The long-stroke MROI vacuum delay lines: from concept to production

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ABSTRACT

We report on test results on the delay line system for the MRO Interferometer, currently under construction in Cambridge, UK. The delay lines are designed to provide 380 metres of vacuum path delay in a single stage, offering rapid star-to-star slews, high throughput and high transmitted wavefront quality. Details of the final design adopted for these delay lines are presented, together with lessons learnt from successful performance tests of the full-scale prototype trolley in a 20-metre long vacuum test rig. Delivery of the first production trolley is expected in New Mexico in early 2009.

Keywords: Delay lines, stellar interferometry

1. INTRODUCTION

The past two years since the last SPIE meeting in Orlando have seen a major rise in the scientific productivity of optical interferometers, particularly the CHARA and VLTI arrays. While the reasons for this are manifold, there seems little doubt that the gradual shift from an "experimental" to a "facility" mode of operation, with associated changes in the operational efficiency of interferometers has been critical to this success. The Magdalena Ridge Observatory Interferometer[1] (MROI), currently under construction on the Magdalena Ridge in southwest New Mexico, is being designed to provide a facility-class array optimised for the imaging of faint and complex targets. The COAST[2] team in the Cavendish Laboratory at the University of Cambridge are collaborating in this effort, and as part of their activity are delivering the long-stroke delay lines for the array.

In this paper we review progress on the design of the delay lines for the MROI and provide an overview of the design architecture that has been adopted. We report on performance testing of the full-size prototype delay line trolley in a test rig in Cambridge and summarise our plans for delivery at New Mexico Tech (NMT) in early 2009.

2. DELAY LINE BACKGROUND AND REQUIREMENTS

2.1 Background

The most significant shortcoming of the current generation of optical and infrared synthesis arrays is often perceived to be their lack of sensitivity. This has been a major hurdle in attempts to extend interferometric studies to the extragalactic domain, and is also frequently a major factor limiting the sizes of samples of interferometric targets in statistical studies. A major contributor to this lack of sensitivity is the large number of optics in the optical train from "Unit Telescope" (UT) to beam combiner, which can typically exceed 20. From an interferometric perspective, complex mirror trains can diminish performance in at least different three ways:

- The flux throughput of the system will be reduced. Even with an optimistic reflectivity of, e.g. 98%, a 20-mirror optical train will loose 33% of the light incident from the target;

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- Multiple reflections will add both low- and high-order wavefront aberrations to the beams of light from each telescope. These will lead to concomitant reductions in the measured fringe contrast and signal-to-noise ratio (SNR). In general, this will be a more significant penalty than that arising from throughput losses because the interferometric SNR — at least in the photon-limited regime — scales as a higher power of the rms wavefront error than the detected flux;
- Multiple reflections — if at non-normal incidence — will introduce diattentuation of the light from each telescope and hence compromise the polarization purity of the array (see, e.g. Baron *et al.*, these proceedings, paper 7013-13).[3] This can be problematic for observations of polarized targets at high angular resolution.

A major driver for the MROI delay line system design has thus been to minimise the number of reflections needed to introduce the large optical path differences (OPDs) needed, of up to 380m, at the MROI.

Two other less technical, but just as important, drivers have also shaped the MROI delay line architecture. These are the desire to realise *fast* reconfigurations of the OPD introduced by the delay line system and the need to deliver a satisfactory system at low cost per metre of injected delay. The first of these is directly related to the observing efficiency of the array while the second is particularly relevant for the MROI because of its long baselines which lie in the range 7.5–350 m.

2.2 Functional and technical requirements

The specific functional and technical requirements for the MROI delay lines have been presented in outline before,[4] but we have listed below the principal design desiderata which are likely to be of interest to interferometric architects and engineers reading this article.

Wavelength range: The MROI has been designed to operate scientifically in the wavelength range 0.6–2.4 μm and so the delay lines are required to meet their performance requirements in all the ground-based photometric bandpasses within this range;

Range of delay: Delays from 0 m to 380 m must be available so as to allow equalisation of the optical paths for any pair of telescopes located along the 200 m long array arms for all targets with elevations greater than 30°;

Throughput: The throughput of the delay line system must equal or exceed 85% at all wavelengths within the range 0.6–2.4 μm;

Clear aperture: This must be at least 125 mm so as to accommodate the 95 mm diameter collimated exit beam from the UTs with a sufficient margin to allow for diffraction while propagating along the array arm and delay line paths, and to accommodate any alignment errors;

Delay precision: There are two separate criteria for the delay precision based on intra- and inter-night requirements. Within any given night, any OPD error must be $< 10\,\mu$m rms, i.e. comparable to or less than the typical random OPD error expected from the atmosphere on long (> 10 m) baselines. Between nights, a more relaxed requirement of $< 100\,\mu$m rms applies based on an expectation that the day-to-day stability of the baseline will only be at the tenth of a millimetre level;

Slew speed: The slew speed must allow 15 m of physical travel of the delay line trolley in less than 30 seconds, and travel over the full delay line stroke (190 m) in less than 5 minutes. Both of these are associated with delivering an enhanced duty-cycle for scientific observations, in the first case when switching between science and calibrator targets close together (i.e. within a few degrees) on the sky, and for the second when slewing over significant fractions of the UTs' field of regard;

Sidereal tracking: This must be possible at rates of physical travel of the delay line carriages of up to 15 mm/s with a jitter of no more than $\lambda/40$ rms over a time period of twice the coherence time, t_0. For atmospheric conditions appropriate for the MROI site, this corresponds to a maximum jitter of 15 nm on 10 ms timescales (for observations at 0.6 μm), of 41 nm on 35 ms timescales (for observations at 1.65 μm), and 55 nm on 50 ms timescales (for observations at 2.2 μm);

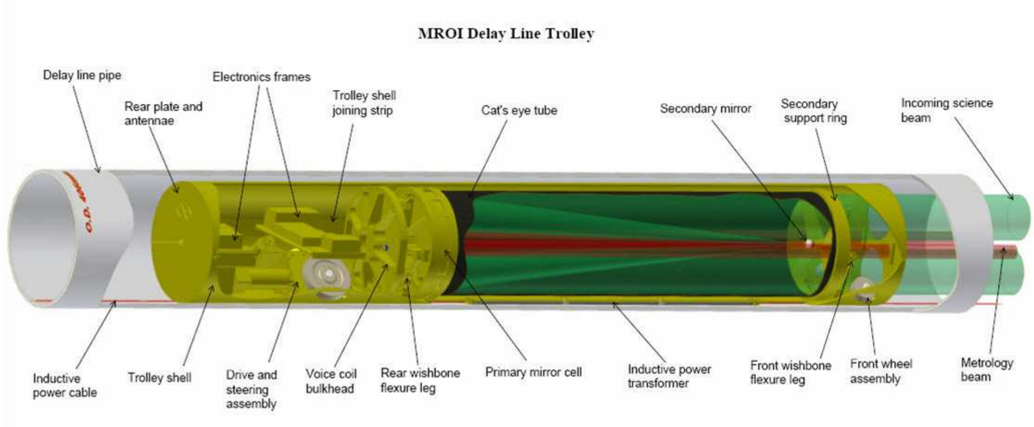

Figure 1. A 3-d cutaway view showing the principal design features of the MROI delay line system with the optical assembly mounted within its concentric mechanical carriage and the whole trolley running within an evacuated pipe. In this schematic the incoming science beam enters at right, is retro-reflected by the parabola/flat cat's eye, and returns to the right underneath the incoming beam. The input and output metrology beams enter and exit at right too, but remain in the same horizontal plane. The carriage motor, control electronics and communications and power systems are all located to the left of the delay line trolley, behind the primary mirror and voice-coil bulkhead. The supports carrying the vacuum pipe are not shown here.

Induced static wavefront error: The total wavefront error introduced by the full delay line system must be less than 60 nm rms for the transmitted beam including focus errors. This is so as to be consistent with the overall MROI wavefront quality error budget;

Induced dispersion: There must be less than 0.175 radians of differential optical phase across any bandpass (after subtracting the linear component of phase change with wavenumber) with a fractional bandwidth of 5% anywhere within the J, H and K astronomical photometric bands and across any bandpass with a fractional bandwidth of 0.5% anywhere within the astronomical R and I bands. As for a number of the other derived performance requirements, these criteria flow down from the top-level interferometer visibility loss budget, and correspond to visibility losses of less than 1% per spectral channel;

Induced polarization: The delay line optical elements are required to introduce no more than a 1% diattenuation of the light collected by the unit telescopes for wavelengths between 600 nm and 2400 nm so as to maintain the required level of polarization purity;

Induced pupil shear: Any shear of the output science beam is required to be kept below 1 mm rms so as to limit this contribution to any visibility losses to less than 1%;

Dynamic tracking performance: The delay lines must be able to accept commands from an external fringe tracker with a step response time of less than 30ms for step sizes of up to 10 microns so as to permit low-bandwidth group-delay-tracking.

3. DESIGN ARCHITECTURE ADOPTED

The architecture adopted for the MROI delay lines incorporates a single-stroke movable carriage carrying retro-reflecting optics and running in an evacuated aluminium pipe. A 3-d cutaway diagram showing the basic elements of the design is presented in Fig. 1 which reveals the optics, carriage and vacuum pipe but does not show how the pipe itself is supported. Further details of the additional hardware components for the full delay line system are shown schematically in Fig. 3.

In many ways the design parallels many existing delay line implementations. The optical assembly utilises a standard configuration of a parabolic primary mirror with a flat secondary located at the M1 focus, and is itself supported on flexures (in an inverted pendulum geometry) mounted on a motorised carriage. The location

Figure 2. (Left) Photograph of the front face of the prototype delay line carriage travelling within the delay line vacuum pipe. The two large vertically spaced apertures show where the science beam enters and exits, while the smaller apertures to left and right show where the laser metrology beam passes. The lighter structures just outside the metrology beam apertures, to right and left, are the sensors that trigger when the carriage approaches the end of the vacuum pipe run. The wire used to supply power inductively to the carriage can just be seen running along the bottom of the pipe. (Right) CAD drawing of the details of the secondary mounting stage located at the front of the delay line carriage. The mounting and actuators for focus and tip-tilt control of the secondary are in the centre of the picture. This whole assembly is hidden behind the front entrance plate shown in the photograph to the left.

of the cat's eye is monitored by a commercial laser metrology system where the only modification has been to expand the laser beam to approximately 20 mm diameter to accommodate the long propagation path. However, the design also incorporates a number of unusual features which are significant departures from the norm. A full list of these can be found elsewhere,[4] but for reference we summarise some of the most important below:

1. Perhaps most importantly, the delay line architecture involves the motorised carriage running *directly* on the interior surface of the aluminium pipe that provides the vacuum vessel for the system. To accommodate the imperfections that characterise the interior finish of the extruded pipe, the carriage uses compliant polyurethane tyres rather than hard metal wheels.

2. Because the aluminium pipes used to define the trajectory of the carriage are themselves not guaranteed to be straight, the secondary mirror is adjustable in tip and tilt (see the right hand panel of Fig. 2) so as to correct for the shear introduced by any lack of pipe straightness. The shear is detected by picking off a fraction of the return metrology beam and sensing its location on a low-cost CCD camera. Even at slewing speeds, only a low control bandwidth is necessary because the length scales on which the vacuum pipe is "bent" are relatively large (i.e. many tens of cm).

3. Unlike some other implementations, the whole of the optical path in the MROI delay lines is kept under vacuum. By operating at a nominal pressure of 1 millibar, problems associated with internal seeing and longitudinal dispersion are minimized while still allowing sufficient heat transfer via conduction to take place between the delay line electronics chassis and the vacuum pipe walls (see the left hand panel of Fig. 2).

4. One interesting peculiarity of the MROI delay line design is that, by eliminating the use of rails to define its trajectory, the delay line carriage is unconstrained in rotation about the vacuum pipe axis. This "roll" degree of freedom is controlled both by design — the center of gravity of the delay line carriage is below the vacuum pipe centerline — and also through an on-board tilt sensor which measures the roll angle in real time so that the undriven rear wheel of the carriage can be steered to correct any roll errors. As is the case for the shear variations, only low-bandwidth control (a few Hz) is necessary.

5. The distribution of power and control signals to the carriage is performed in a "contactless" manner. Power is transmitted inductively, using a wire lying in the bottom of the vacuum pipe (see the left hand panel

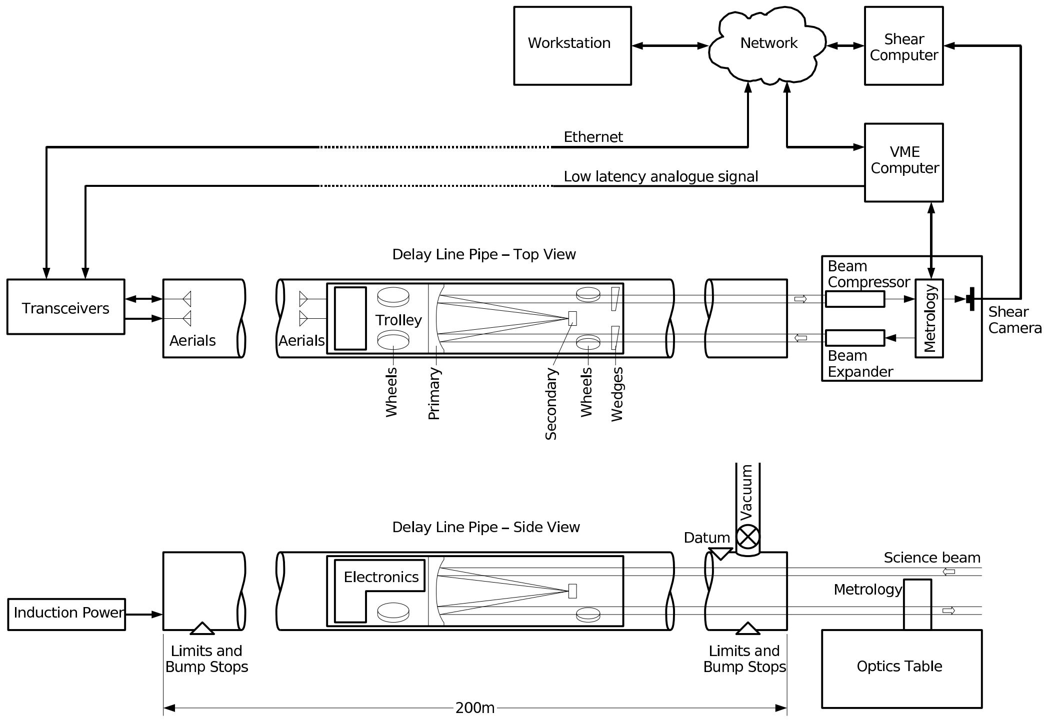

Figure 3. Schematic top and side views of the complete delay line system, showing the physical locations of all the major components. For the testing at Lord's Bridge, essentially all of this system was deployed in prototype form, though with a reduction in overall length of the vacuum pipe run from 200 m to 20 m.

of Fig. 2) which slides through a long transformer core attached to the bottom of the carriage. On-board power storage to manage periods of high load is also made available through the use of a bank of super-capacitors. Control signals to the carriage use two separate radio links. The first is a commercial 2.4 GHz wireless Ethernet link used for high data-rate communication between the on-board micro and external control computers, while the second is a dedicated low-latency 900 MHz link used to close the servo-loop controlling the OPD when tracking astronomical targets.

In the list above we have focused primarily on the hardware features of the delay line system. Readers who are interested in the details of the software design and control of the delay line system are referred to Ref. 4.

4. DELAY LINE TESTING STRATEGY

Tests of the prototype delay line carriage were performed in a shortened, but otherwise full-size, test rig installed in the COAST bunker at Lord's Bridge (Figs. 3 and 4). Our goal was to mimic the final implementation at the MROI as closely as possible, and so as much of the hardware as possible, e.g. the vacuum pipe system and supports, the power and communication systems etc. and the trolley itself, were of essentially the same design as we intend to deploy on-site in New Mexico. The only substantive differences between the test rig and the expected final delivered system were as follows:

1. The length of the COAST bunker restricted the length of the delay line pipe run to only 20 m, i.e. roughly ten times shorter than will be installed eventually on the Magdalena Ridge.
2. Not all of the pipe sections used to fabricate the test rig were compliant with the specifications required for the MROI installation. This can be seen in the right hand panel of Fig.4, where the pipe trajectory across the joints at approximately 5 m and 8 m along the test rig can be seen to show very rapid changes

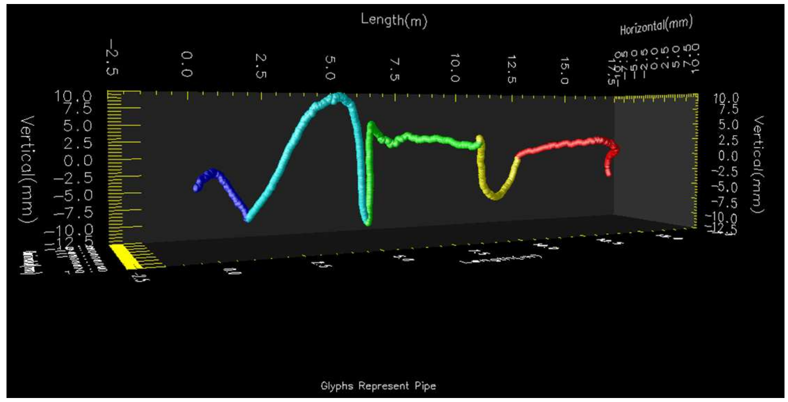

Figure 4. (Left) Photograph of the vacuum rig used for testing the prototype MROI delay line with one end open. The detail closest to the camera shows one of the seals used to join successive pipe sections as well as the "anchor" leg for the pipe supports. The total length of the rig is 20 m. (Right) A graphical representation of the 3-d trajectory defined by the five pipe sections making up the test rig. Abrupt changes in the trajectory denote the pipe joints. The actual data plotted is the uncorrected shear of the metrology beam in the x and y directions as a function of length, z along the test rig. When divided by two — the range shown in the plot is roughly ± 10 mm — the shear is a proxy for the actual deviation of the inner surface of the pipe from a straight line.

in its deviations from a straight line. These very fast changes in the trajectory defined by the inner pipe surface are not expected to be replicated at the MROI installation.

3. The majority of the joints between pipe sections in the test rig were not compliant with requirements developed for the MROI installation. Vertical "steps" between pipe sections were typically several hundred microns in size, rather than the 10s of microns expected based on earlier test with jointed pipes. Such large step sizes are not expected to be replicated at the MROI installation.
4. The metrology system used for the tests utilised a Zygo laser head and interferometer optics, rather than the Agilent system which will be deployed in New Mexico. The Zygo laser head has a somewhat shorter coherence length than desired for the 190 m installation required at the MROI. Furthermore, the laser launch optics breadboard used was of a prototype design that has subsequently been re-engineered for improved stiffness and thermal stability.
5. The prototype delay line trolley did not incorporate the optical wedges positioned at the entrance and exit apertures for the metrology beam which are used to steer the footprint of the metrology light away from that of the science beam at the secondary mirror. We do not expect the additional mass of this small subsystem to affect the dynamical performance of the carriage.

Notwithstanding its short length, the 20 m test rig allowed for tests of the performance of the delay line system to be made at all carriage speeds up to the slewing requirement (0.7 m/s). Long distance performance was tested by commanding the carriage to traverse back and forth along the rig thereby allowing us to emulate very long (i.e. $\gg 190$ m) trolley motions.

Installation of the vacuum pipe rig in the COAST bunker was completed very rapidly. A team of three engineers were able to install and align the prefabricated parts in the course of single day using a set of custom jigs and a theodolite. This highlights a further advantage of the novel architecture adopted, i.e. significantly reduced requirements and overheads for installation and alignment as compared with delay line systems based on the use of precision rails.

5. DELAY LINE TEST RESULTS

The full test results of the prototype MROI delay line system are contained in a lengthy set of compliance matrices refering to the functional and performance requirements for the overall system, and in which each entry

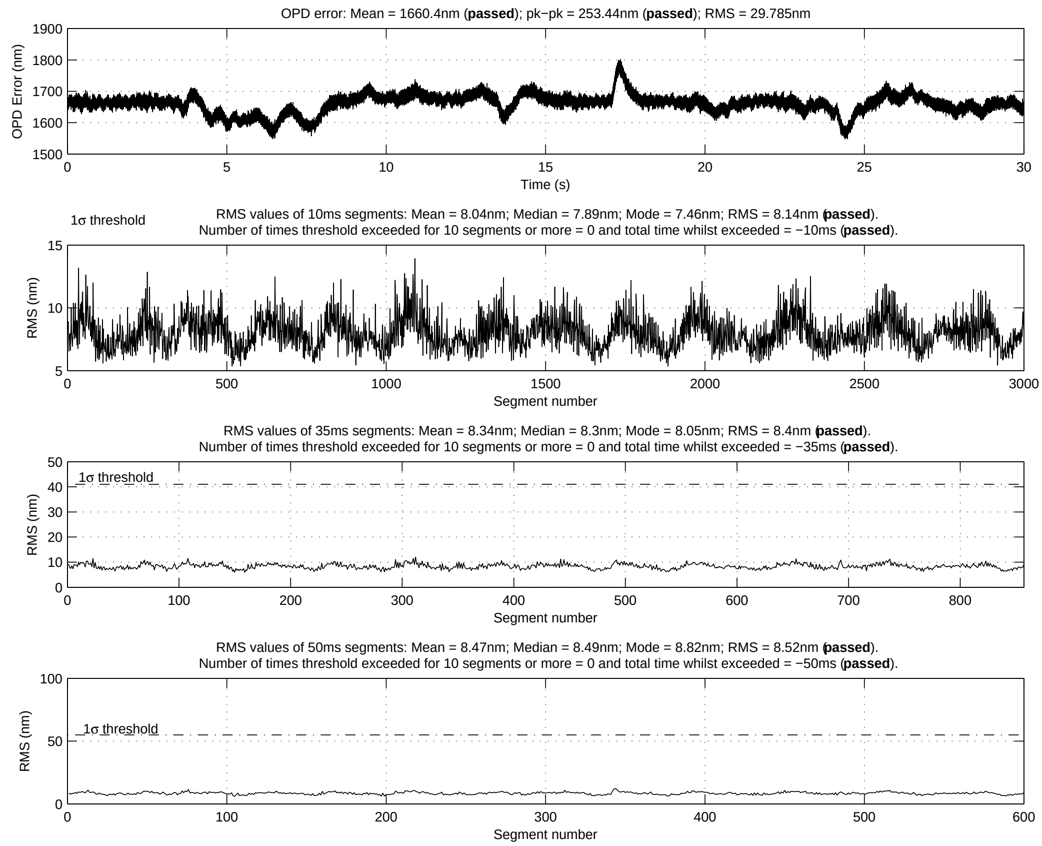

Figure 5. A typical test result summary for the delay line carriage when commanded to follow a 1 mm/s constant velocity trajectory. The panels show from top to bottom (i) the OPD error as a function of time and the rms OPD error over (ii) 10 ms (iii) 35 ms and (iv) 50 ms time bins. In the bottom three panels the threshold under which the rms OPD jitter must lie is shown by the dashed horizontal line (this coincides with the top panel boundary in the first of these panels). In all cases the OPD jitter is well below the maximum allowed, indicating excellent disturbance rejection and very smooth tracking performance.

is directly traceable to either a top-level or derived system or subsystem requirement. A presentation of these matrices together with a full and detailed commentary is beyond the scope of this presentation, so instead we have attempted to summarise the key elements of our test results in the short paragraphs below.

5.1 OPD tracking performance

The opto-mechanical behaviour of the MROI delay lines is captured well in Fig. 5. This shows the measured OPD error, i.e. the deviation between the commanded OPD and that delivered by the delay line system, as a function of time over 30 s and while tracking at a velocity of 1 mm/s. The absolute error has a mean of 1.7 μm which is well within the requirement of 10 μm, and the peak-to-peak variation of 0.2 μm is easily low enough to guarantee that any OPD errors uncorrected by the MROI's group-delay fringe tracker will give rise to coherence losses of less than a fraction of a percent in any science spectral channel. More importantly, the jitter on short timescales of 10, 35 and 50 milliseconds is always well below the requirements of 15 nm, 41 nm and 55 nm respectively. Similar results were obtained at all positive and negative velocities from zero to 15 mm/s apart from the small number of instances where the carriage crossed one of the non-compliant pipe section joints (see below for a further discussion of this type of "failure").

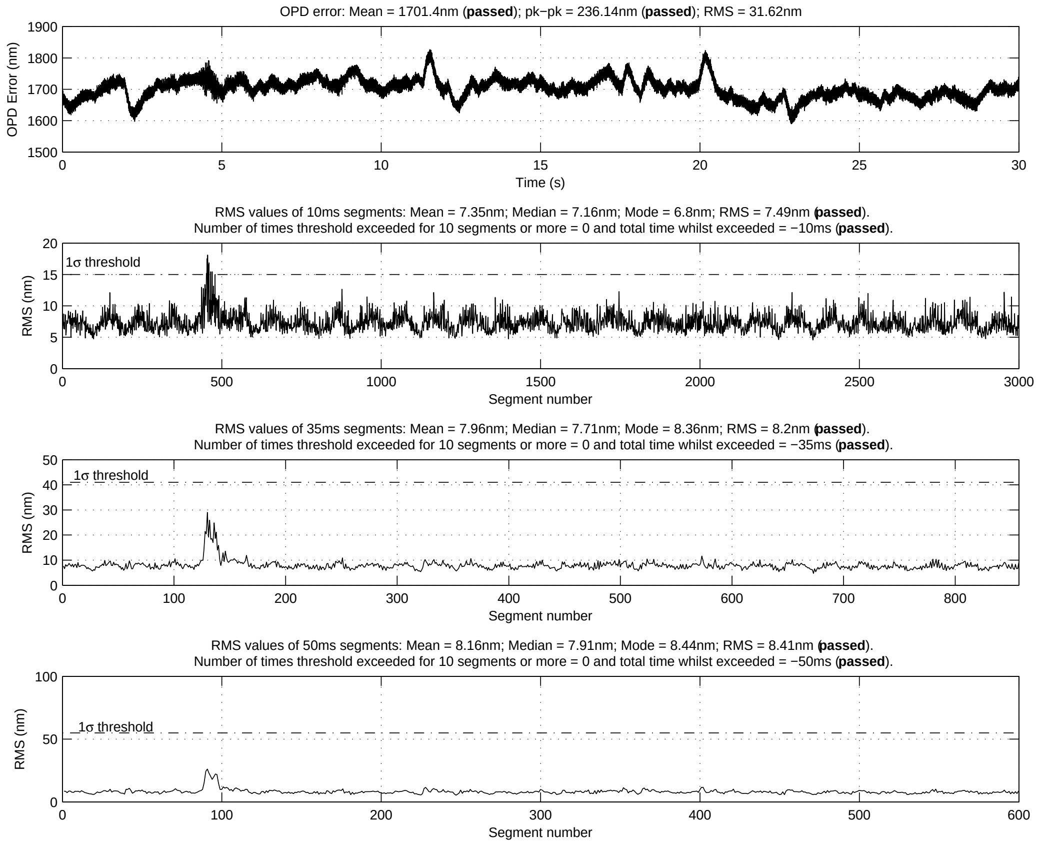

Figure 6. OPD test result summary during which a steering actuation occurred. This causes the short period of enhanced excursions in OPD jitter seen towards the left hand side of panels (ii) through (iv). Despite this perturbation, the overall OPD jitter criteria are still met. The details of the plots are the same as in Fig. 5. This type of "failure" has now been eliminated by using a different algorithm for actuating the wheel that is steered.

5.2 Roll correction

The impact of the steering actuations needed to control the roll of the delay line is shown in Fig. 6. Here, the steering actuation causes a short period of enhanced OPD jitter, but the time over which the jitter specification is not met is sufficiently short that the loss in fringe visibility expected is still below the requirement threshold. Tuning of the steering actuation algorithm has now eliminated this behaviour fully, so that roll correction introduces no substantive perturbations to the tracking performance.

5.3 Joint crossing

As mentioned above, the pipe sections and joints in the test rig were not compliant with the requirements for the MROI installation. As a result, sidereal tracking tests that included "joint crossings" typically failed the OPD peak-to-peak error and OPD jitter tests when either the front or rear sets of wheels traversed a joint "step". The time to recover ranged from a few tenths of a second to a as long as a few seconds in the worst cases. The maximum rate at which joint-crossing occurs will be limited by the wheelbase of the carriage (roughly 2.0 m) and the maximum tracking speed (15 mm/s) to no more than once per 2 minutes, and typically will be much lower. As a result, the reduction in fringe visibility induced by joint crossings remains within that allowed by the top level system requirements which permit the OPD jitter criteria to be exceeded for up to one second per minute. When slewing, the OPD error and jitter criteria need not be satisfied, and so joint-crossing when slewing has not proven problematic since even at high speed the metrology signal never loses lock.

5.4 Functional and subsystem performance results

Overall, the performance of the prototype delay line system was very good. All positioning time, velocity and acceleration tests were satisfied, and all the major subsystems, e.g. the power supply, metrology system, RF communication, and shear sensor hardware, met their performance goals. By way of example, at a tracking speed of 15 mm/s the rms two-axis uncorrected beam shear as measured over a 120 s time interval was 0.14 mm, close to a factor of 4 better than required by the specification.

5.5 Vacuum tests

After an initial set of testing in air, the system performance was re-checked with the vacuum system pumped down and broadly speaking similar results were obtained. None of the problems that might have been expected of the vacuum system were realised. The requirement on maximum leak rate was easily met, with the test set-up only needing re-pumping every week rather than each day, and as predicted, heat dissipation through the "soft" vacuum of the test rig was more than sufficient to ensure that none of the on-board electronics exceeded their safe operable temperature range.

5.6 Production modifications

In a few instances testing of the prototype system did reveal the need for small changes to the delay line system design. The response of the delay line to large (10 μm) offsets from an external fringe tracker led to an unreasonably large OPD jitter temporarily, and so it was decided to pre-filter such large offsets to that they are applied over several cycles of the basic 0.2 ms cycle time of the metrology servo-loop. A more significant enhancement will be the replacement of the existing motor encoder with a higher-resolution device. We expect this to allow us to tighten the motor servo considerably and reduce the impact of disturbances induced by, for example, steps in the pipe inner surfaces at the joints between pipe sections. We expect an additional reduction of these disturbances will be realised when we replace the carriage wheels with ones with smaller crown radii: this should help mitigate the effects of joining pipe sections with different cross-sections. One final enhancement we intend to pursue is that of improving the mounting of the secondary mirror to increase its rejection bandwidth to external disturbances.

At this moment in time (July 2008) only a small number of final tests remain to be undertaken before closing on the final design and fabricating the first production system. These include some remaining opto-mechanical stability tests on the metrology launch optics and M2 focus, and a demonstration that the installation of the metrology wedges does not affect the system performance.

5.7 Results review

Overall, the results of our performance testing have been very promising. We have demonstrated compliance with essentially all of the high-level and derived system and sub-system requirements, no show-stoppers have been identified and where small performance shortcomings have been exposed, mitigation strategies have been identified and developed. Perhaps most interestingly, none of the most novel aspects of the design such as the elimination of the use of precision rails and the adoption of an ultra-long-stroke impementation have turned out to be problematic.

6. SUMMARY

We have executed a broad-ranging set of performance tests on the MROI prototype delay line system in preparation for finalising the design for the manufacture of the first production delay line carriage and vacuum system. The system performance in air and when evacuated has been excellent: no show-stoppers have been identified and the ability of the system to introduce a user-specified and controlled optical delay suitable for use in high-sensitivity astronomical interferometers has been demonstrated. We expect fine tuning of the design to be completed within the next few months and shipment of the first carriage to New Mexico in early 2009.

7. ACKNOWLEDGEMENTS

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