of tip-tilt reference object | x | | | x | | |
| 52 | Facility to override reference object selection | x | | | x | | |

## Operating mode & functional requirements checklist continued

| No. | Description | D | A | I | F | S | Comments |
|---|---|---|---|---|---|---|---|
| 53 | Relocation procedure | x | | x | x | | |
| 54 | Provision of relocation hardware | x | | x | | | |
| 55 | Withstanding shock-loads of $\leq X$ g | x | | | x | | |
| 56 | Relocation time $\leq 2$ hrs | x | | | x | | |

## 8.2 Performance requirements checklist

| No. | Description | D | A | I | F | S | Comments |
|---|---|---|---|---|---|---|---|
| 57 | Environmental conditions for operation: Electronics housing temp in range $+10$ to $+40^\circ$ C, ambient temperature in range $-5$ to $+20^\circ$ C, ambient relative humidity in range 10% to 70% | x | | | x | | Goal for ambient temp range: $-10$ to $+20^\circ$ C, goal for ambient relative humidity range 10% to 90% |
| 58 | Environmental conditions for survivability: ambient temperature in range $-25$ to $+40^\circ$ C, ambient relative humidity in range 5% to 95% | x | x | | | | |
| 59 | Dichroic clear aperture $\geq 110$ mm | x | | | | | |
| 60 | Dichroic throughput $\geq 97\%$ | x | | x | | | Inspection of measured throughout test certificate |
| 61 | Dichroic diattenuation $\leq 1\%$ | x | | x | | | Inspection of measured diattenuation test certificate |
| 62 | Dichroic surface quality: 60:40 or better | | | x | | | Inspection of measured test certificate |
| 63 | Dichroic transmitted WFE $\leq 16.4$ nm | x | x | x | | | Inspection of FEA results and measured interferogram |
| 64 | Limiting magnitude for acquisition $V = 16$ | x | x | | | x | |
| 65 | Residual tip-tilt in fast tip-tilt mode $\leq 0.060'''$ at $V = 16$ or brighter | x | x | | x | x | Validation of a model for performance at different target magnitudes and seeing conditions would be adequate for verification purposes |
| 66 | Stability of tip-tilt zero-point: $0.015'''$ for $\Delta$T$\leq 5^\circ$ | x | x | | x | x | Factory test required to demonstrate that requirement is likely to be met |

## 8.3 Software requirements checklist

| No. | Description | D | A | I | F | S | Comments |
|---|---|---|---|---|---|---|---|
| 23 | Provision and documentation of API | x | | x | | | |
| 24 | Control of system functions using API | x | | | x | | Unit tests of individual commands — ISS not required |
| 25 | Demonstration of GUI(s) | x | | | x | | |
| 26 | Operation of GUI(s) from control room | x | | | x | | |
| 27 | Disabling of GUI controls | x | | | x | | |
| 28 | Operation from laptop | x | | | x | | |
| 29 | Run GUI while streaming to ISS data collector | x | | | x | | MRO will provide a simple data collector for FATs |
| 30 | Operation without ISS, FTTA, UTM | x | | | x | | |
| 31 | Stand-alone archiving capability | x | | | x | | |
| 32 | Recording/display of multiple datasets | x | | | x | | |
| 33 | Local storage for detector image data and telemetry $\geq$2 GB | x | | | | | |
| 34 | Stand-alone image recording at user-selectable rate $\leq$ rate of original acquisition | x | | | x | | |
| 35 | Stand-alone telemetry data items (see sec. 5.9.1) | x | | | x | | |
| 36 | Stand-alone recording: time-stamps accurate to 1 ms | x | | | | | |
| 37 | Data transmission to ISS | x | | | x | | MRO will provide a simple data collector for FATs |
| 38 | Time-stamps on data transmitted to ISS accurate to 1 ms | x | | | | | |
| 39 | Reduced-data-rate low-latency ($\leq$0.2 s) transmission to ISS | x | | | x | | MRO will provide a simple data collector for FATs |
| 40 | Sub-sampling for reduced data rate (at $\geq$10 Hz) | x | | | x | | MRO will provide a simple data collector for FATs. Permissible to lose up to 1% of data |
| 41 | Reduced-data-rate telemetry items to ISS (see sec. 5.9.1) | x | | | x | | ″ |
| 42 | Full-data-rate high-latency ($\leq$300 s) transmission to ISS | x | | | x | | MRO will provide a simple data collector for FATs. Max. FTT mode duration 300 s |
| 43 | Reliable protocol for full-data-rate transmission to ISS | x | | | | | |

## Software requirements checklist continued

| No. | Description | D | A | I | F | S | Comments |
|---|---|---|---|---|---|---|---|
| 44 | Full-data-rate telemetry items to ISS (see sec. 5.9.1) | x | | | x | | MRO will provide a simple data collector for FATs |
| 45 | Alternative: Full-data-rate low-latency ($\leq$0.2 s) transmission to ISS | x | | | x | | ″ |

## 8.4 Thermal, power & maintenance requirements checklist

| No. | Description | D | A | I | F | S | Comments |
|---|---|---|---|---|---|---|---|
| 67 | Use of electronics housing | x | | x | | | |
| 68 | Surface temp close to beam path within 2° C of ambient | x | | | x | | Requirement is for night-time observing conditions |
| 69 | Total power consumption $\leq$ 250 W | x | x | | x | | Excludes UTM and FTTA |
| 70 | Routine maintenance interval $\geq$ 3 months | x | | x | | | |
| 71 | Design lifetime of 10 years | x | x | | | | |
| 72 | Provision of maintenance plan for control system software & hardware | | | x | | | Various options possible: e.g. provision of source code or annual/hourly fee etc. Goal that control software run under the Xenomai real-time Linux o/s |

## 8.5 Interface requirements checklist

| No. | Description | D | A | I | F | S | Comments |
|---|---|---|---|---|---|---|---|
| 73 | Provision of list of ICDs and enumeration of authors | | | x | | | |
| 74 | Compatibility with agreed space envelope | | | | x | | |

# A Technical Background

This appendix *does not* serve to specify any requirements explicitly, but rather to explain the context from which requirements given in earlier sections were derived. Wherever there is an apparent conflict between this appendix and a requirement given in any other section of this document, the requirement from the other section will take precedence.

## A.1 Alignment procedure

The tip-tilt zero point defined in Sec. 2 is determined as part of the start-of-night alignment of the interferometer beam relay mirrors M4 & M5. This procedure involves both M4 and M5 and the components shown conceptually in Figure 3 which assumes the same detector for both acquisition and tip-tilt sensing.

The procedure consists of the following steps:

- A collimated beam of light is sent out from the central Beam Combining Facility. This beam is directed to be parallel to the axis of the relevant interferometer delay line.
- A fraction of this beam will follow the optical path (1) described in the caption to Figure 3, forming an image on the FTT/NA detector.
- The telescope tertiary mirror will be set to its nominal retro-reflection angle, hence the alignment beam will form a second image on the FTT/NA detector via the optical path (2) outlined in the caption to Figure 3.
- Any slight mis-pointing of the tertiary mirror will be corrected based on observations of the second image motion as the telescope outer axis is rotated.
- The position of the second image now defines the tip-tilt reference point. The relay mirrors are then adjusted to (a) superimpose the first image onto the second, and (b) match the shear of the UT and alignment beam axes (using a dedicated MRO-provided shear sensor which will also installed on the Nasmyth table).
- The alignment beam images can then be centred on the detector as required (by either lateral translation of the CCD or tilting of the focusing optic), to maximise the field-of-view available for target acquisition.

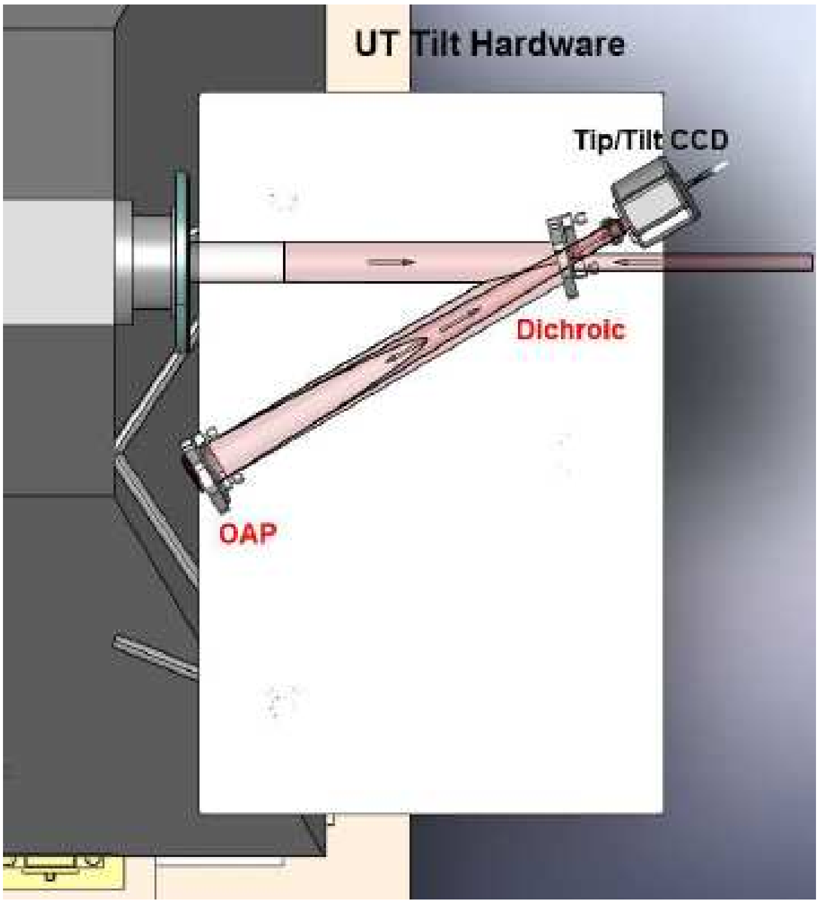


Figure 3: Plan view of the UT Nasmyth optical table, with only a subset of the components shown. *The layout is purely conceptual, and does not imply any preference for the locations or designs of the FTT/NA optical components*. An alignment beam transmitted from the Automated Alignment System in the BCA enters from the right. Two images are formed on the FTT/NA detector from this beam. Image 1 is formed by the beam reflected by the dichroic. After reflection, this beam meets a corner cube retro-reflector (not visible in the figure) located underneath the FTT/NA detector. On retro-reflection, a portion leaks through the dichroic and is focused onto the detector by the focusing optic (labelled "OAP" in this figure). Image 2 is formed by the portion of the light from the BCA that leaks through the dichroic initially and is retro-reflected by the tertiary mirror of the UT (off the figure to the left) before encountering the dichroic and focusing optic on the way to the detector.