MRO FTT/NAS & FLC

FTT/NAS Interim Testing Report

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The Cambridge FTT Team

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ASTROPHYSICS

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Change Record

Revision	Date	Author(s)	Changes
0.1	2011-12-14	JSY	Outline, based on Interim PDR Report outline
0.2	2011-12-15	CAH	Initial draft content
0.3	2011-12-22	CAH	First draft of main text
0.4	2011-12-22	CAH	Added JSY & MF corrections
1.0	2011-12-22	JSY	Added conclusions; final corrections

Objective

To report the current status of the PDR-phase testing of the prototype FTT/NAS opto-mechanical components.

Scope

This document outlines the preliminary designs of the prototype FTT/NAS optic mounts and describes the procedures and apparatus used for laboratory tests of their thermal stability. Initial results from these tests are summarized and the plan for further testing during the remainder of the PDR phase is presented. The other aspects (such as camera readout and software) of the FTT/NAS system design will be described at PDR.

Acronyms and Abbreviations

CTE	Coefficient of Thermal Expansion
DLT	Dog-Leg Transmissive (layout)
FTT	Fast Tip-Tilt
FLC	First Light Camera
LVDT	Linear Variable Differential Transformer
MROI	Magdalena Ridge Observatory Interferometer
NAS	Narrow-field Acquisition System
NMT	New Mexico Tech
PDR	Preliminary Design Review
TBC	To be confirmed
TBD	To be determined
UT	Unit Telescope

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1 Introduction

This report presents an update of the testing activity associated with the MROI Fast Tip-Tilt/Narrow-field Acquisition System, currently being developed by the University of Cambridge-based team at the Cavendish Laboratory, UK. Although considerable work has been undertaken on multiple aspects of the FTT/NAS, for example in the areas of opto-mechanical design, algorithm design, camera readout and software implementation, we focus here exclusively on the component-level testing of the prototype opto-mechanical mounts that have been designed to hold the optical elements of the system. Details of these other tasks, together with system-level opto-mechanical testing, will be presented at the Preliminary Design Review.

As was made clear at the Conceptual Design Review, the top level requirements for the FTT/NAS lead to very challenging requirements on the stability of its optical components when located at ambient conditions on the UT Nasmyth Table. Our proposed solution strategy at that time was to utilise a folded optical path with a transmissive focusing optic, with all the optical components, save the camera head itself, being mounted on a single compact base-plate (see Fig. 1). Our concept for the overall opto-mechanical system design has not changed from this initial “dog-leg transmissive” (DLT) layout and the test results reported below are compared with the requirements of this baseline implementation.

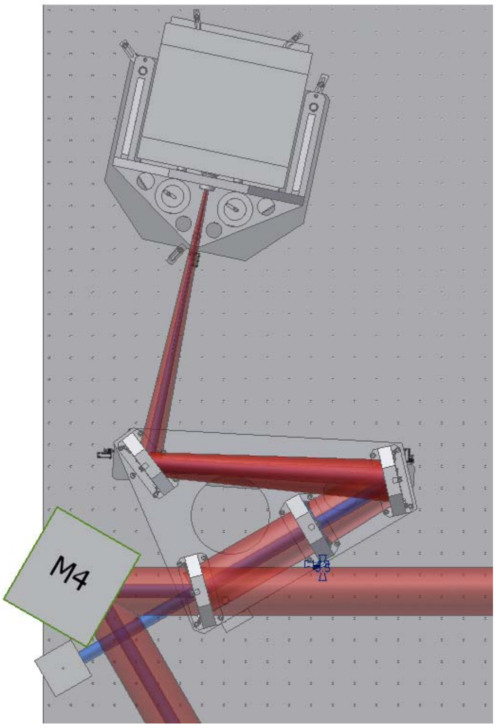

Fig. 1: A schematic diagram outlining the core elements of the current FTT/NAS opto-mechanical design. The beam from the UT tertiary mirror enters from bottom right and is intercepted by the dichroic to the right of the M4 mirror. The reflected beam passes through an apochromatic lens, and is focused onto the FTT/NAS camera sensor (at top) after reflection off two fold mirrors. All four of the mounts for these optical components are co-mounted on a single triangular base-plate that is kinematically located on the Nasmyth optical table.

The three key elements of our strategy for maintaining optical stability have been to design mounts that are as simple as possible, that have no adjustable sub-assemblies, and that are as symmetric as possible (so as to minimize the consequences of potential thermal gradients). Both the dichroic/mirror mounts and lens mount share this design approach and, as will become apparent below, are very similar in bulk form.

In the Derived Requirements document (MRO-TRE-CAM-0000-0101) a global error budget was presented for the individual component stabilities for the favoured DLT layout. This is repeated below for completeness, but provides a useful reference to which the test results can be compared. The only substantive change since the CoDR has been a small tightening of the focus tolerance of the optical system based on our latest lens optical design which has a slightly poorer depth of field, but lower fabrication costs.

Element	Degree of freedom	Allocation to global stability budget
Dichroic	$\Delta\theta_x$	0.047″
	$\Delta\theta_y$	0.045″
Focusing optic	Δx	0.47 μm
	Δy	0.35 μm
	Δz	**140 μm**
	$\Delta\theta_x$	0.75″
	$\Delta\theta_y$	0.70″
Fold mirror #1	Δz	0.59 μm
	$\Delta\theta_x$	0.090″
	$\Delta\theta_y$	0.049 ″
Fold mirror #2	Δz	0.31 μm
	$\Delta\theta_x$	0.064″
	$\Delta\theta_y$	0.074″
Camera mount	Δx	0.47 μm
	Δy	0.35 μm
	$\Delta\theta_z$	2.32″
	Δz	**140 μm**

Table 1: The budget allocations for the DLT optical layout as based on the top level design requirements for the FTT/NAS. In each case the optic must not move by more than this amount for a 5 ℃ change in temperature. Values in bold text have been updated from those presented at the CoDR (see MRO-TRE-CAM-0000-0101). The co-ordinate system used has the z-direction normal to the named optical component, and the x- and y-directions perpendicular to this. In all cases, the x-direction is perpendicular to the surface of the Nasmyth optical table.

The remainder of this document is structured as follows. In Section 2 we explain the basic experimental strategy adopted for our opto-mechanical testing and present the results of the three most critical tests of mount performance that have been undertaken so far. In each case the results are compared against the requirements of Table 1. Our conclusions are presented in Section 3 together with our commentary on these results, our schedule for further opto-mechanical tests and the prospects for further risk mitigation.

2 Opto-mechanical tests

The fundamental stability requirements for the optical components of the FTT/NAS are associated with its primary use case in which the tilt of an incoming beam of light from a UT must be maintained so as to be equivalent (at a level of 0.015″ on the sky) to that of a fiducial beam generated in the late afternoon prior to observing in the night. The need to maintain this “zero-point” stability over the course of the night when the ambient temperature is expected to change by up to 5°C (at a rate of up to 1.5°C/hour) is the most challenging aspect of the opto-mechanical design of the overall system[1].

Table 1 shows the flow-down of this high-level requirement to the stability of the various optical elements

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[1] The M4 and M5 turning mirrors are subject to an equivalent stability requirement, and so the results of our testing are likely to be of interest those responsible for that MROI sub-system.

that intercept the beam in the current FTT/NAS design along its path from M3 to the FTT/NAS camera head. The most critical requirements can be summarised as follows:

- Dichroic – tilts perpendicular to the beam propagation direction;
- Focusing optic – shear in the directions perpendicular to the beam propagation direction;
- Fold mirror 1 – tilts perpendicular to the beam propagation direction and piston motion along the beam propagation direction;
- Fold mirror 2 – tilts perpendicular to the beam propagation direction and piston motion along the beam propagation direction;
- Camera mount – shear in the directions perpendicular to the beam propagation direction.

Our testing activity has focused on assessing to what extent the prototype optical component mounts of the FTT/NAS are able to meet these stability requirements in the presence of the temperature changes expected at the Magdalena Ridge. To this end we have designed and fabricated an environmental chamber within which the mounts can be placed, and which allows for optical and mechanical interrogation of the optics and mounts, as well as adjustment of their temperature.

In subsection 2.1 below we describe the design and operation of this thermal test facility, while in the following three subsections we detail the test procedures and results obtained to date on the dichroic mount tilt stability (sub-section 2.2), the focusing lens mount shear stability (sub-section 2.3) and the fold mirror mount piston stability (sub-section 2.4).

The reader should note that the dichroic and fold mirror mounts are identical in design, and so the tests of the stability of the dichroic mount in tilt can be used to assess the tilt stability of the fold mirror mounts which have a slightly less stringent stability requirement. Similarly, the lens and dichroic/fold mirror mounts share a common design for the hard mounting of the optical components, and so we have not yet explicitly tested the tilt stability of the focusing lens mount but instead have focused on the much more challenging (roughly ×15 more stringent) stability requirement for the dichroic/fold mirror mount.

The FTT/NAS camera mount is currently being fabricated, and so it has not been possible to present any stability test results for this hardware component in this document. However, the most stringent stability requirement for this mount is **not** that it maintain the location of the camera head to ± 0.4 μm in the x- and y-directions in an inertial reference frame, but rather that the motion of the camera head in the x- and y-directions mimics that of the vertex of the focusing lens in its mount. Both the camera and focusing lens mounts will be fabricated out of the same batch of stress-relieved Aluminium and so the most relevant test results in this regard are those in sub-section 2.4 which aim to assess to what extent the vertex of the focusing optic maintains its centration in its mount as the temperature changes.

2.1 Thermal test facility

A pair of diagrams showing the basic structure of the thermal test facility is shown in Fig. 2. Its basic structure is that of a heat exchanger enclosed within a chamber formed by panels of insulation. The heat exchanger is mounted on an aluminium base-plate and consists of three sections of connected cold plates arranged in an inverted U fashion. This forms a frame which is large enough to accommodate any of the test mounts and measurement devices. To improve heat transfer the inside faces of the cold plate sections are fitted with finned heat sinks. Tubing connects the cold plates so that water can be circulated through the heat exchanger from an external temperature-controlled recirculating chiller unit. In addition, two small fans are mounted on the base-plate to prevent temperature gradients from developing within the enclosure.

The frame sits on a panel of insulation to prevent any substantial heat transfer to the optical table on which the apparatus is mounted. Other panels of insulation are glued into position to form a rigid frame to which removable front and rear panels can be attached to form a sealed box. The rear panel has small apertures through which the cooling pipes and power and signal cables pass, while the front panel has large apertures to allow an optical beam to be passed to specific areas of the chamber. A smaller panel with a single aperture into which a window is fitted is used to seal one of the apertures in the front panel while allowing light through the other aperture. The component mount to be tested is usually placed on an aluminium platform so that measurement probes can be inserted into the base of the mount for some of the testing.

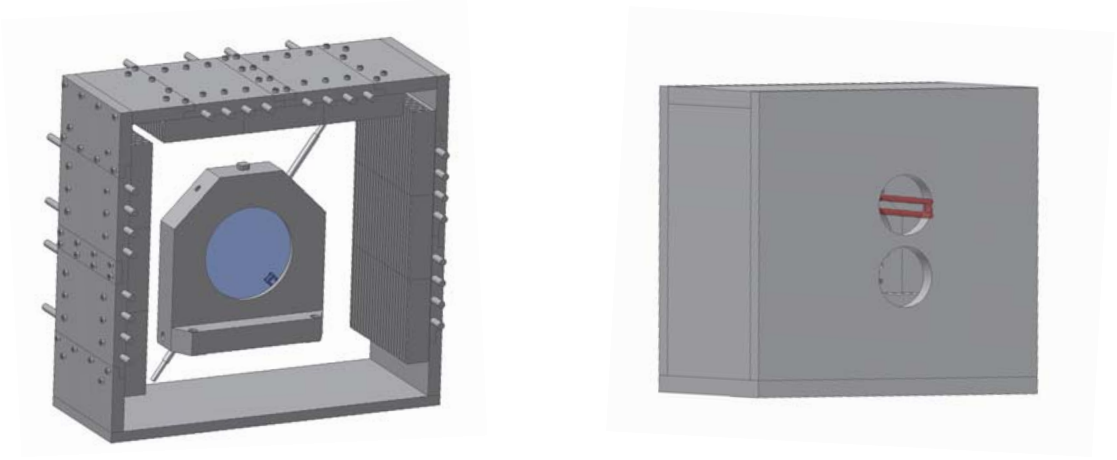

Fig. 2: Schematic diagrams showing the basic structure of the thermal test facility. The image at left shows the interior components of the chamber, i.e. the U-shaped series of cold plates with their finned heat sinks, together with a "floating" focusing lens mount and two LVDT sensors attached. The right hand cartoon depicts the exterior of the chamber and shows the two entrance apertures and a pair of light beams in red. Normally, one of the apertures is sealed with insulating material while the other allows light in/out via a fused silica window.

The broad approach we have used for the majority of our tests has been to introduce the mount under test into the chamber and then to cool it down relatively rapidly to typically 10–15°C below ambient. The temperature is then held there for an hour or two at a stable equilibrium and thereafter the component is allowed to warm up to room temperature at a rate of typically 1.5°C/hour, i.e. at a rate comparable to that expected in the Magdalena Ridge. Measurements are normally made in a temperature controlled room, for the whole temperature cycle, and repeated several times to check the reliability of the data.

The range of temperature excursion used in the tests, i.e. at least 10°C, is greater than that demanded by the requirements themselves[2], but allows for a larger signal to be detected by the test apparatus.

2.2 Dichroic/fold mirror mount tilt stability test

The dichroic/fold mirror tilt stability requirement has been by far the most challenging to both test and meet. The requirement corresponds to a tilt stability of roughly one-twentieth of a second of arc in the directions perpendicular to the beam propagation direction for a 5°C temperature swing. This angle corresponds to a motion of only a few tens of nanometres across the edges of a 125 mm diameter optic. In the sub-sections below we summarise the key design elements of the dichroic/fold-mirrror mount design, describe our test setup and present our test results with some commentary.

2.2.1 Mount design

Our prototype dichroic/fold mirror mount is shown schematically in Fig. 3. This is a monolithic symmetric aluminium component in which the front reflective surface of the optic (dichroic or fold mirror) is sprung loaded onto three symmetrically disposed hard points. These define the orientation of the reflecting surface in the θ_x and θ_y directions, i.e. perpendicular to the beam propagation direction. The optic is supported at its base on two machined surfaces of the mount and is lightly sprung loaded from the top so as to restrain it from moving in the vertical direction – the associated spring plunger can be seen at the very top of the mount in both panels of Fig. 3.

In the presence of temperature changes the whole of the mount is designed to expand about its centre. The

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[2] These specify the maximum allowable component motion over a 5 degree Celsius temperature swing.

mount has the optical hard points located in the central plane of the mount so that as the mount expands and contracts, the angle of the optic should not change. However, if the mount deforms, i.e. the initial central plane of the mount warps on expansion or contraction, this would likely lead to the mount not meeting its stability requirements[3].

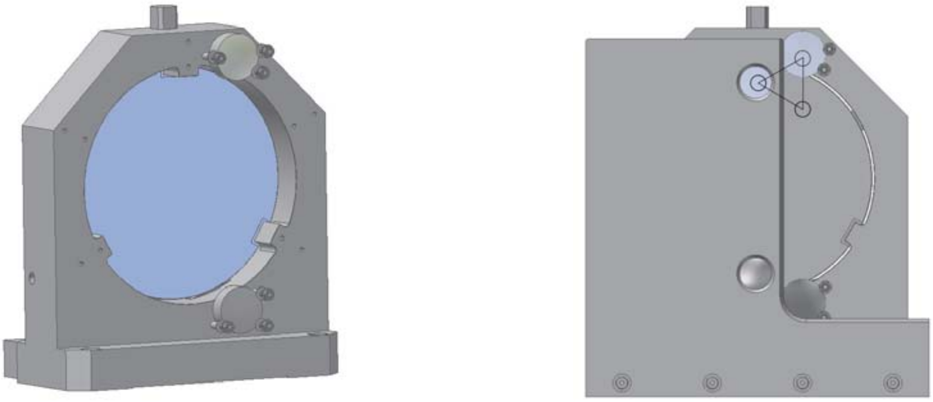

Fig. 3: Two views of the solid aluminium dichroic/fold mirror mount. The three hard points on which the optic is located can be been in the left hand panel, which also shows the two aluminium "reference" mirrors that can be attached to the mount, towards the right at top and bottom, for testing. The right hand view shows a face-on view of the mount seated on its L-shaped invar "reference bracket" with its own two reference mirrors. The circles at the vertices of the triangle at the top of the figure shows the footprints of the collimated probe beams that can be used to measure the relative tilt of the top of the dichroic relative to the mount or invar reference (see text for details).

2.2.2 Test & test results

The basic test setup we have been using to assess the dichroic/fold mirror tilt stability is outlined in Fig. 4. This is a differential test in which a collimated beam from a laser is split into two, and these two probe beams are then sent so as to reflect off both the dichroic/mirror under test and a chosen reference surface. This can be either an aluminium mirror mounted directly on the aluminium mount (see Fig. 3) or a fused silica mirror mounted directly on an invar reference bracket on which the mount can sit (right hand panel of Fig. 3).

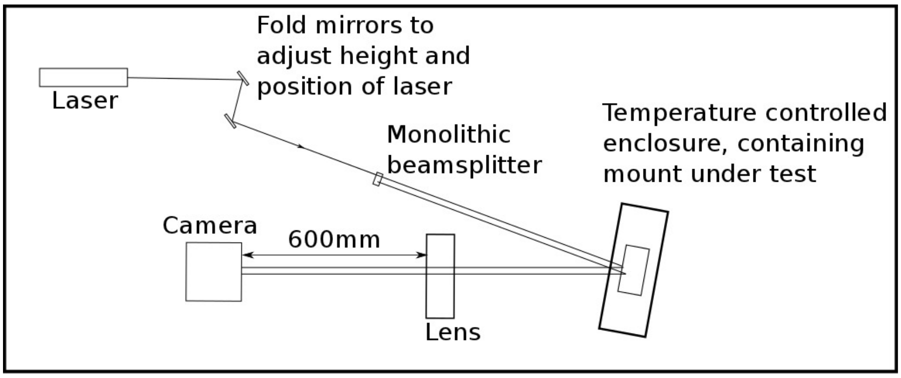

Fig. 4: Cartoon view of the optical test setup for monitoring the tilt stability of the dichroic/fold mirror mount (see text for details).

Both beams are then intercepted by a long focal length lens and focused onto a fast readout CCD camera. With this optical arrangement, any change in the relative tilt between the collimated beam reflected off the

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[3] If the dichroic/mirror substrate warps on warming up or cooling, then the beam stability requirement is unlikely to be met either. However, we do not expect this to be an issue for the fused silica substrates we have selected for the dichroic and fold mirrors.

test optic and the beam returned from the reference surface will manifest itself as a change in the separation of the two focused spots seen on the CCD camera. Changes in the orientation of the laser head, the beamsplitter, the orientation of the mount on its supporting block, or of the focusing lens and CCD all lead to common-mode motion of both focused spots, and so give no differential signal.

Unfortunately, multiple calibration tests undertaken with both probe beams reflecting off a zerodur mirror have identified a number of unexplained systematic effects that are limiting our ability to measure small angular perturbations reliably. Over the course of the last few months we have reduced these to a level that is now roughly 5× the level of the FTT/NAS requirements, but this is not yet satisfactory. We intend to continue trouble-shooting the test setup, but in the meantime have developed a different mechanical test that has improved on the optical test setup.

This second interim test uses a pair of linear variable differential transformer (LVDT) probes to directly measure the location of the front surface of the optical component relative to the optical mount. A schematic diagram of this test can be seen Fig. 5 which shows at left the mount with the two LVDT probes attached, and at right a schematic of the identically dimensioned aluminium calibration block that has been used to calibrate the probe measurements in the thermal test chamber.

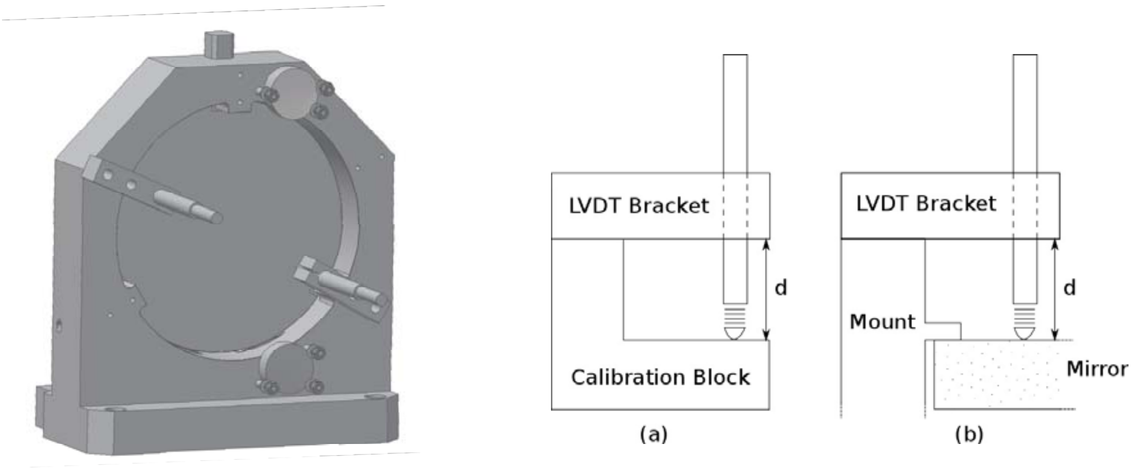

Fig. 5: A 3-d view of the dichroic/fold mirror mount with two LVDT probes attached. These directly measure the distance to the surface of the mounted optic from the LVDT bracket fixtures. Any change in the tilt of the optic relative to the mount is revealed in a differential change in the LVDT readings with temperature. Equal changes in the LVDT readings signify a piston motion in the z-direction. The two right hand panels show the method by which the probes and their mounting fixtures are calibrated by measurement of an aluminium calibration block that has the same material properties and dimensions as the dichroic/fold mirror mount.

This more direct measurement of the front face of the optic relative to the body of the mount is sensitive to both piston (i.e. in the z-direction) motion and tilting of the dichroic/fold mirror: the latter through differential changes in the LVDT readings and the former via common-mode changes. Tests with this direct tilt measurement are currently compromised by systematic errors at a level of 4× the level of the FTT/NAS requirements[4], but at this level the mount appears to be stable.

2.2.3 Discussion

Although our testing of the dichroic/fold mirror mount is not yet complete, our interim results are very promising. The mount appears to be stable to a level that is no worse than 4× the requirement which corresponds to an angular stability of roughly one-fifth of a second of arc. We believe this confirms that the basic strategies adopted for the dichroic/fold mirror mount design are sensible and that any adjustments that may be necessary to meet the FTT/NAS requirements are unlikely to involve major and/or complex redesign

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[4] These are primarily due to the repeatability in the behavior of the probe/bracket interface rather than any issues to do with the probes themselves or the readout circuitry.

work.

Our plans for the near term are to improve the LVDT test reliability by a factor of at least two – we expect to be able to reduce the level of systematic uncertainty in our tilt measurements by this factor in the near term through a more complete calibration strategy and we are investigating the purchase of a better 4-axis probe system to speed up the testing itself – and, in parallel, to continue to debug the optical test setup so that testing at the level of the actual FTT/NAS requirement can be undertaken in due course.

2.3 Lens mount stability test

Our testing of the stability of the mount for the FTT/NAS focusing optic have concentrated on its stability in shear, i.e. how well it can maintain the position of the lens vertex as the external temperature changes. The top-level requirements demand that this be stable at roughly the half a micron level since otherwise the focused target image will move across the FTT/NAS sensor as the temperature changes. The piston and tilt stability specifications are much less demanding and indeed our results with the dichroic/fold mirror mount already suggest these will be met. In the sub-sections below we summarise the key design elements of the lens mount design, describe our test setup and present our test results with some commentary.

2.3.1 Mount design

The prototype lens mount we have tested is shown schematically in Fig. 5. It is similar to the dichroic/fold mirror mount in that it is a monolithic symmetric aluminium component in which the front surface of the lens is sprung loaded onto three symmetrically disposed hard points. However, unlike the dichroic/fold mirror mount, the base of the lens sits on two pins of a polymer with a high coefficient of thermal expansion.

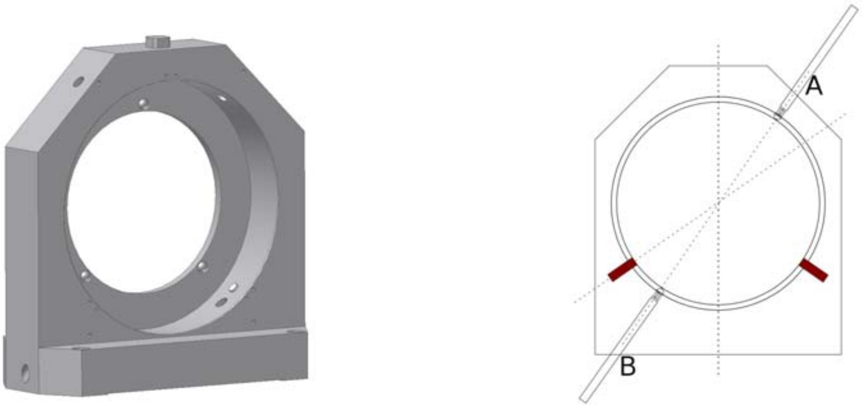

Fig. 6: At left: a 3-d view of the prototype lens mount. The three hard points against which the lens is located can be been seen around the periphery of the clear aperture, as can one of the polymer supporting pins on which the lens rests at lower right. The figure in the right hand panel shows a face-on view of the mount with the measurement LVDTs in place and the polymer pins coloured red.

In the presence of temperature changes these expand/contract in such a way that the combination of the CTE of the polymer pins and the lens glass exactly mimics the expansion of a solid block of aluminium. This “material compensation” allows for the differential motion between the mount and the lens to be corrected if the length of the polymer pins is suitably chosen and thereby maintains the position of the vertex of the lens at the centre of the mount’s clear aperture independent of temperature.

2.3.2 Test & test results

The basic test setup we have been using to assess the lens shear stability is outlined in the right hand panel of Fig. 6. We have used a pair of LVDTs to directly measure the location of the lens with respect to the body of the lens mount as a function of temperature. Fig. 6 shows the LVDTs located such that the uppermost sensor (A) is towards the right of the figure and the lower (B) towards the left. Measurements can also be made with sensor A at top left and sensor B at bottom right, and with the sensors interchanged in their vertical positions.

The sensors themselves can measure distances with a resolution of 30 nm, but calibration datasets suggest that the level of uncontrolled systematic errors on our measurements of the lens vertex stability is roughly one half of the requirement.

Our tests to date have utilised polymer pins with two different lengths. Our first set of tests used pins whose lengths were calculated from the nominal CTE of the compensating material and showed that the lens vertex was being displaced upwards from the nominal mount centre by as much as 3 μm for a 5°C temperature decrease, i.e. not enough material compensation was being introduced. By adjusting the lengths of the polymer pins, beyond that which we expect to be needed, we have subsequently demonstrated overcompensation close to the expected amount, and so we are confident that by suitable adjustment of the pin length, we will be able to meet the requirement straightforwardly.

2.3.3 Discussion

The interim results from the prototype lens mount testing are very encouraging. Although the mount is not yet stable at the 0.5 μm level required, the design approach we have chosen – that of material compensation – works well and all that should be required to meet the derived requirement is that the length of the polymer support pins be optimised. A recent analysis of our experimental data suggests that up to half of the lens shear measured may have been due to an oversight in the installation of the polymer pins – future tests will not be subject to this uncertainty.

Our plans for the near term will be to finalise a complete set of new tests using all combinations of LVDT locations, and then optimise the polymer pin lengths for operation at the median night-time temperature for the Magdalena Ridge (roughly 5°C).

2.4 Fold mirror mount piston stability test

The final test we have been undertaking is that for the piston stability, i.e. stability in the beam propagation direction, of the fold mirror mounts. Although piston motion of the dichroic has no impact on the FTT/NAS performance, piston motion of the fold mirrors can lead to a shear of the focused beam across the FTT/NAS sensor focal plane. The reader should note that the base-plate on which the four optical mounts are located is pinned to the Nasmyth optical table close to the final fold mirror so that its motion relative to the FTT/NAS sensor is expected to be very small. However, if the fold mirror mirrors piston in their mounts by as little as half a micron, the target image will be sheared with respect to the focal plane and the overall system stability requirements will not be met. In the sub-sections below we summarise the key design elements of the fold mirror mount design, describe our test setup and present our test results with some commentary.

2.4.1 Mount design

The basic fold mirror mount design has already been presented in sub-section 2.2.1 and the reader is refereed to that part of the document and the left hand panel of Fig. 3 for more details.

2.4.2 Test & results

The test setup used to measure piston motion of the fold mirrors as a function of temperature is identical to that shown in Fig. 5. We have used a pair of LVDT probes to directly measure the location of the front surface of the fold mirror relative to its mount. As for the measurements of the tilt stability of the mount, the probes and test setup were calibrated using an identically-dimensioned aluminium calibration block that was measured in the thermal test chamber.

Measurements of our calibration block confirm that we are able to measure piston motions as small as 100 nm reliably. Although we have only used one arrangement of the LVDT probes – the mount allows for these to be used to measure across two differently oriented diameters of the mirror – our initial results suggest motion of only 130 nm for a 7.5°C temperature change. This is roughly a factor of three times smaller than the budget allocation of Table 1, and so confirms that the prototype mount is likely to meet the requirement straightforwardly.

2.4.3 Discussion

The interim results from the prototype fold mirror mount testing are excellent. Initial measurements across one diameter of the mirror show that the mount is behaving as expected and under certain assumptions meets the requirement.

Our plans for the near term will be to finalise a complete set of new tests using all combinations of LVDT locations and measurements across two different diameters of the test optic. We expect to be able to undertake these tests relatively rapidly using a new 4-channel measurement system.

3 Conclusions

The test results we have obtained thus far indicate that the preliminary designs of the FTT/NAS optic mounts are viable, and that only minor rework will be needed to meet specification. We have demonstrated the ability to make sufficiently accurate measurements for the majority of the relevant degrees of freedom. The fold mirror piston stability requirement has been met (subject to cross-checking), and we expect that the lens displacement requirement will be met once the lengths of the polymer pins have been adjusted.

We anticipate some further difficulty in measuring the tilt stability of the dichroic/fold mirror mount at the required level, but we are confident that we will be able measure at twice the level of the requirement prior to PDR. The mount has been measured to be stable at four times the requirement, and no undesirable behaviour has yet been detected.

3.1 Schedule & prospects

The remaining tests to be carried out prior to the PDR in late March 2012 are as follows:

- Repeat lens mount stability test using multiple LVDT probe configurations
- Repeat dichroic/fold mirror mount LVDT tilt test using better calibration strategy
- Investigate systematic effects in dichroic/fold mirror mount optical test (if time permits)
- Camera mount stability test (using LVDT probes)
- Integrated stability test (tests common base-plate)

We anticipate that the first two tests (which are repeats of tests we have already done) will take less than a week each, leaving a month for each of the two tests which have not been attempted yet. These last two tests will however use many of the same techniques and items of test apparatus as the earlier ones.

In conclusion, we believe that the risks associated with the opto-mechanical stability of the FTT/NAS system have been substantially mitigated. We are looking forward to presenting a definitive set of test results at PDR, and we believe we can secure these measurements in accordance with the latest agreed schedule.