Technical Requirements:
Unit Telescopes for the MRO Interferometer

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Contents

Chapter 1

Introduction

1.1 Background

Funds administered through the Naval Research Laboratory have been awarded to New Mexico Tech (NMT) to build the Magdalena Ridge Observatory (MRO). The observatory will be sited in the Magdalena Mountains, part of the Magdalena Ranger District of the Cibola National Forest in central New Mexico. Further information about the observatory can be found on the web at `http://www.mro.nmt.edu/`

The Magdalena Ridge Observatory will include one 2.4 meter fast-tracking telescope and a long-baseline imaging interferometer. The subject of this document is the interferometer only.

The Magdalena Ridge Observatory Interferometer (MROI) will be a high-sensitivity imaging optical/IR interferometer consisting of an array of up to 10 "unit telescopes" arranged in an equilateral "Y" configuration, as shown in Figure 1.1.0. Each unit telescope will send a parallel beam of starlight to a beam-combining facility located close to the array center, where the light will be combined to generate the interferometric signals used to reconstruct astronomical images. The telescopes will be relocatable amongst a set of 28 discrete foundations, giving baseline lengths (i.e. inter-telescope spacings) from $\sim$ 7.5 meters to $\sim$ 350 meters. The array will operate interferometrically at wavelengths from 600-2400nm. Starlight in the passband from 400nm-600nm will be used to sense atmospheric wavefront errors in a fast tip/tilt correction servo loop.

Although the MROI is designed as a 10-telescope array, operation will commence at the completion of six (6) telescopes. A second phase (currently unfunded) will upgrade the interferometer to the capability of up to a 10 telescope configuration, allowing "snapshot" imaging.

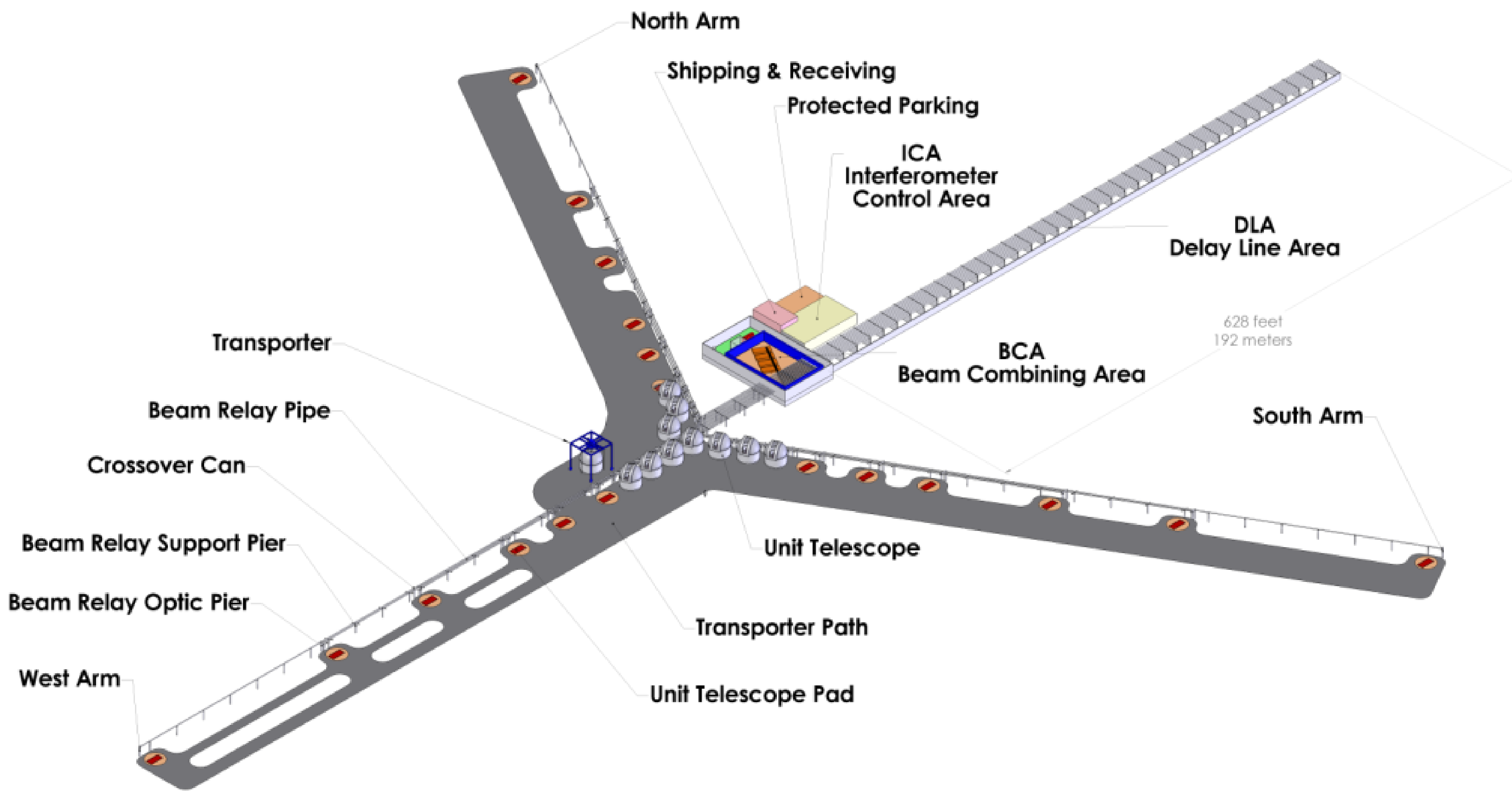

Figure 1.1.0: Perspective view of the MROI array in its most closely-packed configuration, showing 10 unit telescopes in their enclosures. It also shows the 28 possible foundations for the telescopes and their enclosures. An additional telescope is shown being relocated, within its enclosure, to a new foundation. This drawing is schematic only and is not intended to indicate a preference for a particular design for the unit telescope, enclosures, or relocation system.

1.2 Scope of supply

The scope of this effort includes the design, fabrication, testing, delivery, installation, training, and documentation of the system described in this document of specifications. This specification establishes the performance requirements for the relocatable unit telescope. The major subsystems of this telescope consist of

1. a telescope tube assembly including support structures and fixtures for the MRO-provided primary, secondary, and tertiary mirrors
2. an elevation over elevation gimbal mount that contains bearings, angle position sensors, electrical drive motors, and cabling;
3. a wide-angle acquisition telescope mounted on the side of the main telescope tube;
4. a "Nasmyth" optical table fixed to the side of the telescope gimbal;
5. a telescope base to interface between the gimbal and the telescope piers;
6. off-gimbal control electronics including drive servo electronics and motor drive power amplifiers;
7. the computer hardware and software to allow control of the operation of the telescope over an Ethernet interface.

The specifications listed in this document are the minimum allowable. The Vendor may exceed performance on any or all of the listed specifications. Wherever there is the perception of conflicting specifications, the more stringent one is required.

All components supplied for use on the MRO site shall[1] be compliant with the MRO Environmental Impact Statement.

1.3 Format and structure of this document

This document is divided into chapters giving the top-level requirements for the major subsystems, for safety and maintenance, the environmental specifications under which the telescope performance is specified, conditions for delivery and site installation, and requirements for acceptance testing.

Appendix A contains the technical background to how some of the requirements in the rest of the document were obtained. None of the explanation in the appendix should be interpreted as setting any requirements not stated elsewhere in the document.

The superscripts following each "shall" requirement in this document refer to the acceptance verification plan in chapter 12. Where a "shall" requirement has no superscript it is because a sufficient condition for fulfilment of that requirement is that successful acceptance tests take place on other requirements which do have a superscript — typically the relationship between the superscript and un-superscripted requirements can be deduced from the context.

Unless otherwise specified, all angles specified in this document are angles referred to the sky.

1.4 Related documents

1. INT-403-CON-0010, 27th October 2006: "Statement of Work: Unit Telescopes for the MRO Interferometer"'
2. INT-403-CON-0011, 27th October 2006: "Request for proposals No. 1007005: Unit Telescopes for the MRO Interferometer";
3. INT-403-TSP-0003, 27th October 2006 (this document): "Technical requirements: Unit Telescopes for the MRO Interferometer";
4. INT-403-TSP-0002, 8th September 2006: "Requirements for the Unit telescope optics for the MRO Interferometer";
5. Final Environmental Impact Statement (EIS) for Proposed Magdalena Ridge Observatory and Record of Decision for Proposed Magdalena Ridge Observatory, Cibola National Forest, Socorro County, New Mexico, December 2003.

1.5 Acronyms used in this document

API	Applications programming interface
CCD	Charge-coupled device
CDR	Conceptual design review
FAT	Factory acceptance test
FOR	Field of regard
FDR	Final design review
FTTA	Fast tip/tilt actuator
FWHM	Full width to half maximum
ICD	Interface control document
ICS	Interferometer control system
LED	Light-emitting diode
MRO	Magdalena Ridge Observatory

MROI	Magdalena Ridge Observatory Interferometer
NAS	Narrow-angle sensor
NMT	New Mexico Institute of Mining & Technology
OPD	Optical path difference
PDF	Portable Document Format
PDR	Preliminary design review
RMS	Root-mean-squared
SAT	Site acceptance test
SISO	Single-input single-output
UTCS	Unit-telescope control system
WAS	Wide-field acquisition sensor

Chapter 2

Telescope structure and gimbal assembly

2.1 Optical Assembly

The optical prescription for the MROI unit telescopes is that of a Mersenne beam compressor, taking an input collimated beam of diameter 1400 mm and delivering a collimated exit beam of diameter 95±1 mm. The MRO-supplied optical elements comprising this optical system are described in detail in INT-403-TSP-0002 "Requirements for the Unit Telescope Optics for the MRO Interferometer". Briefly, the system consists of an f/2.25 concave parabolic primary (M1) with a nominal diameter of 1425 mm, a convex parabolic secondary (M2) with a nominal diameter of 115mm and a flat tertiary mirror (M3) to direct the exit beam horizontally out of the telescope. The nominal M1-M2 spacing is 2936.25 mm. Fig. 2.1.0 shows the arrangement of the optical elements.

The telescope "tube" structure shall[2] consist of a rigid open frame structure connecting the primary mirror, the telescope gimbal, and the secondary and tertiary mirror assemblies in such a way as to meet the optical and mechanical performance requirements set out herein.

2.2 Telescope gimbal geometry

The telescope mount shall[3] have an elevation-over-elevation geometry with an articulated tertiary mirror directing the collimated exit beam horizontally as shown in Figure 2.2.0. The two rotation axes of the telescope mount are denoted as the "outer" (i.e. fixed) and "inner" elevation axes.

The exit beam centerline shall be along the direction of the outer elevation axis. The telescope shall[4] be designed for operation with a nominal direction of propagation of the exit beam of 104.47 degrees East of North when the telescope is installed and aligned at the array on the Magdalena Ridge.

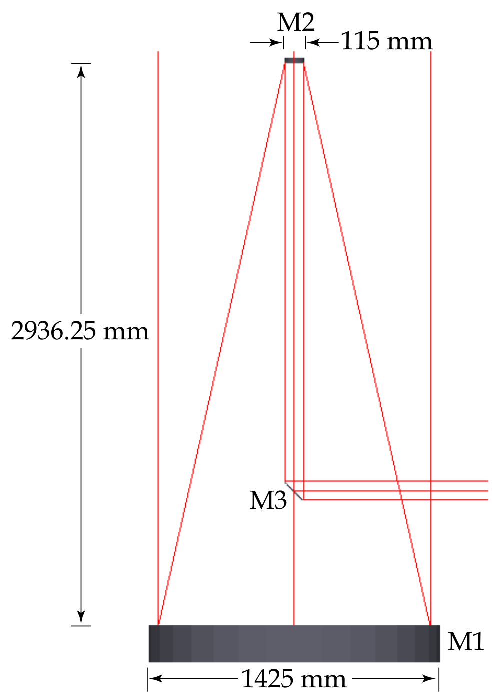

Figure 2.1.0: The nominal layout of the MROI unit telescope optics

2.3 Operational Field of Regard

The operational Field of Regard (FOR) shall[5] be such that all astronomical objects which meet *both* of the following criteria can be accessed:

1. They are above 30 degrees in elevation.

2. They can be accessed with an inner axis rotation angle between $+40°$ and $-50°$ where the positive rotation angle means that the angle of incidence of the starlight beam on the tertiary mirror is greater than $45°$ and a negative angle means that the angle of incidence is less than $45°$

Figure 2.3.0 shows how this requirement maps onto the regions of the celestial sphere accessible with this telescope.

2.4 Optical obscuration and field of view

The telescope optical system has a nominal clear aperture 1400mm in diameter. The total optical obscuration of the clear aperture shall[6] be no more than 5% over a field of view of radius 10 arcseconds from the telescope optical axis and over the field of

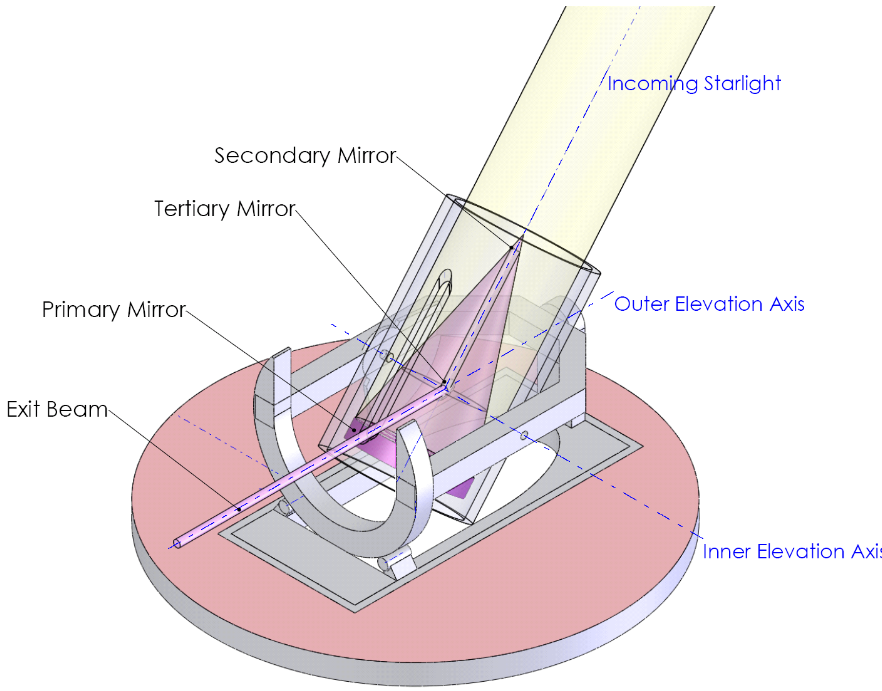

Figure 2.2.0: Cartoon of the telescope showing the elevation-over-elevation geometry. The diagram is schematic only: it is not intended to indicate a preference for any particular detailed design for the telescope (for example gimbal design), only the overall layout of the labelled components.

regard as specified in section 2.3. Off-axis vignetting at a radius of 50 arcseconds from the optical axis shall[7] be no more than 30%.

When the telescope is operated in the "tube offset" mode described in section 5.2, there shall[8] be an un-obscured path for a collimated beam of starlight 95mm in diameter to pass near the secondary mirror of the telescope and reflect off the tertiary mirror to travel along the direction of the telescope exit beam.

2.5 Telescope slewing and pointing

2.5.1 Slew and acceleration Rates

Slew and acceleration rates shall[9] be chosen to enable re-pointing the telescope between two points within the operational FOR separated by 10 degrees within 20 seconds, and anywhere within the operational field of regard within 120 seconds. These times are the elapsed interval between the receipt of the slew command by the UTCS and the time at which the telescope has settled to within 0.5 arcseconds of its final pointing at the end of the slew.

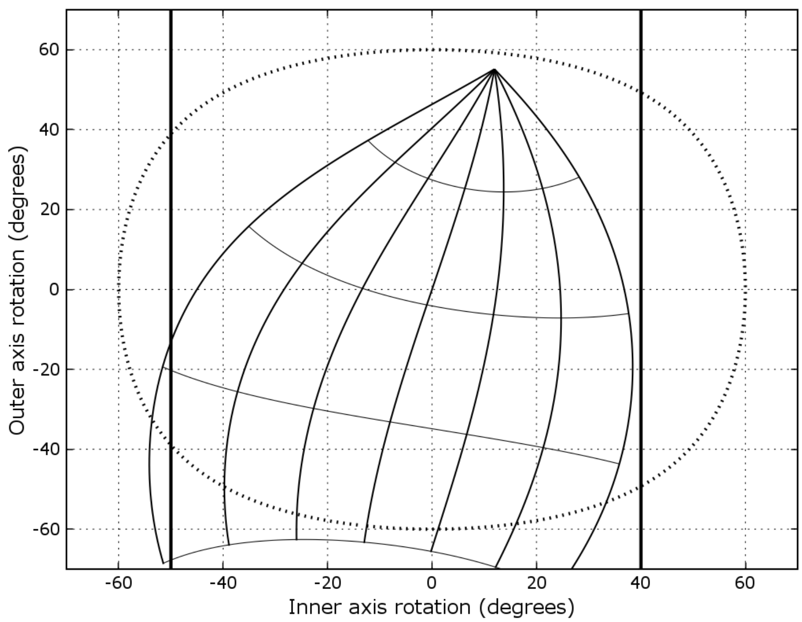

Figure 2.3.0: The Field of Regard requirements for the telescope in terms of the inner and outer telescope axis rotation angles. The dotted line encloses all regions which are above 30 degrees in elevation and the thick solid lines show inner axis rotation angles of $+40°$ *and* $-50°$*. The telescope must be able to point at all sources which are within the region bounded by the two thick solid lines and the dotted line. The thin solid lines show the corresponding celestial coordinates (for a telescope sited at latitude 34N, and with the telescope exit beam running horizontally* $104.47°$ *E of N): lines of constant Hour Angle at 0 hours,* ± 1 *hours,* ± 2 *hours, and* ± 3 *hours, plus lines of constant Declination at* $-30°$, $0°$, $30°$, *and* $60°$.

2.5.2 Telescope pointing

The telescope shall[10] be able to perform a pointing calibration sequence under the control of an MRO-owned Interferometer Control System (the ICS: see chapter 8). The calibration sequence is explained in more detail in section A.2.1, but the important details for the purposes of the pointing specification are given in the following paragraph.

The ICS will command the Vendor-supplied Unit Telescope Control System (UTCS: see chapter 8) to slew in turn to the nominal directions of a sequence of 10 reference stars spread approximately evenly over the telescope FOR. For each star in the sequence, the ICS will make use of the information supplied by MRO-owned acquisition cameras (one of which is fixed to the telescope optical table and viewing the star via the telescope primary, secondary and tertiary mirrors) to supply offset commands to the UTCS in order to center the telescope on the star direction. When the star is centered in the field of view of the camera fixed to the optical table to an accuracy of 0.5 arcsecond or better, the ICS will inform the UTCS of this fact and then initiate a slew to the next star in the sequence. At the end of the sequence of 10 stars, the ICS will command the UTCS to update its pointing model based on the pointing offsets required to center the reference stars in the camera field.

Up to 12 hours after performing this pointing calibration sequence, the telescope shall[11] point at any angle within the operational FOR with an accuracy of 20 arcseconds RMS, as measured by the acquisition camera fixed to the optical table and previously used as part of the pointing calibration sequence.

2.6 Telescope tracking

2.6.1 Introduction

During target acquisition, the telescope will be operated in an "open-loop" tracking mode where the telescope is expected to track sidereal motions without any external angular error feedback. Once the target has been acquired, the telescope will operate in a "closed-loop" tracking mode, in which an MRO-owned tip/tilt sensor (most likely located on the "Nasmyth" optical table) will measure the tracking error on the target star and an MRO-owned control system will supply correction signals to the Vendor-supplied telescope mount control system and fast-tip-tilt secondary actuator. The tracking requirements for these two modes are described below.

2.6.2 Open-loop tracking

The open loop tracking accuracy shall[12] be 1 arcsecond RMS over any 20 second period and 5 arcseconds RMS over any 100 second period. Open loop tracking accuracy will be determined by pointing the telescope at a reference star, tracking for the time interval and finding the pointing error after the interval. This process will be repeated on 20 objects distributed uniformly over the telscope Field of Regard and the RMS value of the errors calculated.

2.6.3 Closed-loop tracking

The ultimate closed loop tracking requirement (as detailed in section A.4) will be achieved with the aid of an MRO-owned closed-loop tip/tilt servo system. The Vendor-supplied telescope mount and fast tip/tilt secondary mirror will form part of this servo system. The following specifications serve to specify what MRO believes are the requirements on the Vendor-supplied components of this servo system in order that the system can meet the ultimate tracking requirement. The Vendor is not responsible for demonstrating closed loop tracking performance, but may suggest alternative approaches to the design and implementation of the closed-loop system if the Vendor believes that the same ultimate performance can be achieved at lower overall cost and risk.

The models for the MRO-owned tip/tilt servo and the sources of disturbance to this servo are explained in section A.4, which also explains the reasoning behind the telescope requirements levied in the following subsections. In summary, the modelled tip/tilt servo consists of a fast ($f_{3\mathrm{dB}} > 10\,\mathrm{Hz}$) loop which actuates the secondary mirror Fast Tip/Tilt Actuator (FTTA), and a slow ($f_{3\mathrm{dB}} = 0.1\,\mathrm{Hz}$) loop which offloads slow tracking errors to the telescope mount. For the purposes of setting requirements on the Vendor-supplied hardware, the net tracking error seen when the MRO-owned tip/tilt servo is in operation is model-ed as being a high-pass-filtered version of the tracking errors intrinsic to the Vendor-supplied hardware, i.e. without the MRO-owned tip/tilt servo.

Definition of disturbances

As explained in section A.4, the input disturbances to the MRO-owned tip/tilt servo are separated into three categories:

1. The **atmospheric seeing tip/tilt** disturbance which is defined in section A.4.

2. The **mount error residuals** are defined as the telescope tracking errors in the absence of any significant wind load and in the absence of any angular correction signals from the MRO-owned tip/tilt servo controller: this can include, but is not limited to, the effects of any encoder errors and drive errors as modified by the Vendor-supplied mount control loop and mount dynamics, and any pointing model errors.

3. The **wind shake residuals** are defined as the telescope tracking errors due to static and dynamic wind loading on the telescopes, as modified by the Vendor-supplied mount control loop, but in the absence of any angular correction signals from the MRO-owned tip/tilt servo controller.

The wind shake residuals and mount error residuals are assumed to add in a root-mean-square sense to give the total tracking disturbance on which requirements are levied. The wind shake residuals are specified separately from the mount error residuals because it is expected that these two requirements will be tested separately: the mount error residual requirement will be tested by direct performance tests of the as-supplied hardware in a sheltered environment, whereas it is expected that testing of wind-shake criteria will depend on a combination of analytical and numerical analysis of the effects of wind on the telescope, tests of telescope mount stiffness and dynamics, and telescope mount servo performance tests.

High-pass filter definition

In the requirements below, we use the term "RMS high-pass-filtered" and an associated filter frequency $f_{3\mathrm{dB}}$, applied to a set of tracking disturbances, e.g. mount error residuals or wind shake residuals. The definition of these terms can be explained through the following procedure used to high-pass filter the given set of tracking disturbances:

1. The relevant tracking disturbances are first expressed as angular disturbances referred optically to the sky.

2. These angular disturbances as a function of time are then decomposed into angular disturbances in a pair of orthogonal directions as $\theta_x(t)$ and $\theta_y(t)$.

3. The angular disturbances $\theta_x(t)$ and $\theta_y(t)$ are separately filtered using a high-pass "RC" filter with a frequency transfer function $g(f)$ given by

$$g(f) = \frac{1}{1 + i f_{3\mathrm{dB}}/f}$$

where $f_{3\mathrm{dB}}$ is the 3dB-frequency of the filter, yielding the filtered disturbances $\theta'_x(t)$ and $\theta'_y(t)$ respectively. The amplitude of this frequency transfer function for the two different values of $f_{3\mathrm{dB}}$ used in this document is shown in Figure 2.6.3.

4. The RMS high-pass-filtered disturbance is defined as

$$\sqrt{\langle\theta'_x(t)^2\rangle + \langle\theta'_y(t)^2\rangle}$$

where the angle brackets denote averaging over periods of at least 100 seconds and over a sufficient set of independent tests as to give confidence in the statistical significance of the result.

Allowable tracking disturbances

The maximum telescope RMS high-pass-filtered tracking disturbances present when tracking at sidereal rates in the "optimal observing" environmental conditions specified in section 10.3 shall[13] be as shown in Table 2.6.3.

The wind-shake residuals specified above shall[14] be met assuming that the enclosure provides no wind shielding in the region around the secondary mirror but does provide a 50% reduction in windspeed when compared with ambient conditions in the region around the primary mirror. Wind-shake specifications shall[15] apply in the ambient wind conditions set out in the "optimal observing environment" as specified in section 10.3. Standard Davenport wind models or their equivalent shall[16] be used in any analysis required for determining compliance to the wind shake specifications. If the Vendor believes that significant overall cost or risk reduction may be

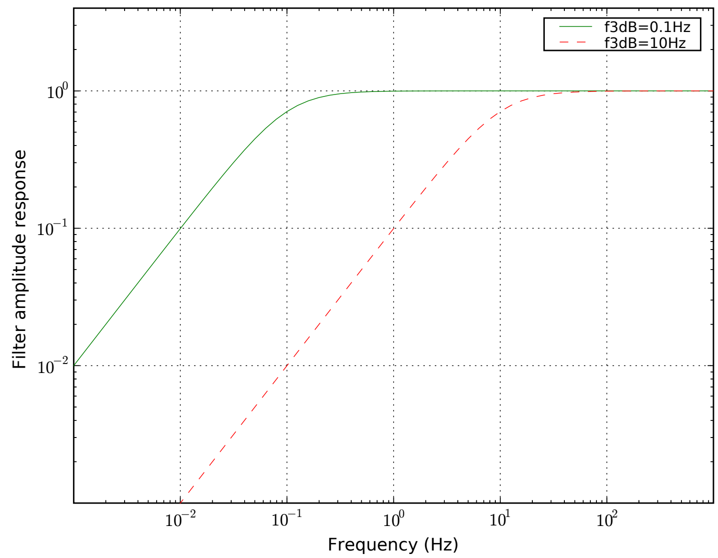

Figure 2.6.3: Amplitude response for the two high-pass filters used in defining the allowable tracking disturbances. The disturbance passing through the 0.1 Hz-cutoff filter corresponds to the residual disturbances that the tip-tilt system must correct. The disturbance passing through the 10 Hz-cutoff filter corresponds to the residual disturbances that are seen after correction by the tip-tilt system.

Disturbance source	RMS residuals (arcseconds)	
	$f_{3dB} = 0.1\,\text{Hz}$	$f_{3dB} = 10\,\text{Hz}$
Mount error	0.7	0.02
Wind shake	1.0	0.03

Table 2.6.3: The maximum allowable high-pass-filtered tracking disturbances for two different high-pass filter frequencies

obtained by assuming greater levels of wind shielding from the telescope enclosure, they are encouraged to specify alternative wind loading assumptions as part of their proposal together with an estimate of the level of cost and/or risk reduction that would result from adopting these alternative assumptions.

Telescope mount response

The telescope mount control system shall[17] accept telescope mount angular offset commands from the MRO's tip/tilt servo system at update rates of at least 1 Hz, and shall[18] have a step response time (command received to 95% response) of less than 1 second for step sizes of less than 5 arcseconds. The response to a step offset command of less than 5 arcseconds shall[19] have a maximum overshoot and ringing of no more than 10% of the step size (or 0.05 arcseconds, whichever is the greater) and shall[20] settle to within 2% of the step size (or 0.05 arcseconds, whichever is the greater) within 2 seconds of receipt of the command.

2.7 Pathlength stability

The following pathlength stability requirements shall apply when in the "optimal observing" environmental conditions specified in section 10.3 and under the assumption that the enclosure provides no wind shielding in the region around the secondary mirror but does provide a 50% reduction in windspeed when compared with ambient conditions in the region around the primary mirror.

2.7.1 Pathlength variations due to vibration

The variation of the optical pathlength through the telescope (i.e. the temporal variation of wavefront piston aberration in the beam exiting the telescope) due to vibrations of the telescope structure shall[21] not exceed the values shown in Table 2.7.1 when the telescope is tracking objects at sidereal rates and the tertiary mirror is operating in "sidereal tracking" mode or "tube offset" mode, and when the telescope is stationary and the tertiary mirror is in "retro-reflection" mode.

Time interval	RMS pathlength fluctuations over interval
12 msec	23 nm
17 msec	30 nm
26 msec	44 nm
35 msec	57 nm
52 msec	78 nm

Table 2.7.1: Maximum allowed vibration-induced pathlength fluctuations as a function of measurement interval

2.7.2 Pathlength variations as a function of pointing angle

When two telescopes are pointed at the same star, it is important to be able to model any difference in the optical paths travelled by the light from the star to a pair of fixed reference surfaces at the exits of the two telescopes. For a pair of identical telescopes, this model will depend only on the angular position of the star in the sky and the vector baseline between the telescopes. If the telescopes are not identical, there will be additional variations of the pathlength difference as a function of the position of the star, due to, for example, misalignment of the tertiary mirrors with the telescope axes.

The Vendor shall [22] provide a model, including measured values of any model parameters pertaining to each telescope, for any such additional variations in pathlength, such that the difference in pathlength between any two telescopes can be calculated to an accuracy of better than ±0.5mm over the operational FOR. Any component of the optical pathlength difference (OPD) that is independent of the star position may be ignored for these purposes. This model may be the null model, i.e. no OPD changes with angle. Any un-modelled changes in pathlength shall [23] vary smoothly with angle such that there is less than 700 nm RMS of un-modelled OPD variation for a change in pointing corresponding to tracking a star at sidereal rates for 1 second.

2.7.3 Pathlength variations as a function of temperature

When two telescopes are pointed at the same point in the sky, the OPD between the telescopes shall[24] change by less than ±0.1mm over a 5°C change in the ambient temperature (when the rate of change of temperature is less than 1.5°C per hour).

2.8 "Nasmyth" optical table

The Vendor shall[25] attach an optical table to the side of the telescope where the collimated beam exits after reflection from the tertiary mirror. The Vendor shall[26] attach this table rigidly to the telescope in a horizontal position such that its top surface is 150±0.5 mm below the centerline of the telescope exit beam, and is parallel to the exit beam direction to within 0.1 milliradian. The table shall[27] have a suitable pattern of fixing holes in order mount the following MRO-owned optical instrumentation:

1. Atmospheric dispersion corrector (weight less than 10kg).
2. Acquisition and fast tip/tilt sensor, including dichroic pickoff, focusing paraboloid, electron-multiplying CCD, and retroreflector (weight less than 30kg)
3. Adaptive optics module (weight less than 50kg)
4. Removable beam folding mirror (used when telescope is sited on West arm, weight less than 5 kg)

The table and its support structure shall[28]have a lowest design modal frequency of greater than 80 Hz when the MRO-owned instrumentation is installed. The Vendor shall[29] produce at the Preliminary ICD Review an Interface Control Document specifying the maximum shock accelerations expected to be experienced by any equipment mounted on the optical table during telescope relocation. All the MRO-owned

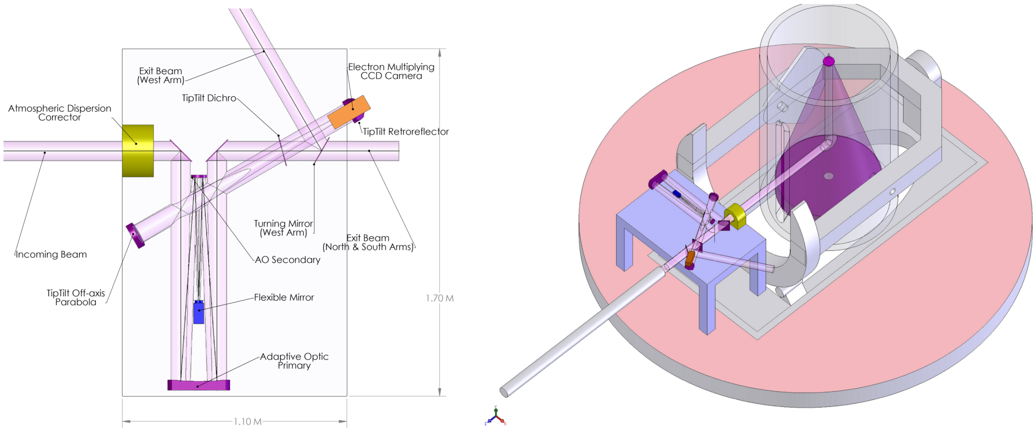

Figure 2.8.0: Schematic drawing showing the approximate layout and sizes of the MRO-owned instrumentation on the telescope Nasmyth optical table in plan view (left) and perspective view (right). The figure should not be interpreted as indicating a preference for a particular method of attaching the optical table to the telescope.

instrumentation to be mounted on the Nasmyth Optical Table (i.e. items 1-4 described above) will be designed either to survive the shock loads involved in telescope relocation or to be removed from the telescope before telescope relocation and restored after relocation.

The exact dimensions, hole pattern, and shape of the optical table shall[30] be agreed between the MRO and the Vendor at Conceptual Design Review (CDR). The horizontal dimensions of the table will be no larger than 1.7m×1.1m, and the space envelope will be consistent with the approximate locations and sizes of the instrumentation shown in Figure 2.8.0.

The Vendor shall[31] provide attachment points to allow the fitting of an MRO-owned cover over the optical table and the components on it.

2.9 Wide-field acquisition telescope

The Vendor shall[32] provide a finder telescope attached to the side of, and co-aligned with, the "tube" of each telescope. The finder telescope is intended for acquisition of bright stars when the telescope pointing model is ill-determined. The finder telescope shall[33] have a clear aperture of diameter at least 50mm and shall[34] provide optical and mechanical interfaces to an MRO-owned CCD acquisition camera such that the pixel scale is approximately 1 arcsecond/pixel, and the broadband (400nm-800nm) point-spread-function has a FWHM of less than 4 arcseconds over a field of view of 5 arcminutes radius. The center of the field of view shall[35] be co-aligned with the optical axis of the telescope to within 1 arcminute. The MRO-owned CCD acquisition camera will be an amateur astronomy camera with optical and mechanical interfaces similar to those of the Starlight Xpress SXV-H5.

2.10 Thermal management

The telescopes shall[36] be designed with the objective of achieving a level of thermal management that is adequate for minimizing the disturbance to the local atmospheric "seeing" conditions at night-time. The thermal management measures that should be considered as part of the design include, but are not limited to:

- Minimizing the heat dissipation into the enclosure of any powered equipment.
- Designing telescope components which equilibrate quickly with the external air temperature at night.

The MRO will make available within the UT enclosure an insulated housing for the Vendor-supplied control electronics as specified in subsection 6.2.1. The following specifications apply to all Vendor-supplied equipment which is not inside this housing.

All Vendor-supplied hardware shall[37] dissipate a total of no more than 50W of power to the air underneath or within 30cm of the path traversed by a beam of starlight passing through the clear aperture of the telescope. The total heat dissipation (averaged over any 5-minute period) of all Vendor-supplied equipment to the air within 3m radius of the telescope pivot point shall[38] not exceed 200W.

The temperature of any surface of the telescope underneath or within 30cm of the optical beam shall[39] be within 2°C of the ambient air temperature during night-time observing conditions. It may be assumed that the rate of change of ambient temperature is less than 1.5°C/hour.

2.10.1 Emissivity

The Vendor shall[40] apply a low-emissivity coating (for example low-emissivity paint or Mylar tape) to the telescope structure, in order to (a) minimize the supercooling of the structure at night and hence minimize thermal gradients (b) minimize the thermal background emission seen by the interferometer instrumentation.

2.10.2 Temperature sensors

The Vendor shall[41] affix 4 temperature sensors to the telescope structure and 4 temperature sensors to the primary mirror, at locations to be agreed with the MRO. The temperature readings from the sensors shall[42] be made available through the UTCS API. The readings from the sensors shall[43] have an accuracy of better than 0.5°C and a repeatability of better than 0.2°C over the temperature range from -20°C to +30°C.

Chapter 3

Primary mirror assembly

3.1 Mirror support

The MRO will provide a primary mirror as described in INT-403-TSP-0002 "Requirements for the Unit Telescope Optics for the MRO Interferometer". The Vendor shall[44] provide a passive radial and axial support mechanism for the MRO-furnished telescope primary mirror, including any attachments or fixtures to be attached to the said mirror. This support system shall maintain the alignment of the primary and secondary mirrors at the levels required to meet the requirements in section 4.3. The radial and axial supports shall[45] not induce deformations of the primary mirror front surface of greater than 10 nm over the temperature range of the "optimal observing conditions" given in 10.3 and over the FOR of the telescope given in section 2.3. The support system shall[46] include sufficient telemetry of the forces from the mirror support system to verify that the support system is not over-constraining the mirror. This could, for example, include load cells at each of the defining points on the mirror. This telemetry shall[47] be made available through the UTCS API.

At the Preliminary ICD Review, the Vendor shall[48] define the locations of all the axial defining points for the primary mirror so that the mirror can be polished in a dummy mirror cell with the correct support configuration. At the same time, the Vendor shall[49] specify any attachments and/or machining required on the primary mirror for connection of the axial and radial support mechanisms.

3.2 Primary Mirror Cover

The telescope shall[50] have a cover which protects the primary mirror from dust and falling objects when the telescope is not in use. When closed, the cover shall[51] be able to withstand the impact of a wrench 200g in mass falling from a height of 3m above the primary mirror. It shall[52] be possible to open and close the cover under computer control.

3.3 Pupil alignment LEDs

The Vendor shall[53] affix a ring of 4 light-emitting diodes (LEDs) equispaced around the perimeter of the primary mirror, oriented to illuminate the secondary mirror. This is in order to facilitate the optical determination of the location of the center of the projected telescope pupil image. The LEDs shall[54] be located outside of the telescope entrance clear aperture but less than 725 mm from the telescope optical axis. The LEDs shall[55] have luminous intensities of at least 1000 mcd and have the capability to be individually switched on and off through the UTCS API.

3.4 Mirror cleaning

The mirror cell shall[56] be designed to allow frequent (once every two weeks) cleaning of the primary mirror with CO_2 “snow”. The telescope shall be designed so that the primary mirror can occasionally be washed *in situ* with distilled water and detergent: in particular the mirror cell shall[57] be designed to allow drainage and collection of liquids used for washing the mirror surface when the telescope gimbal has been rotated to an appropriate position.

Chapter 4

Secondary mirror assembly

4.1 Secondary mirror support

The MRO will provide a lightweighted secondary mirror as described in INT-403-TSP-0002 "Requirements for the Unit Telescope Optics for the MRO Interferometer". The Vendor shall[58] mount this mirror rigidly to the active secondary system described below in such a way that the surface figure of the mirror over the central 98 mm diameter of clear aperture does not deform by more than 2.5 nm when compared to the surface figure measured when the mirror is rested on its back. This specification shall apply over the optimal operational temperature range given in section 10.3 and the Field of Regard specified in section 2.3.

At the Preliminary ICD Review, the Vendor shall[59] specify any support pads or fixtures required on the secondary mirror for mirror support.

4.2 Active secondary system

The Vendor shall provide an active secondary mirror system (including any support pads or fixtures required on the secondary mirror) and associated controls on each telescope. The active system shall provide at least the following functions:

- Control of tip, tilt, focus, and, if required, transverse position of the secondary mirror for low-bandwidth alignment and collimation of the telescope.
- Low-bandwidth compensation of focus errors arising from changes in the primary mirror to secondary mirror despace due to temperature changes or changes in the telescope pointing direction.
- Fast steering to allow correction of tip and tilt errors arising from a combination of atmospheric turbulence, wind buffeting and telescope tracking errors when used in conjunction with a tip/tilt sensor and control system owned by the MRO.

For the remainder of this document a 2-stage active system is assumed, consisting of a fast small-angle tip/tilt mirror mounted to a low-bandwidth large-angle tip/tilt and focus stage, with traverse translation if needed. A single stage system is acceptable as long as it meets the performance requirements within manageable interface constraints.

4.3 Low-bandwidth actuation and collimation

4.3.1 Range of actuation

The range of actuation of the secondary mirror in all translational and rotational degrees of freedom shall[60] be sufficient to include the perfectly-aligned (i.e. zero-wavefront-error) position and orientation of the secondary mirror with respect to the primary and tertiary mirrors, taking into account any inaccuracies in construction of the telescope, the manufacturing tolerances on the mirrors, the deformations of the telescope structure due to thermal effects and wind loading in the environmental conditions given in section 10.4 and gravitational deformation over the field of regard given in section 2.3. It may be assumed that the enclosure provides no wind shielding in the region around the secondary mirror but does provide a 50% reduction in windspeed when compared with ambient conditions in the region around the primary mirror.

It is acceptable for there to be no motorized adjustment of the position of the secondary mirror in the plane orthogonal to the optical axis ("decenter"), providing the design and the manufacture of the telescope is such that the optical vertex of the secondary mirror can be guaranteed to be always within 65 μm of the optical axis of the primary mirror. In the case where there is no motorized adjustment in this "decenter" degree of freedom, there shall[61] be provision to manually adjust the position of the secondary mirror in this degree of freedom by at least $\pm$1mm. This is in order to permit the use of secondary mirrors with slight manufacturing variations of their dimensions.

4.3.2 Resolution of actuation

The resolution (that is to say the minimum step size) of the actuation of the secondary mirror position in each degree of freedom shall[62] be as follows:

Focus 0.5 μm

Tip and tilt 10 arcsec (physical motion, not angle referred to the sky)

Decenter 12 μm

4.3.3 Stability of position

An MRO-owned wavefront sensor will be used as part of a start-of-night focusing and collimation procedure. Once the position of the secondary mirror has been initially adjusted at a given ambient temperature and for a given pointing direction, the telescope shall[63] maintain the relative positions of the primary and secondary mirrors to within the following specification over the field of regard specified in section 2.3 and over a temperature range of within ±3°C of the temperature at which the telescope was collimated and focused, for environmental conditions as given in section 10.3

Focus 2.2 μm

Tip and tilt 30 arcsec (physical motion, not angle referred to the sky; specification applies to the maximum tilt in any direction, not to tip and tilt separately)

Decenter 45 μm (specification applies to the maximum translation in any direction, not to the X and Y axes separately)

It is acceptable to achieve any or all of these specifications through the use of automated adjustments of the position of the secondary based on measurements of temperature of the telescope structure (or measurements of the strain of the structure), and a model of the telescope deformation under gravity and temperature. If this approach is adopted, the telescope vendor shall install all necessary sensors, provide all models and related look-up tables for each telescope and perform validation of these models through experimental tests. The telescope software API shall[64] allow the user to temporarily switch off any such automatic updates to the position of the secondary when desired.

4.4 Fast tip/tilt actuator (FTTA)

4.4.1 Range and resolution

The fast tip/tilt actuators (FTTA) shall[65] be able to mechanically move the secondary mirror over an angular range of at least ±50 arcseconds in both axes, i.e. approximately ±6.8 arcsec when referred to the sky. The minimum secondary mirror angular range as a function of frequency shall[66] be as specified in Table 4.4.1. The angular resolution of the FTTA shall[67] be better than 0.1 arcseconds (mirror physical motion) in both axes and the actuators in both axes shall[68] have a linearity of better than 1% over the angular range of motion.

Frequency (Hz)	Angular range (arcsec)
0.1	100
0.2	50
0.5	50
1	50
2	42
5	37
10	16
20	10
50	6
100	3
200	2

Table 4.4.1: Minimum single-axis peak-to-peak angular actuation range as a function of frequency for sinusoidal actuation of the fast tip/tilt actuators. The angular values given refer to the physical motion of the mirror, and not to angles projected on the sky.

4.5 Bandwidth

The FTTA control interface shall[69] accept tilt actuation commands at rates of up to 1kHz with a step response time (command received to 95% response) of less than 2 milliseconds for angular step sizes (physical motion of the mirror) of up to 2 arcseconds. The response to a step input shall[70] have overshoot and ringing of less than 10% of the commanded step size and shall[71] settle to within 2% of the step size within 4 milliseconds of receipt of the command.

The lowest structural resonance of the actuated secondary mirror system when mounted on the telescope shall[72] be such that it supports a closed-loop 3 dB bandwidth ($f_{3\mathrm{dB}}$) anywhere in the range between 10 Hz and 50 Hz (see section A.4 for a description of the closed-loop system and the definition of $f_{3\mathrm{dB}}$). As a goal, the lowest resonant frequency of the secondary mirror assembly (mirror combined with the tip-tilt and focus stage) should be greater than 250 Hz. If there are design resonant frequencies less than 250 Hz, the Vendor shall[73] demonstrate that the closed-loop performance requirements can still be met with $>60°$phase margin at 50 Hz closed-loop 3 dB bandwidth.

4.5.1 Tilt-to-piston coupling

The variation of the optical pathlength through the telescope due to actuation of the secondary mirror FTTA shall[74] not exceed the values shown in Table 4.5.1 when the FTTA is driven with an MRO-supplied time series of tip/tilt commands simulating the correction of random tilt errors due to atmospheric seeing and telescope jitter. The MRO-supplied time series will consist of two statistically independent pseudo-

Time interval	RMS pathlength fluctuations over interval
12 msec	23 nm
17 msec	30 nm
26 msec	44 nm
35 msec	57 nm
52 msec	78 nm

Table 4.5.1: Maximum allowed pathlength fluctuations due to the tip/tilt actuator as a function of measurement interval.

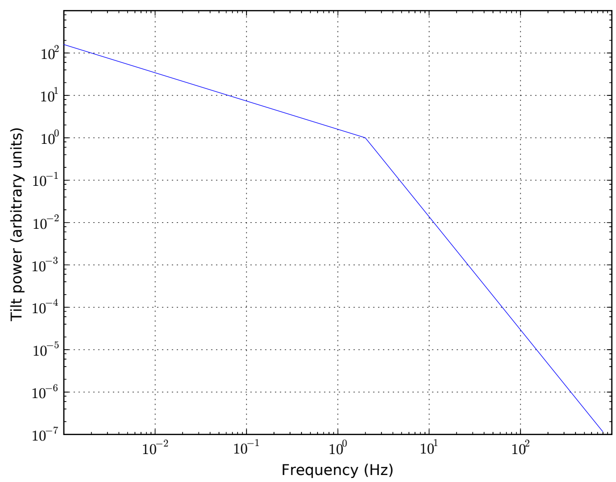

Figure 4.5.1: Spectrum for the tip/tilt fluctuations adopted for the purposes of this document. The scaling in the power axis is arbitrary.

random Gaussian processes (one each for tip and tilt) each of whose RMS amplitudes correspond to 10 arcsec of physical mirror motion. The power spectrum $\Theta(f)$ of these processes will be given by

$$\Theta(f) \propto \begin{cases} (f/f_1)^{-2/3} & \text{for } f < f_1 \\ (f/f_1)^{-8/3} & \text{for } f > f_1 \end{cases}$$

where $f_1 = 2\,\text{Hz}$. The form of this spectrum is shown in Figure 4.5.1.

It should be noted that the tilt-to-piston coupling requirement stated above can be met if the secondary mirror is constrained to rotate about a fixed pivot point that is within approximately 1 mm of the telescope optical axis. However, this is only one possible way of meeting the requirements, and the Vendor may propose any implementation which meets the requirement stated in the previous paragraph.

4.6 Secondary mirror LED

The Vendor shall[75] affix an LED mounted the central hole in the telescope secondary mirror in such a way that it illuminates the tertiary mirror. The LED shall[76] have a luminous intensity of at least 1000 mcd and have the capability to be switched on and off under computer control.

Chapter 5

Tertiary mirror assembly

5.1 Tertiary mirror support

The MRO will provide an elliptical tertiary mirror as described in INT-403-TSP-0002 "Requirements for the Unit Telescope Optics for the MRO Interferometer". The Vendor shall[77] mount this mirror rigidly to the tertiary mirror articulating system in such a way that the surface figure of the mirror over the central 240 mm×98 mm elliptical region of clear aperture does not deform by more than 2.5 nm when compared to the surface figure measured when the mirror is rested on its back. This specification shall apply over the optimal operational temperature range given in section 10.3 and the Field of Regard specified in section 2.3.

At the Preliminary ICD Review, the Vendor shall[78] specify any support pads or fixtures required on the tertiary mirror for mirror support which they intend to provide and use.

5.2 Tertiary mirror pointing

The telescope tertiary mirror shall support three telescope pointing modes as specified below.

1. In the "sidereal tracking" mode, the tertiary mirror shall rotate smoothly and accurately so as to ensure that the starlight as seen through the combination of the primary, secondary and tertiary mirrors meets all the pointing, tracking, and pupil stability requirements stated in subsections 2.5.2, 2.6, and 5.3.

   There is a partial degeneracy between the angle of the tertiary mirror and of the inner elevation axis, namely that errors in the pointing of the tertiary mirror can be approximately compensated for by suitably adjusting the angle of the inner elevation axis. The reason that this compensation is approximate is that it gives rise to wavefront errors in the telescope output beam due to the starlight traversing the primary-secondary pair at an angle to the optical axis. The telescope tracking system shall[79] be designed such that this error, i.e. the angle on the sky between the M1-M2 optical axis and the direction of a starlight beam which emerges parallel to the exit beam axis shall[80] be less than 42 arcseconds referred to the sky.

2. In the "tube offset" mode the tertiary mirror shall[81] point and track at the angles it would have adopted had the telescope been commanded to point in a given direction in sidereal tracking mode, while at the same time the optical axis of the telescope primary-secondary mirror pair is offset about the inner rotation axis from the direction it would have adopted in the sidereal tracking mode, with an angular offset chosen such that the secondary mirror is not blocking the direct view of the starlight, as shown in Figure 5.2.0. This is in order to view starlight reflected off the tertiary mirror without incurring the wavefront errors due to the primary-secondary mirror pair. The angular offset between the tube direction in sidereal-tracking mode and that in tube-offset mode shall be chosen so as to allow an unobstructed optical path avoiding the secondary mirror, as specified in subsection 2.4. It is acceptable for different angular offsets to be used for different pointing directions in order to avoid mechanical interference problems at the edges of the FOR. The telescope shall[82] be able to switch between tube-offset mode and sidereal tracking mode (pointing at the same star in both modes) in less than 20 seconds. In the tube offset mode, the tertiary mirror shall[83] meet the pointing and tracking requirements set forth in subsection 2.5.2 and section 2.6, except that all angular requirements referring to angles on the sky are to be relaxed by a factor equal to the nominal magnification of the primary-secondary mirror pair. The telescope shall[84] respond to tracking offset commands in way which is optically equivalent (i.e. in terms of angular motion on the sky) to the response that would have been achieved in sidereal mode.

3. In the "retro-reflection" mode, the normal to the tertiary mirror shall[85] be pointed along the direction of the telescope outer elevation axis, and the UTCS shall[86] accept adjustment commands to offset the angle of the normal to the tertiary mirror around the telescope inner axis with a mechanical angular resolution (i.e. not referred optically to the sky) of 0.25 arcsecond or better. This is so that the mirror normal can be aligned with the direction of the telescope outer axis with the aid of external optical measurements or otherwise.

In this document, the tertiary is assumed to be in the sidereal tracking mode unless otherwise specified.

It is acceptable to sense the direction of a pilot beam (e.g. a laser beam) or beams reflected off the front and/or back surface of the tertiary mirror in order to meet any or all of the above requirements. If such pilot beams are used, the total light scattered from such pilot beams in any direction within 15 arcminutes of the direction of propagation of the telescope exit beam shall[87] have a peak radiance of no more than 3nW/steradian/m^2 in the wavelength range 400nm to 5000nm.

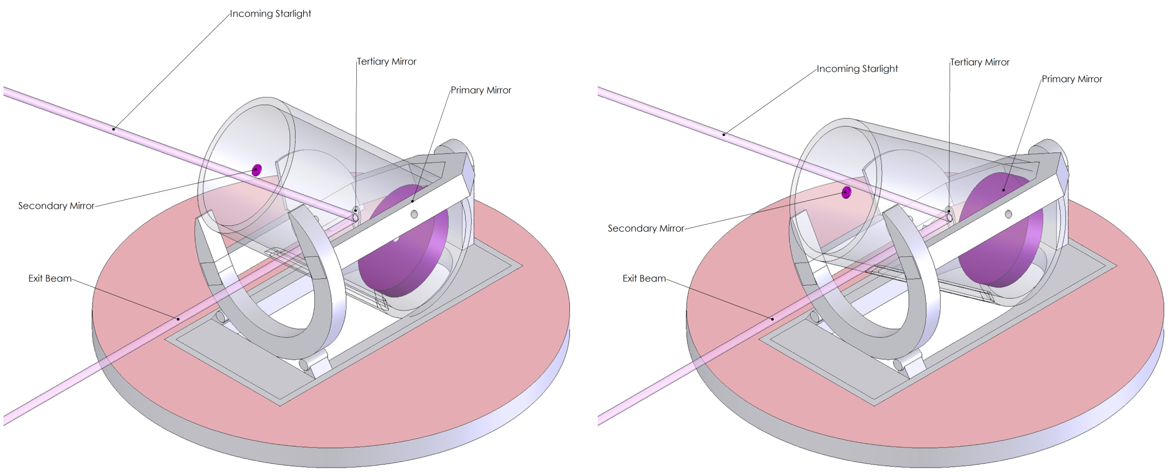

Figure 5.2.0: Schematic drawing showing the optical path traversed by starlight when the telescope is in the "tube offset" mode. In this mode, the starlight "misses" the telescope secondary mirror and reflects directly off the telescope tertiary mirror to travel along the exit beam direction. The two diagrams indicate opposite offsets of the telescope tube.

5.3 Pupil stability

The position of the center of the optical image of the telescope primary mirror as seen through the combination of the secondary and tertiary mirrors (hereafter called the "projected telescope pupil image") from a location mechanically independent of the telescope shall[88] vary by less than ±0.5mm over the operational field of regard. This requirement has implications on at least the following features of the telescope assembly:

- the accuracy of alignment of the tertiary mirror surface with the tertiary rotation axis;
- the accuracy of alignment (both angular and translational) of the tertiary rotation axis with the telescope inner gimbal axis;
- the shortest distance between the telescope inner gimbal axis and the telescope outer gimbal axis;
- the accuracy of alignment of the telescope M1–M2 optical axis with the mechanical pivot point of the gimbal.

It is the Vendor's responsibility to allocate the error budget amongst these and any other relevant sources of pupil position instability.

Chapter 6

Telescope interface to enclosure and relocation requirements

6.1 Role of enclosure

The MRO shall be responsible for providing an enclosure for each telescope. The enclosure will serve to house the telescope and ancillary equipment, protect the telescope against environmental conditions such as wind and rain during the daytime and during poor weather conditions, and to act as the interface to the telescope relocation system.

6.2 Enclosure interface

At the Preliminary ICD Review, the Vendor shall[89] submit a draft enclosure ICD including telescope clearance envelope dimensions. The telescope clearance envelope shall[90] be designed to facilitate the design of an enclosure which allows for a minimum center-to-center separation between the nearest-neighbour enclosures of 7.5 m while allowing access to the telescope for maintenance. The MRO will use this information to procure the enclosures. The Vendor will review and approve the enclosure design prior to the MRO's procurement of same.

6.2.1 Interface to electronics housing

As part of the telescope enclosure, a light-tight and thermally-insulated environmental housing will be provided for the Vendor-supplied electronics rack associated with control of the telescope. This housing will be sited either within the telescope enclosure or attached to the outside of the telescope enclosure. The telescope Vendor shall[91] specify the dimensions of the Vendor-supplied electronics rack, the maximum and minimum operating temperature and humidity for the rack, the total heat dissipation of the Vendor-supplied equipment in this rack, and cabling runways required between the housing and the telescope gimbal as part of the enclosure specification document.

6.3 Relocation requirement

The telescope shall[92] have a set of lift points suitable for supporting the telescope weight and constraining its motion in both translation and rotation during relocation. During the relocation procedure (i.e. while the telescope is in its "relocation mode") these lift points will mate with corresponding attachment points within the enclosure and the telescope and enclosure will be moved as a unit. At the Preliminary Design Review (PDR), the Vendor shall[93] submit a telescope relocation plan including pick-up points and maximum loads, shock limits, and any external stabilization required. The MRO will use this information to design the interface to the enclosure and procure the transporter. The Vendor shall[94] review and approve the enclosure and transporter design prior to the MRO's procurement of same.

The Vendor shall[95] design and document a procedure whereby the telescopes can enter its relocation mode, where it is secured for relocation, and a corresponding procedure for undoing the effects of the relocation mode to allow normal operation after relocation. The MRO will incorporate this procedure into the procedure whereby any telescope and its associated enclosure (including the Nasmyth optical table and associated instruments) can be relocated between any two array stations. It is expected that the MRO will relocate the telescopes at intervals of approximately 3-6 months.

The Vendor shall[96] supply all required clamps and other equipment required to protect delicate parts of the telescope during relocation, particularly optics and mechanisms. The procedure for entering relocation mode and the procedure for returning to normal operation shall[97] require no more than three persons. The total time required to enter relocation mode and, subsequent to relocation, to return to readiness for normal operation shall[98] take no more than 5 hours. The telescope is defined as being ready for normal operation when the telescope is ready to perform on-sky collimation procedures.

Chapter 7

Telescope interface to pier

7.1 Context

The MRO will install on the Magdalena Ridge an array of 28 “stations”, consisting of concrete foundations for the telescopes and their enclosures. Each station will have separate foundations for the enclosure and the telescope; the foundations for the telescope are hereafter called the “piers”.

7.2 Foundation ICD

At the Preliminary ICD Review, the Vendor shall[99] submit a telescope support plan describing the requirements for supporting the telescopes and including anchor locations and maximum static and dynamic loads, requirements for isolation from enclosure foundations, and any limitations on overall footprint. The MRO will use this information to design foundations for each of the 28 piers. The Vendor shall[100] review and approve the foundation designs prior to installation. The Vendor shall[101] design the telescope footprint so as to facilitate placing the telescopes and enclosures in a compact array with a minimum center-to-center spacing of 7.5 m between telescopes.

7.3 Objectives for telescope location precision

The Vendor is responsible for specifying an interface to the pier that allows the telescopes to be precisely located and oriented with respect to the sky. The most important objectives for this interface from the point of view of the performance of the array are:

1. The exit beam from *any* telescope placed on a given foundation must land within the clear aperture of the first relay mirror (M4) which directs light down

the beam relay vacuum pipes (the centerline of the exit beam is taken to be co-linear with the outer elevation axis). In the case of telescopes on the N and S arms of the array, the M4 mirror is on a separate pier which may be up to 11 m away from the telescope pier.

2. The “pivot point” of the telescope is defined as the midpoint of the shortest line connecting the centerlines of the inner and outer telescope elevation axes. It must be possible to predict the vector separation of the pivot points of any two telescopes on different piers to sufficient accuracy to narrow the search range for interference fringes between light beams from the two telescopes.

3. When a telescope is first placed on any foundation, it must be possible to acquire pointing model calibration stars within the field of view of the wide-field acquisition sensor (WAS) described in section A.2.

The following requirements are levied on the telescope in order to achieve these performance objectives. The Vendor may propose alternative ways of meeting these objectives if these will lead to a lower overall system cost.

7.4 Telescope location requirements

7.4.1 Description of the two-part interface

It is envisaged that the interface to the pier will be a two-part interface. The MRO-provided telescope pier will have a pattern of anchor bolts which is positioned to an absolute accuracy of ±12 mm and with a relative accuracy between the positions of the anchor bolts on any one pier of ±6 mm. The Vendor will design hardware for providing more precise locating points on the pier (the “pier locating points”), for example a sole-plate or a set of locating pins that attach to the anchor bolts. The telescope will have a corresponding set of mating points that mate with these precisely located pier locating points.

7.4.2 Interface hardware

The Vendor shall[102] supply 28 sets of hardware for pier locating points, one set for each pier. The pier locating points shall[103] be designed for a minimum operational lifetime of 20 years with minimal maintenance in the environment set forth in section 10.5.

7.4.3 Installation hardware and procedure

The Vendor shall[104] supply an installation jig or other hardware which allows the pier locating points to be precisely positioned relative to each other on each pier.

The Vendor shall[105] document a procedure which makes use of the installation jig to allow the installation of the locating points to the precision required to meet the following specifications below.

7.4.4 Locating hardware

The Vendor shall[106] supply a "locating jig" (which may be the same as the installation jig) which can be placed on the pier locating points once installed and will be used to define the nominal position and orientation of all telescopes placed on that foundation.

7.4.5 Nominal pivot point

The Vendor shall[107] document a method for computing a "nominal pivot point" (see item 2 of section 7.3) for any telescope-pier combination based on standard surveying measurements of the locating jig when placed on each of the piers and on Vendor-supplied parameters for each telescope.

7.4.6 Nominal pointing model

The Vendor shall[108] document a method for computing a "nominal pointing model" for any telescope-pier combination based on standard surveying measurements of the locating jig when placed on each of the piers and on Vendor-supplied parameters for each telescope.

7.4.7 Nominal centerline

The locating jig shall[109] emit a collimated "reference beam" of light, for example a laser beam, whose centerline defines the "nominal centerline" of the exit beam from the telescopes. The reference beam shall[110] have a diameter (FWHM) of between 5 and 10 mm, a wavelength of between 450 nm and 650 nm and an optical power of at least 0.5 milliwatts.

7.4.8 Telescope location accuracy

The MRO will install the pier locating points and will determine the position for the M4 mirror using the reference beam from the locating jig. When any telescope is subsequently installed on the locating points, the centerline of the telescope exit beam shall[111] pass within 10 mm of the intersection of the "nominal centerline" and the M4 mirror.

When a telescope is placed on the pier locating points the telescope shall[112] be able point to any point within the operational Field of Regard to an accuracy of 2 arcminutes RMS based on the "nominal pointing model" for that telescope pier.

7.4.9 Telescope relocation accuracy

When a telescope is placed in relocation mode, is then lifted off the locating points and is subsequently replaced on the same locating points and put back in operational mode, the telescope pivot point at the end of this procedure shall[113] be within a 2mm radius of the location it had before being placed in relocation mode.

7.4.10 Mechanical adjustment after relocation

It is desirable that no mechanical adjustment of the telescope after its relocation will be required in order to meet the specifications in this chapter, but if any such adjustment is necessary, then the time required to perform the adjustment is to be counted as part of the total relocation time for the telescope as specified in section 6.3.

Chapter 8

Electrical and Software Requirements

8.1 Electrical requirements and interfaces

8.1.1 AC Power Interface

The MRO will make available a 120V/15A single phase AC power supply within the enclosure electronics housing. The telescope shall[114] draw all of its power from this supply point. If the Vendor believes that use of a three-phase 208V AC power supply instead of the 120V single phase supply described above would lead to significant cost and/or risk reductions, they are encouraged to indicate this in their proposal.

8.1.2 Electrical Grounding Interface

The MRO will make available a ground point along with the AC Power Interface. The Vendor shall[115] supply and install cabling to appropriately connect the telescope electrical ground system to this point. The Vendor shall[116] ensure that the grounding system implements industry standard electrical grounding characteristics so as to not introduce undesirable noise in "ground loops". The vendor shall[117] suggest any additional grounding if required as part of the telescope-enclosure ICD.

8.1.3 Network Communications Interface

The MRO will make available within the enclosure a network communications interface in the form of up to 16 ports of a standard RJ45 gigabit Ethernet switch. The Vendor-supplied UTCS shall[118] be capable of using this switch as the sole network interface for all network connections internal and external to the UTCS. The Vendor shall[119] review and approve the MRO's specification for the Ethernet switch prior to the MRO's procurement of same.

8.1.4 Cable Wraps and Wireways

Cable wraps and wireways shall[120] be supplied to support all the cabling necessary within the telescope system, with the exception of the cable run between the base of the telescope structure and the electronics housing described in subsection 6.2.1. The Vendor is responsible for installation of Vendor-supplied electronics and all cabling into the MRO-provided electronics housing and cable runs within the telescope enclosure.

Spare space consisting of 3 square inches shall[121] be provided within the on-telescope cable wraps for MRO-owned cabling and liquid cooling loop for the MRO-owned camera mounted on the wide-field acquisition telescope. All Vendor-provided cable wraps and wireways shall[122] be easily accessible for maintenance and addition or removal of cables from the wrap.

8.2 Software requirements and interfaces

8.2.1 General

The underlying philosophy is to equip the unit telescope with a Vendor-supplied Unit Telescope Control System (UTCS) which interfaces to Vendor-supplied electronics interfaces, sensors, and actuators, providing a higher-level remote control communications interface to the MRO-owned Interferometer Control System (ICS).

All Vendor-supplied software shall[123] be documented to a sufficient standard to allow the MRO to operate the software and associated hardware systems, to develop relevant interfaces to the software, and to debug and maintain the operation and interfaces of the software.

8.2.2 Unit Telescope Control System

The Vendor shall supply hardware and software for the Unit Telescope Control System (UTCS). UTCS functionality shall[124] allow, at minimum, a trained operator to exercise and monitor all telescope functionality. The UTCS shall perform all functions necessary to accomplish acceptance testing of all operational requirements. The UTCS shall[125] provide a graphical user interface comprehensively covering all unit telescope functionality and operations. The UTCS shall[126] allow all telescopes to be operated independently from one another.

8.2.3 Local and Remote Operations

The UTCS shall[127] be capable of local control and monitoring within the telescope enclosure and remote control and monitoring over the local area network. Local operations may be provided though the same mechanism as remote operations by utilizing a laptop computer at the enclosure as the local operations interface to the UTCS.

8.2.4 Power Up and Initialization

The UTCS shall[128] be capable of powering up, initializing, and running continuously without operator intervention. Remote monitoring of power up and initialization shall[129] be provided. Remote capability to reboot and cycle power shall[130] be provided.

8.2.5 Applications Programming Interface

The Vendor shall[131] provide and document an Applications Programming Interface (API) which permits the MRO to integrate the UTCS with the MRO-owned Interferometer Control System (ICS). The API shall[132] provide control of all telescope functions through a simple, robust and well-documented TCP/IP communications protocol over Ethernet. All telescope telemetry and status information shall[133] be available through an identical or similar, simple, robust and well-documented TCP/IP communications protocol over Ethernet.

8.2.6 Motion control parameters

For any motorized components of the telescopes which have externally programmable slew and acceleration rate limits, programming and querying of these parameters shall[134] be made available through the UTCS API.

8.2.7 API Level of Operation

The following lists of available commands and available status parameters are indicative of the level of operation required for the API. The lists are not intended to be comprehensive or complete.

Where appropriate, and unless otherwise specified, the coordinate system for any given command can be assumed to be in terms of the telescope inner and outer elevation axis angles.

- Initialize/shut down telescope:
  - Power up/down motors and other actuation systems
  - Shutdown/reboot control systems
  - Self test
  - Reset encoders (if applicable)
  - Park telescope

- Set mount axis angles
- Set tertiary axis angle
- Set telescope tertiary pointing mode: sidereal/tube offset/retro-reflection
- Slew to, and start tracking, specified RA and Dec
- Apply offset to current pointing direction
- List names of status parameters
- Get named status parameter
- Adjust secondary mirror collimation
- Adjust secondary mirror focus
- Automatic collimation on/off (if applicable)
- Automatic focus compensation on/off (if applicable)
- Set FTTA zero position (if applicable)
- Store pointing data
- Recalculate pointing model
- Save pointing model (on telescope control computer or on Network-Attached Storage)
- Load pointing model
- Retrieve modelled OPD for given pointing direction
- Perform coordinate conversion using current pointing model (inputs: either HA & Dec or Horizontal & Vertical as seen from optical table, outputs: inner elevation, outer elevation)

Where appropriate, status parameters should come with a time-tag of an appropriate resolution giving the time when the value was measured. Available parameters should include at least the following:

- Encoder counts & flags
- Current mode (track, slew, fixed position, park, ...)
- Target/position parameters
- Offsets
- Quasi-static focus & collimation positions
- Quasi-static focus & collimation modes (automatic/manual)

8.2.8 API Diagnostics and Debugging

The UTCS shall[135] provide for remote diagnostics and debugging of the communications through the API between the UTCS and ICS.

8.2.9 Calibration & Configuration Management

The UTCS API shall[136] allow the ICS to query, and at a later time restore, individual unit telescope configurations, initializations, calibrations, pointing models, and other data unique to each unit telescope as part of an ICS configuration management strategy. The Vendor shall[137] document all relevant configuration parameters and the most convenient methods for setting and querying them in a systematic fashion.

8.2.10 Fast tip-tilt interface

The Vendor shall[138] supply and document an interface which allows the MRO's tip/tilt servo system to control the fast tip-tilt secondary mirror at update rates of up to 1 kHz. This interface may be an analog or digital interface.

8.2.11 Mount offset commands for closed-loop tracking

The Vendor shall[139] supply and document an interface which allows the MRO's tip/tilt servo system to send telescope mount offset commands to the UTCS as set forth in subsection 2.6.3 over a TCP/IP Ethernet link. It is acceptable to use the UTCS API interface for this purpose as long as it can meet the latency requirements in subsection 2.6.3.

8.2.12 Time Synchronization

The Vendor shall[140] provide a local GPS receiver and associated antenna for time synchronization at each unit telescope. The GPS timing information shall[141] be used wherever relevant in all tracking, commanding and telemetry functions. Hardware timing signals, including a 1 pulse-per-second signal and IRIG-B, shall[142] be made available via a suitable interface to MRO-owned equipment in the enclosure.

Chapter 9

Safety, Maintenance, and Documentation

9.1 Safety

The telescope shall[143] be designed to meet all applicable fire and safety codes. The Vendor shall[144] provide travel limits and associated interlocks to ensure fail safe operation of all aspects of the telescope.

9.1.1 Stops

The Vendor shall[145] provide at a readily accessible location in the enclosure an electrical stop for use at the option of the user which disables the motion of the telescope axes. An interlock shall[146] alert the user by means of an indication on the local console and a status alert to the ICS, to the presence or absence of this electrical stop. Application of the stops shall[147] not over-stress any element of the telescope system.

9.1.2 Clamps

Manually operated clamps which can generate enough torque to overcome any unbalanced condition associated with the axis to be clamped (during normal operation) shall[148] be provided to inhibit motion of each axis.

9.2 Protection

The control system shall[149] contain appropriate sensors and automatic controls to prevent the telescope from being damaged by erroneous or invalid commands.

9.3 Maintainability

The telescope shall[150] be designed and built so as to survive and perform as intended for a minimum of 20 years without any major renovation.

The Vendor shall[151] estimate the maintainability requirements of the telescope. The Vendor shall[152] use common maintenance terms such as mean-time-to-repair and mean-time-between-maintenance-actions. The Vendor shall[153] define recommended maintenance personnel and skill requirements, maintenance training, and support costs in light of a telescope with a 20-year useful operational lifetime.

The Vendor shall[154] develop and document detailed and complete maintenance procedures and schedules. These procedures shall[155] be comprehensive and sufficient to perform all scheduled and unscheduled preventive and corrective maintenance procedures necessary to maintain or return the system to a fully operational capability.

9.3.1 Spare Parts List

The Vendor shall[156] determine what parts should be recommended as spares. The Vendor shall[157] take into consideration all components, parts, assemblies, and end items used in the telescope.

9.3.2 Training

The Vendor shall[158] train three persons to be identified by the MRO in the operation and maintenance of the telescopes, including all associate software systems. This training shall[159] be performed after acceptance testing at a location specified by the MRO. Training shall[160] include hands-on operation of the system and shall[161] result in certification by the Vendor that the trained personnel can satisfactorily collimate, operate and perform scheduled maintenance and probable unscheduled maintenance on the telescope in a safe and efficient manner.

9.4 Mirror installation and removal

The design of the telescope shall[162] allow for the easy and safe removal and re-installation of all telescope mirrors (together with, as necessary, the mirror cells) in order to allow for periodic (estimated every 12 months) re-coating of the mirrors at an off-site coating facility.

Removal and re-installation procedures shall[163] each take less than 6 hours for each primary mirror and less than 2 hours each for the secondary and tertiary mirrors. The removal procedure is defined to end, and the re-installation procedure is defined to start, when the mirror has been placed on/lifted off a MRO-owned flatbed truck. The re-installation procedure is defined to end once optical realignment of the mirror can commence.

The Vendor shall[164] provide all required equipment for handling all the mirrors from the telescopes of the array, but the vendor need only supply sufficient equipment to allow the installation or removal of the mirrors from one telescope at a time, i.e. the Vendor need not supply duplicates for all telescopes of any handling equipment which can be reused from one telescope removal/re-installation procedure to the next.

9.5 Documentation

The Vendor shall[165] deliver at minimum the following documentation. The Vendor should deliver one paper copy ("hard copy") and two copies on CD ("soft copies") of all documentation and drawings below. The soft copy of the documentation and drawings should be supplied in the editable file format of the software used to create the documentation and also in the Adobe Portable Document Format (PDF) file format.

9.5.1 Project planning documents

1. Project plan
2. Configuration item list
3. Error budgets

9.5.2 Reporting documents

1. TIM agendas/reports/minutes
2. Progress reports
3. Change requests
4. Requests for waiver
5. Non-conformance reports

9.5.3 Interface control documents

Any reference in this specification to an interface between the MRO and the telescope Vendor, or between the telescope Vendor and other Vendors associated with the project, shall[166] be governed by Interface Control Documents (ICDs) generated by the telescope Vendor and approved by the MRO. The preliminary list of ICDs is presented in INT-403-CON-0010 “Statement of Work: Unit Telescopes for the MRO Interferometer”, Section 9.

9.5.4 Review material

The material below should include all the analyses and results of analyses performed as part of the review reports, e.g. FEA analyses, thermal analyses etc.

1. Program Review reports
2. Conceptual Design Review reports
3. Preliminary Design Review reports
4. Final Design Review reports
5. Pre-ship review reports
6. Site Acceptance Test reports
7. Shipping/transporting plan

9.5.5 Manuals

1. Pier locating points installation manual
2. On-site Assembly/Integration plan and manual
3. Optical alignment plan and manual
4. Operations manual
5. Relocation manual
6. Programmer manual
7. Maintenance manual
8. Training manual

Operations manuals should include a technical description of the telescopes, and detail all standard operating procedures, including software start-up, diagnostic testing, basic trouble-shooting, and routine operation.

Maintenance manuals should include the following:

1. Maintenance procedures that list all steps required to perform the specified maintenance

2. Reference figures (with item numbers or labels) and relevant drawings
3. Identification of all required tools and sources for specialty tools
4. Proposed spare parts list
5. Suppliers' documentation, e.g. manuals, spec sheets, data sheets
6. A list of all required maintenance supplies and where to obtain specialty supplies
7. A preventive maintenance section that includes schedules of required maintenance
8. A corrective maintenance section that includes a fault tree and detailed trouble shooting procedures
9. A corrective maintenance section that includes repair procedures

9.5.6 Drawings list

Drawing sets shall define at all levels of the project the as-designed and as-built product. At minimum, assembly-level drawings should be delivered to the MRO.

1. Conceptual Design Review drawing set
2. Preliminary Design Review drawing set
3. Final Design Review drawing set
4. As-built drawing set

Chapter 10

Environmental specifications

10.1 General environment on the Magdalena Ridge

Weather statistics at the MRO site over the past few years show a minimum night-time winter temperature of -20°C and a maximum summer daytime temperature close to 25°C. Monthly averages over these periods give minima and maxima of -7°C and 16°C, respectively. Throughout the year, ninety percent of the time the day-to-night change in temperature at the summit is below 11°C. Figure 10.1.0-a illustrates the monthly temperature extremes as well as the maximum diurnal temperature range at the MRO site.

Figure 10.1.0-b illustrates the typical wind speeds and direction at the MRO site. Wind speeds as high as 105mph have been measured at the MRO site, although more routine high wind activity is closer to 60-70mph. Snowfalls as deep as 12-18 inches can occur in the winter season, but most of the time the wind will blow this away sufficiently rapidly that snow will not settle on structures to this depth.

The seismic environment is generally quiet, with total ground motions significantly less than 25nm when integrated over a bandpass from 1 Hz to 100 Hz. For the purposes of meeting vibration specifications, it can be assumed that the seismic displacement noise has a power spectral density of less than $3{\times}10^{-17}f^{-3}\,\mathrm{m^2Hz^{-1}}$ over the frequency range 1 Hz to 1 kHz, where f is the frequency in Hz. There is a low but non-negligible risk that a nearby earthquake of magnitude 5 or greater will occur during the 20-year lifetime of the observatory. This is accounted for in the acceleration specifications below.

10.2 Environmental definitions

The telescopes shall be designed to operate and survive without degradation within the environments described in this chapter. There are a number of different environments in which the various specifications are required to be met and these are defined as follows:

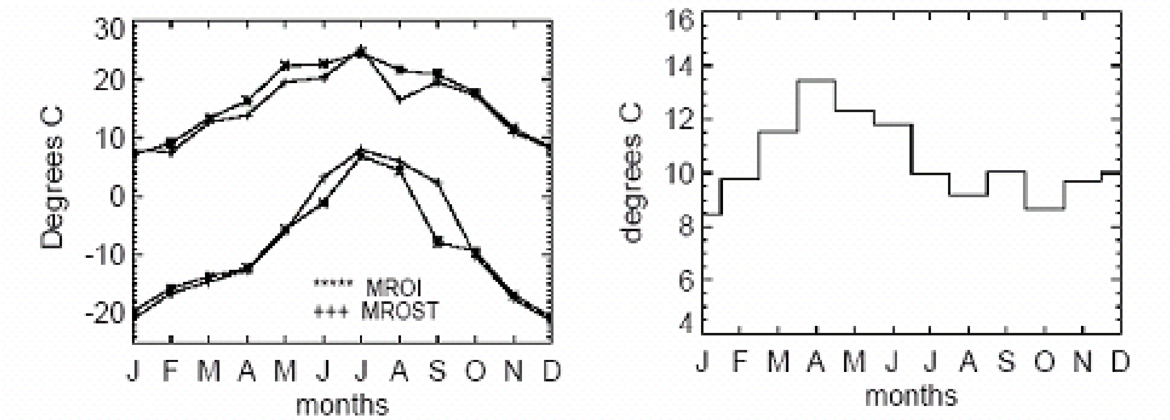

Figure 10.1.0-a: The figure on the left illustrates the temperature extremes for each month at the MRO site, as measured by two separate weather stations (MROI and MROST, with MROI being the more relevant). Note that the maximum temperature for each month almost never occurs on the same day or even year as the minimum temperature. The figure on the right illustrates the maximum daily temperature range at the MRO site. The data for both these graphs was collected from June 2000 through June of 2004

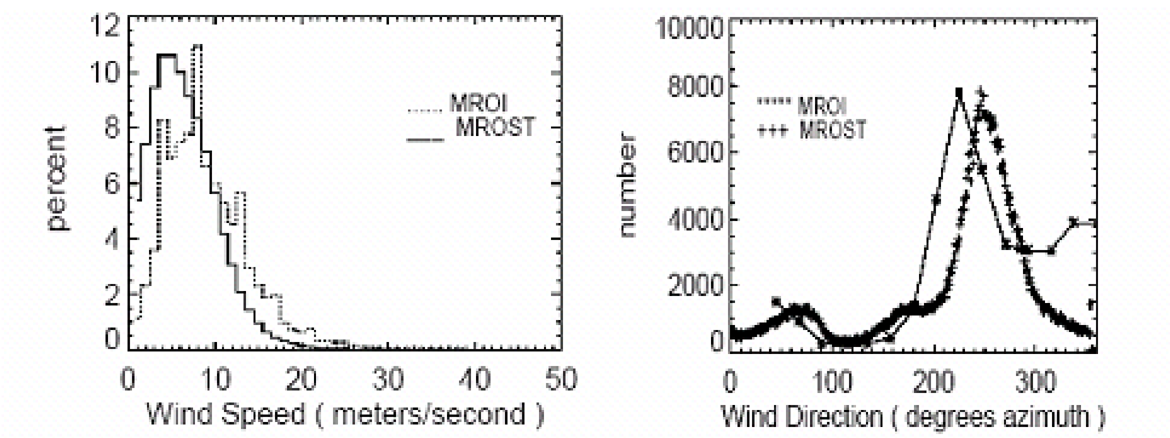

Figure 10.1.0-b: The figure on the left is a histogram of the wind speed measured at two sites on the Magdalena ridge. The figure on the right illustrates that the predominant wind direction on the ridge is from the West or South West. The MROI site is the most relevant to this specification.

The "optimal observing environment" is defined as the environment in which the telescope satisfies all performance specifications described in this document. When these conditions prevail, it can be assumed the telescope enclosure provides no wind shielding in the region around the secondary mirror but does provide a 50% reduction in windspeed when compared with ambient conditions in the region around the primary mirror.

The "reduced performance observing environment" is defined as the environment in which the telescope can be operated, and the allowable mechanical, thermal and electrical stresses in all elements of the telescope are not exceeded. When these conditions prevail, it can be assumed the telescope enclosure provides no wind shielding in the region around the secondary mirror but does provide a 50% reduction in windspeed when compared with ambient conditions in the region around the primary mirror.

The "survival environment" is the environment in which the allowable mechanical, thermal and electrical stresses in all elements of the telescope are not exceeded. The telescope shall[167] be designed and built to survive the expected worst case environmental conditions specified in section 10.5. When these conditions prevail, it can be assumed the telescope enclosure provides an enclosed environment protected from wind and precipitation.

10.3 Optimal observing environment

Time of day	Sun's upper limb below local horizon
Air temperature	-15°C to +20°C
Air temperature rate of change	-1.5°C/hr to +1.5°C/hr
Mean wind speed	1 m/s to 10m/s
Maximum wind gust	15 m/s
Wind gust profile	1 m/s/s linear rise, 1m/s/s linear decay
Altitude	10,000ft to 10,600ft
Relative humidity	10% to 95%
Earthquake load	None

10.4 Reduced performance observing environment

Time of day	Sun < 15 degrees above horizon
Air temperature	-25°C to +20°C
Air temperature rate of change	Unconstrained
Mean wind speed	0 m/s to 17m/s
Maximum wind gust	25 m/s
Gust profile	Unconstrained
Altitude	0ft to 10,600ft
Relative humidity	5% to 95%
Earthquake load	Maximum acceleration less than 0.2g, any axis, in the frequency range 0.5 Hz to 100 Hz

10.5 Survival environment

Air temperature	-30°C to +40°C
Altitude	0ft to 10,600ft
Relative humidity	0% to 100%
Earthquake load	Maximum acceleration less than 0.3g, any axis, in the frequency range 0.5 Hz to 100 Hz

Chapter 11

Delivery and site installation

11.1 Delivery logistics

The Vendor shall[168] deliver and install all telescopes and all related support equipment at the Magdalena Ridge Observatory site on the Magdalena Ridge in Socorro County, NM, USA.

11.1.1 Special tooling

The Vendor shall[169] provide mounting attachments and deliver any special tooling required to ensure the safe transport of the telescope to the Magdalena Ridge Observatory.

11.2 Access to the site

Magdalena Ridge is approximately 28 miles southwest of Socorro, NM. The road from Socorro to the base of the Magdalena Mountains is approximately 20 miles of hard surface public roads that rise gradually from approximately 4,600 ft elevation in Socorro to the about 6,400 feet at the base of the mountain. The remaining $\sim$8 miles to the top is a steep narrow US Forest Service road of compacted crushed soils that rises to the ridge at a final elevation of $\sim$10,600 feet. Sharp bends in the Forest Service road preclude use of trucks longer than about 40 feet.

The trees along the road have been trimmed to allow the passage of vehicles up to 14ft high. A crate measuring 8ft$\times$8ft$\times$25ft and weighing 28,000 lbs has been taken up the road. A semi-cylindrical (i.e. a structure with semi-circular cross-section) structure measuring 10ft wide by 20ft long by approximately 8ft high has been taken up the road.

Vendors intending to deliver loads wider than 8ft or requiring long trailers are encouraged to inspect the road in order to determine the feasibility of delivering their intended load.

Magdalena Ridge has a median wind speed of 15 m.p.h. and the construction season is nominally May through October. The road and ridge are covered with ice and snow in winter and subject to heavy rains, hail and intense lightning from early July through mid-September. The Vendor shall[170] give due regard to the difficulties of constructing a complex apparatus at this altitude. At the time of installation, it is expected that there will be a control building at the array site, with running water, electricity and a connection to the Internet.

Chapter 12

Requirements verification

Verification that the requirements in this document have been met will be made by a combination of reviewing of 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 Acceptance Test Plan developed by the Vendor at Final Design Review (FDR) and approved by the MRO. All tests and their results shall be documented by the Vendor. These tests shall demonstrate that the telescopes perform in accordance with contract specifications.

Preliminary acceptance will be based on Factory Acceptance Tests (FATs) to occur at the Vendor'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). Performing preliminary versions of the SATs at the Vendor's facility is desirable in order to reduce the time needed for on-site testing, but factory tests will not relieve Vendor of the responsibility of performing on-site tests which verify compliance with contract specifications.

The Vendor 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 is a list with references from each "shall" requirement in this specification document. This list 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 summary field is followed by a colon, then a description of the requirement being referred to (the requirement in the main text is to take precedence over the summary description in all cases) optionally followed by a colon and then any explanatory details.

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 MRO will verify whether the requirement has been satisfactorily met by the Vendor. 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) 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 Vendor'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 Vendor'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 of each telescope to the Magdalena Ridge.

Many tests are to be performed only on the first telescope and not on subsequent copies. Requirements which are to be verified on all telescopes are denoted by a '*' at the end of the summary field while requirements which are to be verified on the first telescope only or only as part of the design phase are denoted with a '1'. Subfields corresponding to verifications which are not required are denoted with a dot, so for example the summary field "`D.IF.1`" denotes that verification of this item will be by inspection of the design (`D`), inspection of the as-built component (`I`) and FAT (`F`), and that no analysis (`A`) or SAT (`S`) is required, and that the tests will be done on only the first telescope (`1`). This format allows for the tests of a certain type e.g. SATs to be easily identified by visually scanning down the columns in the following text.

Verification checklist

[1]`D.I..1`: Environmental Impact Statement compliance
[2]`D....1`: Open frame structure
[3]`D....1`: Elevation-over-elevation geometry
[4]`D....1`: Exit beam direction
[5]`D.I..1`: Field of Regard
[6]`D.I..1`: Optical obscuration
[7]`DA...1`: Vignetting
[8]`D.I..1`: Tube offset clear path
[9]`D..FS*`: Slew rates: FAT is only necessary for the first telescope; later telescopes can be verified soley through SAT
[10]`D..F.1`: Pointing sequence

[11]DA..S*: Pointing accuracy after calibration: Sky tests on-site using a minimum sample size of 20 stars

[12]D...S*: Tracking accuracy

[13]DA.FS*: Tracking disturbances: analysis of wind loads and required servo performance, measurements of encoder jitter and servo performance in a wind-free environment

[14]DA...1: Wind shake conditions

[15]DA...1: Wind shake conditions

[16]DA...1: Wind shake conditions

[17]D.I..1: Mount offset commands

[18]D..F.*: Mount response time

[19]D..F.*: Mount overshoot

[20]D..F.*: Mount settle time

[21]D..F.*: Pathlength vibrations: optical metrology and/or accelerometer tests are acceptable

[22]DA.F.1: Pathlength variation with angle: metrology tests of the optical path from the optical table to secondary mirror are acceptable

[23]DA.F.1: Smooth pathlength variation with angle: metrology tests of the optical path from the optical table to secondary mirror are acceptable

[24]DA...1: Pathlength variation with temperature

[25]D....1: Optical table

[26]D.I..1: Optical table location

[27]D.I..1: Optical table fixing holes

[28]DA.F.1: Table resonant frequency: factory test with dummy loads representing MRO instrumentation

[29]D....1: Optical table shock loads ICD

[30]D.I..1: Optical table size

[31]D.I..1: Optical table cover attachment points

[32]D....1: Acquisition telescope

[33]D.I..1: Acquisition telescope clear aperture

[34]D.I..1: Acquisition telescope interface to camera

[35]D...S*: Acquisition camera alignment

[36]D....1: Design for thermal management

[37]D....1: Heat dissipation near beam

[38]D....1: Total heat dissipation

[39]DA.F.1: Temperature of telescope: factory validation using thermal camera

[40]D.I..1: Emissivity

[41]D.I..1: Temperature sensors

[42]D.I..1: Temperature readings available through API

[43]D....1: Temperature accuracy

[44]D....1: Passive primary support

[45]DA.F.*: Primary mirror deformation: factory measurement of defining point loads combined with FEA of mirror

[46]D....1: Primary mirror support telemetry
[47]D....1: Telemetry available through UTCS API
[48]D....1: Primary mirror axial support points ICD
[49]D....1: Primary mirror attachments
[50]D.I..1: Mirror cover
[51]D..F.1: Mirror cover drop test
[52]D.I..1: Mirror cover computer control
[53]D.I..1: Pupil LEDs
[54]D.I..1: Pupil LED location
[55]D.I..1: LED intensity and on/off control: intensity from manufacturer specs, on/off by inspection
[56]D....1: Mirror cell design for CO_2 snow cleaning
[57]D....1: Mirror cell design for drainage of washing liquids
[58]DA...1: Secondary mirror deformation
[59]D....1: Secondary mirror support pads
[60]D.I..1: Secondary mirror adjustment range
[61]D.I..1: Manual decenter adjustment provision
[62]D....1: Secondary mirror actuation resolution
[63]DA.F.1: Stability of secondary position
[64]D....1: Ability to switch off automatic updates to secondary
[65]D....1: FTTA angular range
[66]DA...1: FFTA angular range vs frequency: analysis of mirror drive requirements vs frequency
[67]D....1: FTTA angular resolution
[68]D..F.1: FTTA linearity
[69]D..F.⋆: FTTA response time: in-situ optical or accelerometer tests
[70]D..F.⋆: FTTA overshoot: in-situ optical or accelerometer tests
[71]D..F.⋆: FTTA settle time: in-situ optical or accelerometer tests
[72]DA.F.1: Secondary mirror system structural resonance
[73].A...1: Secondary mirror resonance derogation: inspection of Vendor's closed-loop performance analysis
[74]D..F.⋆: Tilt-to-piston coupling
[75]D.I..1: Secondary mirror LED
[76]D.I..1: LED intensity and on/off control: intensity verified through manufacturers specifications, on/off verified by inspection
[77]DA.F.⋆: Tertiary mirror deformation: FAT is optical measurement of wavefront over central 95 mm diameter region when in the tertiary mirror is in retroreflection mode, and the telescope outer axis is rotated by $\pm 45^\circ$
[78]D....1: Tertiary mirror support pads
[79]D....1: Tertiary tracking error
[80]DA..S1: Tertiary mirror pointing error
[81]D.I.S⋆: Tertiary tube-offset mode
[82]D.IF.1: Tertiary mode switching time

[83]D...S1: Tube-offset mode pointing and tracking
[84]D....1: Tube-offset mode offset commands
[85]D.I..1: Retro-reflection mode
[86]D..F.1: Retro-reflection adjustment
[87]D..F.1: Pilot beam scattering
[88]D..FS⋆: Pupil stability
[89]D....1: Telescope-enclosure ICD
[90]D....1:Telescope clearance envelope
[91]D....1: Electronics housing ICD
[92]D....1: Relocation lift points
[93]D....1: Telescope relocation plan
[94]D....1: Vendor review of enclosure and transporter design
[95]D....1: Secure for relocation
[96]D.I..1: Supply of relocation clamps
[97]D..F.1: Personnel for relocation
[98]D..F.1: Time for relocation
[99]D....1:Telescope pier ICD
[100]D....1: Vendor review of pier design
[101]D....1: Telescope footprint
[102]D.I..1: Supply of pier locating points and installation procedure
[103]D.I..1: Lifetime of pier locating points
[104]D.I..1: Supply of installation jig
[105]D....1: Locating points installation procedure
[106]D.I..1: Supply of locating jig
[107]D....1: Method of locating nominal pivot point
[108]D....1: Method of computing nominal pointing models
[109]D....1: Locating jig reference beam
[110]D.I..1: Reference beam properties
[111]D...S⋆: Telescope exit beam accuracy: test first telescope on at least 3 different piers, subsequent telescopes on at least 1 pier
[112]D...S⋆: Nominal pointing model accuracy: test first telescope on at least 3 different piers, test subsequent telescopes on at least 1 pier
[113]D..F.1: Relocation accuracy
[114]D.I..1: Electrical supply
[115]D.I..1: Grounding
[116]D....1: Ground loops
[117]D....1: Additional grounding as part of telescope-enclosure ICD
[118]D.I..1: Network interface
[119]D....1: Network interface specification
[120]D.I..1: Cable space
[121]D.I..1: Cable spare space
[122]D.I..1: Cable accessibility
[123]D....1: Software documentation

[124]D.I..1: UTCS operation of all functionality
[125]D.I..1: UTCS GUI
[126]D....1: UTCS independent operation
[127]D.I..1: UTCS local and remote operation
[128]D.I..1: UTCS power-up
[129]D.I..1: Remote monitoring
[130]D.I..1: Remote reboot
[131]D....1: API documentation
[132]D..F.1: API control of functionality
[133]D..F.1: API access to telemetry
[134]D....1: Motion control parameters
[135]D..F.1: API access to diagnostics
[136]D..F.1: Configuration management
[137]D....1: Configuration documentation
[138]D....1: FTTA control interface
[139]D....1: Mount offset control interface
[140]D.I..1: GPS receiver
[141]D....1: GPS integration
[142]D.I..1: GPS hardware timing signal
[143]D....1: Fire and safety codes
[144]D.I..1: Limits and interlocks
[145]D.I..1: Telescope stops
[146]D.I..1: Stop alert
[147]D..F.⋆: Stop stresses: intentional operation to activate the stops
[148]D..F.⋆: Clamps: intentional out-of-balance conditions
[149]D..F.1: Protection: issuing intentionally inappropriate commands
[150]D....1: Maintenance lifetime
[151]D....1: Maintainability estimation
[152]D....1: Maintenance terms
[153]D....1: Maintenance resources
[154]D....1: Maintenance procedures
[155]D....1: Maintenance procedures
[156]D....1: Spare parts list
[157]D....1: Spare parts list
[158]D.I..1: Training: satisfactory completion of training
[159]D.I..1: Training: satisfactory completion of training
[160]D.I..1: Training: satisfactory completion of training
[161]D....1: Training certification
[162]D..F.1: Mirror removal: full demonstration at factory of primary, secondary, and tertiary mirror removal and replacement
[163]D..F.1: Mirror removal time
[164]D.I..1: Mirror removal equipment
[165]D....1: Documentation

[166]`D....1`: ICDs
[167]`D....1`: Design for survival conditions
[168]`D.I..1`: Delivery and installation: review of installation plan and all equipment arrives at Magdalena Ridge
[169]`D.I..1`: Special tooling
[170]`D....1`: Due regard to environment: inspection of delivery and installation plan

Appendix A

Technical background

A.1 Preamble

This appendix does not serve to specify any telescope 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.2 System calibration and observing scenarios

The performance required of the telescopes in terms of pointing accuracy, wavefront quality and pathlength stability will be achieved in part by an extensive calibration scheme which involves the whole interferometer, including the unit telescopes. This section serves to indicate the typical procedure that will be used to calibrate the unit telescopes in a way that links the calibration of the telescopes to the calibration of the rest of the interferometer. It also serves to illustrate the expected sequence of telescope operations for normal science observations.

The pointing calibration will involve a number of different pointing sensors. These will include the following three generic functions and their likely implementations:

1. A wide-field acquisition sensor (WAS), consisting of a finder telescope and CCD camera attached to the side of the telescope. The camera will have a plate scale of 1 arcsecond/pixel and will have 512x512 pixels, yielding a field of view of slightly over 8×8 arcminutes. A full-frame readout will take less than 2 seconds and sub-frame modes with higher speeds will be available.

2. A narrow-field acquisition sensor (NAS) mounted on the "Nasmyth" optical table of the telescope. This is currently envisaged to be exactly the same sensor as the tip/tilt sensor, with a plate scale of 0.2 arcseconds/pixel and a field of view of

512x512 pixels, i.e. about 102x102 arcseconds. The full-frame readout time for this camera is expected to be less than 100 milliseconds.

3. A fast tip/tilt sensor (FTTS) consisting of an electron-multiplying CCD with a plate scale of 0.2 arcseconds/pixel and operating in a sub-framing mode with sub-frame sizes of 10x10 pixels, i.e. 2x2 arcseconds. The sub-frame readout time is expected to be less than 2 milliseconds.

A normal sequence of observations for a night will start with a system calibration phase followed by a sequence of target observations that continue for the rest of the night. The calibration scenario described below represents an upper limit on the number of calibration steps needed for normal observation. It is expected that some of these steps would be omitted if the telescope and/or the calibration systems were found to be sufficiently stable on a night-to-night basis.

A.2.1 System calibration

At the start of the night, the following sequence of operations will take place to calibrate the unit telescopes.

1. A collimated beam of light will be sent from the central beam-combining facility out to all the telescopes. Mirrors in the interferometer beam train will be adjusted so that the direction of this reference beam as it enters the telescopes will be along the direction of the telescope outer axis. The direction of this reference beam will define a "reference direction" against which the telescope pointing will be calibrated.

2. The telescope tertiary mirror will be rotated until the reference beam is retro-reflected back on itself. (If necessary, this can be used to set the zero point of the tertiary mirror encoder.)

3. An image of the reference beam as seen on the NAS and the FTTS will be used to set the zero points of these respective cameras.

4. The reference beam will be switched off.

5. The telescope will slew to a suitable bright star.

6. Having reached the nominal pointing direction of the star and commenced tracking, an exposure will be taken on the WAS and the offset of the bright star from the center of the WAS field will be used to send offsets to the UTCS to center the image of the star in the WAS.

7. At this point, a manoeuvre we have chosen to call a "tube-offset" will take place, the net effect of which is to move the telescope secondary mirror out of the way

so that a hypothetical observer looking along the reference direction could see the starlight directly via the tertiary mirror i.e. unmagnified by the telescope primary-secondary mirror pair. The manoeuvre consists of offsetting the inner axis of the telescope by an angle of a few degrees, while keeping the tertiary tracking so that light from the nominal star position is reflected parallel to the reference direction.

8. A sequence of exposures on the NAS will be used to send offset corrections to the tertiary mirror until starlight is travelling within ± 1 arcseconds of the reference direction.

9. The starlight will be intercepted by a wavefront sensor located in the beam combining building and this light will be used to calibrate the wavefront sensor.

10. The “tube-offset” will be reversed to allow the starlight to come through the telescope primary, secondary and tertiary mirrors onto the NAS. (The secondary tip/tilt actuator will have been commanded to be in the middle of its range).

11. A sequence of exposures on the NAS will be used to correct the offset of the telescope tube (i.e. the primary-secondary pair) until starlight is travelling within +/- 1 arcseconds of the “reference direction”.

12. Focus information from the wavefront sensor will be sent as focus correction commands to the telescope.

13. Optionally, collimation corrections to change the primary-secondary alignment for optimum wavefront quality will also be sent to the telescope.

14. At the same time, a reference exposure will be taken on the WAS to measure the offset between the WAS and the NAS for this pointing direction, and the offsets of the tube and tertiary axis rotations from their values as predicted by the telescope pointing model will be recorded and used as necessary to update the telescope pointing model.

15. The FTTS will be switched on, and the information from this will be used to drive the secondary mirror of the telescope to correct fast atmospheric tilt errors. Any large slow tilt offsets of the secondary mirror will be offloaded as offset corrections to the telescope mount.

16. The wavefront sensor pickoff will be removed from the starlight beam. In parallel, all the other telescopes in the array will have been performing the above sequence. The delay lines and fringe acquisition sensors in the beam combining building will now be used to find starlight fringes between all pairs of telescopes and any offset of the white-light fringe positions from the nominal positions will be noted.

17. Steps 5-16 will be repeated (with the exception of steps 12 and 13) for a sequence of 4-10 bright stars spread over the sky.

18. The offsets recorded during the above sequence will be used to derive corrections to the telescope pointing model, using Vendor-supplied software in the UTCS, and corrections to the interferometer baseline model (i.e. the center-to-center vectors of all pairs of telescopes in the array), using MRO-owned baseline-fitting software.

We refer to the above sequence as the start-of-night calibration sequence. Our goal is to keep the duration of this sequence below 45 minutes. Automation of this process is essential to completing the sequence in the required time, and this will be accomplished by the MRO-owned ICS interacting with the Vendor-supplied UTCS via the interface detailed in chapter 8.

It is envisaged that the above sequence, when performed immediately after the telescope has been moved to a new location, will take longer than usual because the starting pointing model is in greater error than usual. Our goal is that the start-of-night sequence will not take more than 2 hours under such circumstances.

A.2.2 Observing sequence

Having performed the start-of-night sequence, the rest of the night is spent on a normal observing sequence, which consists of a repeated set of observations of target objects.

A typical observation in this sequence will consist of the following sequence of steps:

1. The observation of the previous target will be terminated and the telescope will be commanded to slew to a new target, on average 5-10 degrees away. The secondary mirror tip/tilt actuator will be set to its neutral position.

2. Having reached the nominal pointing direction of the star and commenced tracking, an exposure will be taken on the NAS camera. A sequence of exposures on the NAS will be used to make pointing adjustments until the starlight is travelling within +/- 1 arcseconds of the reference direction.

3. The FTTS will be switched on, and the information from this will be used to drive the tip/tilt secondary mirror actuator to correct fast atmospheric tilt errors. Any long-term tilt offsets of the secondary mirror will be offloaded as offset corrections to the telescope mount.

4. In parallel, all the other telescopes in the array will have been performing the above sequence. The delay lines and fringe acquisition sensors in the beam combining building will now be used to find starlight fringes and collect science data.

5. At the end of the interferometric observation, the tip/tilt system will be switched off and all tracking corrections stopped before the slew to the next target.

The cadence of these observations will depend on the brightness of the objects and the variability of the atmospheric conditions, but typical on-source dwell times of between 60 and 600 seconds are envisaged, with less than 60 seconds between the end of one observation and the start of another.

A.3 Atmospheric seeing tip/tilt model

We assume a standard Kolmogorov turbulence model for the atmospheric seeing, characterized by values of the Fried parameter (r_0) in the range 20cm$>$ r_0 $>$5cm, with r_0 being defined at a wavelength of 500nm. This is approximately equivalent to a FWHM of the long-exposure seeing disk in the range 0.5 to 2 arcseconds. The resulting worst-case (two-axis) RMS atmospheric tip/tilt jitter, corresponding to a seeing disk FWHM of 2 arcseconds, is 0.71 arcseconds.

The models for the temporal variation of the seeing-induced tilt errors depend on the details of the wind-velocity distribution as a function of height. For the purposes of this specification, we have adopted the model for the power spectrum of the tilt fluctuations $\Theta(f)$ which is given by

$$\Theta(f) \propto \begin{cases} (f/f_1)^{-2/3} & \text{for } f < f_1 \\ (f/f_1)^{-8/3} & \text{for } f > f_1 \end{cases} \tag{A.1}$$

where $f_1 = 2\,\mathrm{Hz}$. The form of this spectrum is shown in Figure 4.5.1. The seeing is assumed to be isotropic, so that the RMS motion in a single axis ("tip" or "tilt") is $1/\sqrt{2}$ times as much as the the total RMS motion for a given value of the seeing.

A.4 Tip/tilt servo system model

The servo loop consists of an MRO-owned fast tip/tilt sensor being read out at rates of up to 1kHz and an MRO-owned servo controller which splits the integrated tilt errors into high-frequency and low-frequency components. It sends the high-frequency error components to the Vendor-supplied fast tip/tilt secondary mirror and the low-frequency components as offset commands to the Vendor-supplied telescope mount control system.

A possible implementation of the tip/tilt servo loop is shown in Figure A.4.0-a, which shows some of the internal detail of the telescope mount control loop. The loops controlling the tip/tilt (i.e. tracking) errors are modelled as pairs of parallel single-input-single-output (SISO) servos, one for each of the two orthogonal tracking axes labelled tip and tilt: only one of these is shown in the figure, the other being assumed to be identical.

For the purposes of setting the performance parameters of the tip/tilt servo and the telescope, the control system in Figure A.4.0-a has been further simplified to the system shown in Figure A.4.0-b. The simplification serves to remove the dependence

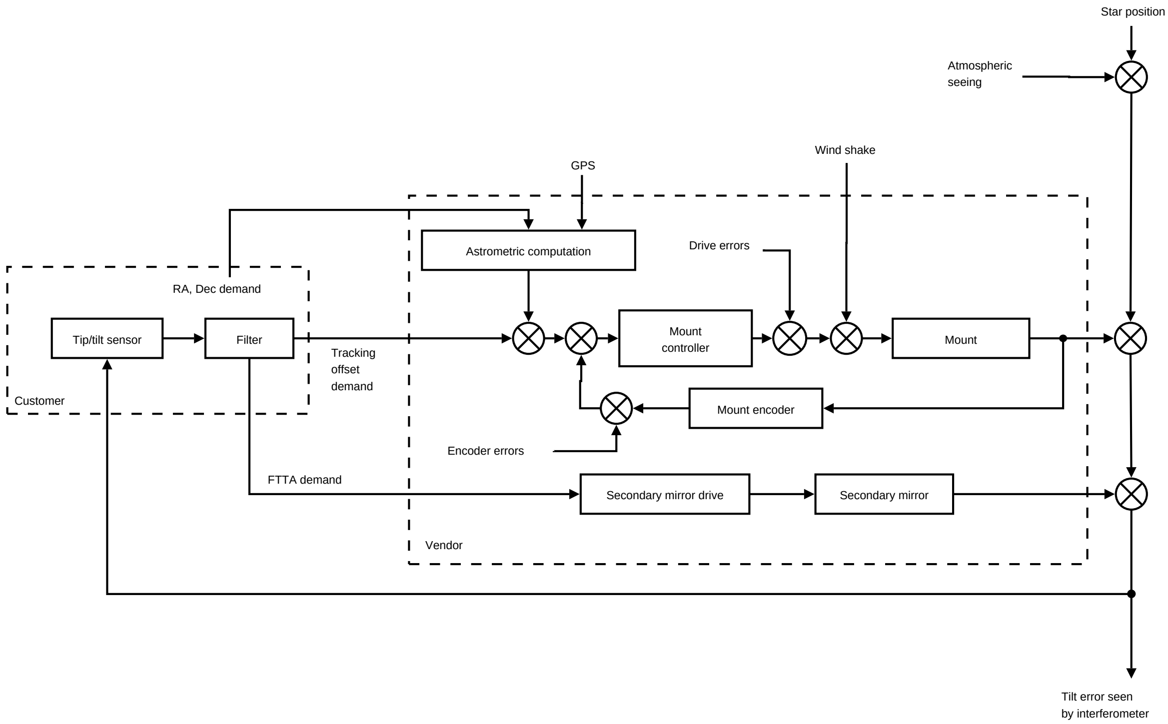

Figure A.4.0-a: Model of telescope and tip/tilt correction servo system

on any particular design of the control loops internal to the telescope, and moves the wind shake and other disturbance sources which are filtered by the mount control loop out of that loop.

In the simplified control loop model, the sources of disturbance which must be rejected by the MRO-owned control system are:

1. The tip/tilt component of the atmospheric seeing, as detailed in section A.3.

2. The effects of any encoder errors, drive errors or astrometric errors (including pointing model errors) as filtered by the telescope mount servo loop and mount structure, hereafter termed the "mount error residuals"

3. The effects of wind-shake on the telescope structure, as filtered by the telescope mount structure and mount servo loop, hereafter referred to as the "wind-shake residuals".

In modelling the servo loops in this system, we assume that all control loops are sampled at a frequency greater than 10 times the bandwidth of the relevant loop ($f_{3\mathrm{dB}}$ defined below), and so they can be approximated as continuous-time servos.

The dynamics of the relevant actuators in the control loops (FTTA for the fast loop, telescope mount and control system for the slow loop) are modelled by assuming that the first pole of the actuator response is at a frequency at least 5 times $f_{3\mathrm{dB}}$

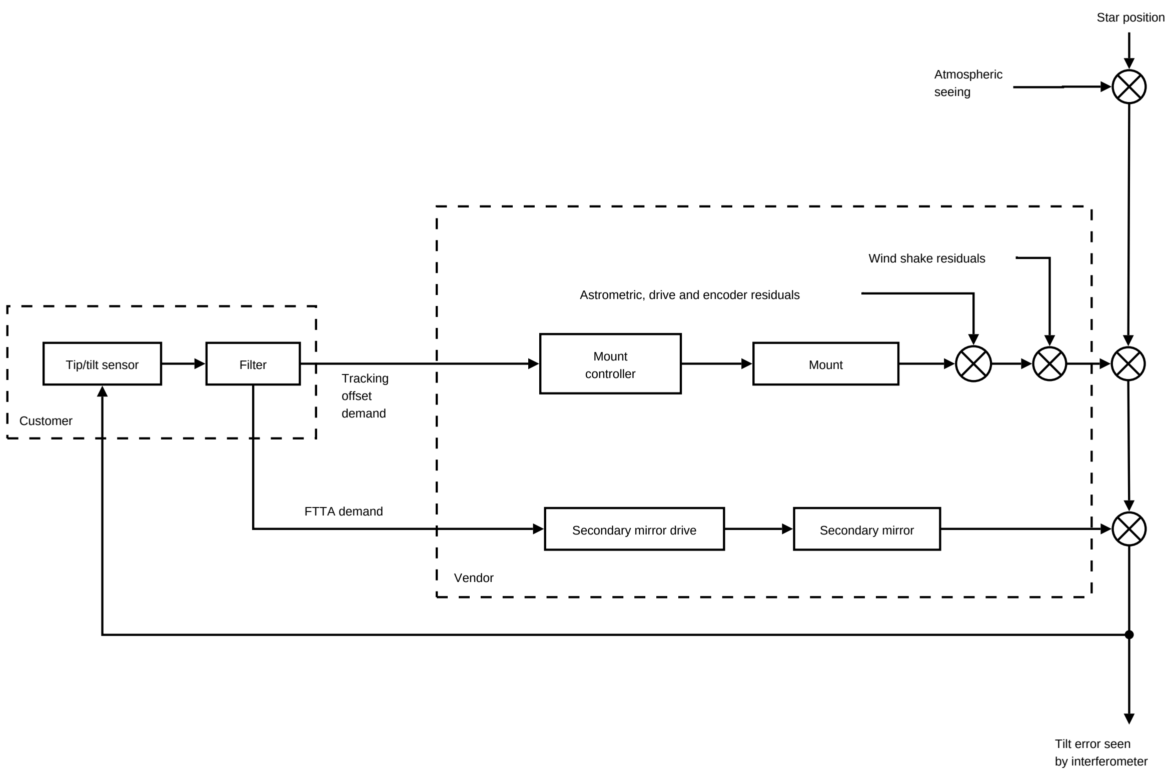

Figure A.4.0-b: Simplified tip/tilt control loop model

i.e. the actuator will give a 95% response to a step input in a time of approximately $1/f_{\rm 3dB}$ if the pole is first-order. This assumption means that a complex control loop design is not needed in order to compensate for actuator dynamics.

The MRO-owned control loops are modelled as a pair of cascaded control loops: a fast loop which tries to null the output of the fast tip/tilt sensor using the Fast Tip/Tilt Actuator (FTTA) on the secondary mirror, and a slow loop which tries to null the position of the FTTA by sending tracking offset demand signals to the telescope mount controller. The loop bandwidths are different by orders of magnitude, so they are approximated as independent loops.

Both loops are modelled as first order servos with open loop frequency responses given by

$$G(f) = i f_{\rm 3dB}/f$$

where $f_{\rm 3dB}$ is the bandwidth of the servo. For input tilt disturbances (whether atmospheric tilt perturbations, telescope mount residuals or telescope wind shake residuals) with spectral content $y_1(f)$ the MRO-owned servo loop will remove the low-frequency content of the disturbance to yield a residual tilt disturbance $y_0(f)$

which is a high-pass-filtered version of the input disturbance, i.e.

$$y_0(f) = \frac{y_1(f)}{1 + if_{3\mathrm{dB}}/f}$$

The fast loop has a bandwidth of 10 Hz < $f_{3\mathrm{dB}}$ < 50 Hz, depending on the brightness of the star being observed. The tracking residuals from this loop will determine the net RMS tilt error seen by the interferometer. For bright stars in poor seeing, $f_{3\mathrm{dB}}$ is set to 50 Hz, and this sets the maximum required frequency response for the secondary mirror fast tip/tilt actuator (FTTA). For the faintest stars in good seeing, $f_{3\mathrm{dB}}$ is set to 10 Hz, and this sets the requirement for the worst case high-frequency telescope jitter in Table 2.6.3.

Given the servo model assumed here and the atmospheric model in section A.3, the RMS residual atmospheric seeing tip/tilt jitter is approximately 0.04 arcsec when $f_{3\mathrm{dB}} = 10$ Hz and $r_0 = 20$cm, and also when $f_{3\mathrm{dB}} = 50$ Hz and $r_0 = 5$cm. Together with the high frequency telescope jitter in Table 2.6.3, this leads to an overall tip/tilt error of approximately 0.05 arcsec RMS.

The slow loop has a fixed bandwidth of $f_{3\mathrm{dB}} = 0.1$ Hz. The tracking residuals from this loop will determine the peak-to-peak excursion of the FTTA. For the purposes of setting requirements for the FTTA, it has been assumed that the atmospheric seeing jitter takes its worst-case value of 0.71 arcsec RMS. We make the approximation that this jitter all takes place at frequencies between 0.1 Hz and 10 Hz. The atmospheric seeing and the telescope tracking errors given in subsection 2.6.3 add in quadrature to give 2 arcseconds RMS total tracking error that must be compensated for by the FTTA, i.e. single-axis value of 1.4 arcsec RMS.

Adopting a ratio between the peak-to-peak excursion and the RMS of 6:1 gives a peak-to-peak single-axis excursion of 8.4 arcsec on the sky, corresponding to a 62 arcsecond peak-to-peak motion of the secondary mirror. An engineering margin of approximately 60% has been added to give a total FTTA actuation range requirement of 100 arcseconds i.e. $\pm$50 arcseconds of travel.

On the assumption that the spectral characteristics of the telescope residual mount error and wind shake disturbances are similar to that of the atmospheric seeing tip/tilt component, the spectrum in Equation A.1 is scaled appropriately to yield the requirement for the angular range of the FTTA in Table 4.4.1 and the input spectrum for the tilt-to-piston crosstalk requirement in subsection 4.5.1.