MRO Delay Line

Production Trolley #1 FATS Results

INT-406-VEN-0301

The Cambridge Delay Line Team

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Objective

This document presents the results of performance tests conducted on production delay line trolley #1 in the test rig established in the COAST facility at Lords Bridge and shows how they relate to the derived requirements placed on the system.

Scope

The tests results presented address the performance of the trolley and shear camera systems, the layout of the metrology system and the VME interface providing the closed loop position feedback. They do not specifically test the metrology laser or the proposed design for the launch/return optics.

While some test results are obtained by direct measurement of a particular parameter the principal tests involving the OPD performance must meet a number of pass criteria simultaneously. For these tests the test criteria are established and explained and the test results presented in a tabulated form. Most tests have associated graphical output where appropriate and these are gathered into a separate set of appendices.

This document also shows how the test list is related to the derived requirements.

Reference Documents

RD1 Top-level requirements INT-406-TSP-0002

RD2 Workstation Software Functional Description INT-406-VEN-0103

Applicable Documents

AD01 Derived Requirements INT-406-VEN-0107

AD02 List of Production Trolley Factory Acceptance Tests INT-406-VEN-0207

Acronyms and Abbreviations

BCA Beam Combining Area

BCF Beam Combining Facility

BRS Beam Relay System

COAST Cambridge Optical Aperture Synthesis Telescope

DL Delay Line

DLA Delay Line Area

ICD Interface Control Document

ICS Interferometer Control System (now SCS)

MROI Magdalena Ridge Observatory Interferometer

MRAO Mullard Radio Astronomy Observatory

NMT New Mexico Tech

OPD Optical Path Delay

SCS Supervisory Control System

TBC To be confirmed

TBD To be determined

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1 Introduction

The FAT tests of the production trolley have been conducted in the test rig which has been installed in the COAST facility at Lords Bridge near Cambridge. Some pre-FAT tests were conducted in the test track set up in the Cavendish Laboratory beforehand to ensure that those subsystems that could be tested were operating correctly before the transfer of the trolley to Lords Bridge.

A subset of the FAT tests was initially carried out with the test rig at atmospheric pressure. This ensures that the trolley is capable of performing to specification before pumping the test rig down to 1 mb but also shows that performance in air is, for the most part, the same as performance in vacuum.

The tests have been designed to verify the performance of the production trolley and to show that the Top Level Requirements (RD1) and the Derived Requirements (AD01) have been met in a 20m test rig. Some requirements cannot be tested without access to the full 200m delay line together with science beam feeds but where possible tests are arranged so that the results can be scaled to 200m. The list of acceptance tests is contained in a separate document (AD02).

The first section of this document briefly describes the test arrangements. The second section shows how the tests are related to the derived requirements. A detailed report of the FAT results are presented in section 3 which tabulates results in the various categories and refers to the graphical output of many of the test results which are contained in a set of appendices.

1.1 The test facilities

The FATs were conducted in a ~ 20m delay line test rig erected in the COAST bunker. It is made up from five 12 foot length of pipes with a 2 foot pipe section at each end. This gives an operating length of just over sixteen metres after end buffers, limits and datum are taken into account. The height of the test rig is slightly shorter than the design developed for MROI because of height restrictions. There are other minor differences in the design of the pipe supports and the anchor method but the essential characteristics of the test rig are the same.

A laser metrology system with beam expander/compressor is arranged to send the expanded beam down the test track and receive the returning beam which, after compression is directed to the interferometer with a small percentage diverted to the shear sensing system. See Figure 1.

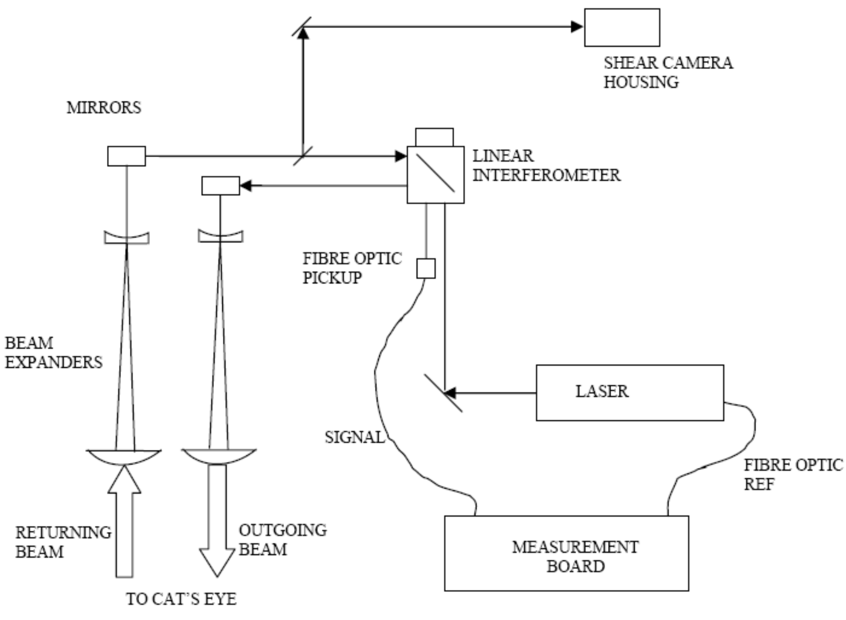

Figure 1: The test track laser metrology arrangement

Figure 2: Test rig at the COAST facility at Lords Bridge

The metrology system is set up on a small optical table which is supported by a framework at the correct height for the metrology entrance windows into the test rig. A space of approximately 3m exists between the metrology table and the near end of the test rig pipe to allow the trolley to be loaded into or removed from the pipe. A photograph of the test rig is shown in Figure 2. The metrology layout for the test rig, see Figure 3, uses the same components and is laid out in a similar fashion to the test track in the laboratory. Photos of the production trolley at the test rig are shown in Figure 4 and Figure 4

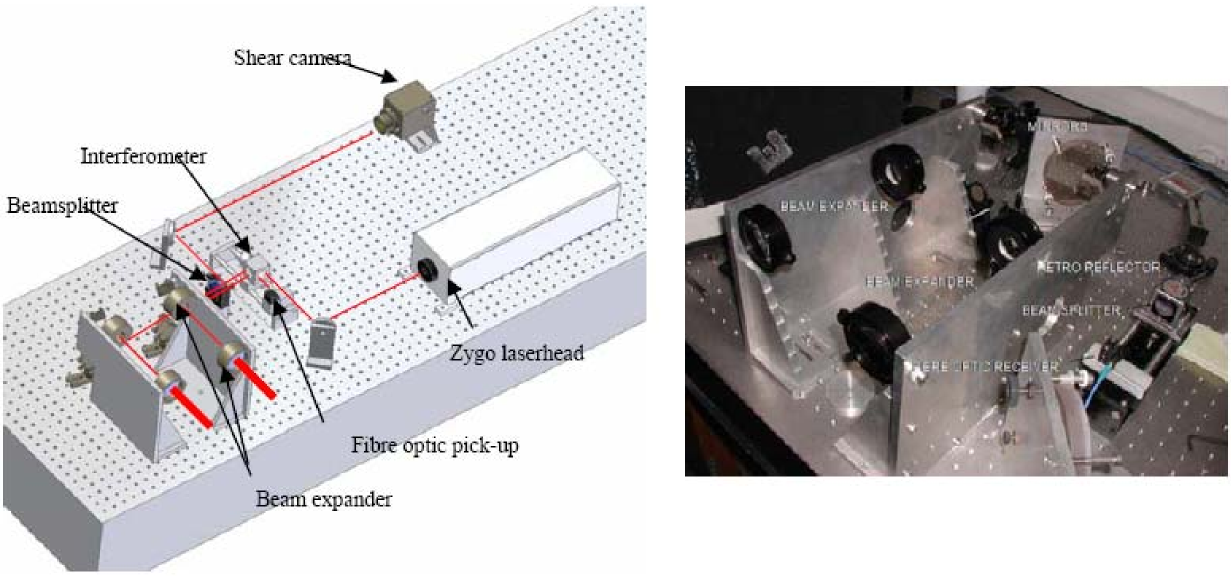

Figure 3: Metrology arrangement for the test rig at COAST

Figure 4 Production trolley on the gurney and about to be loaded into test rig.

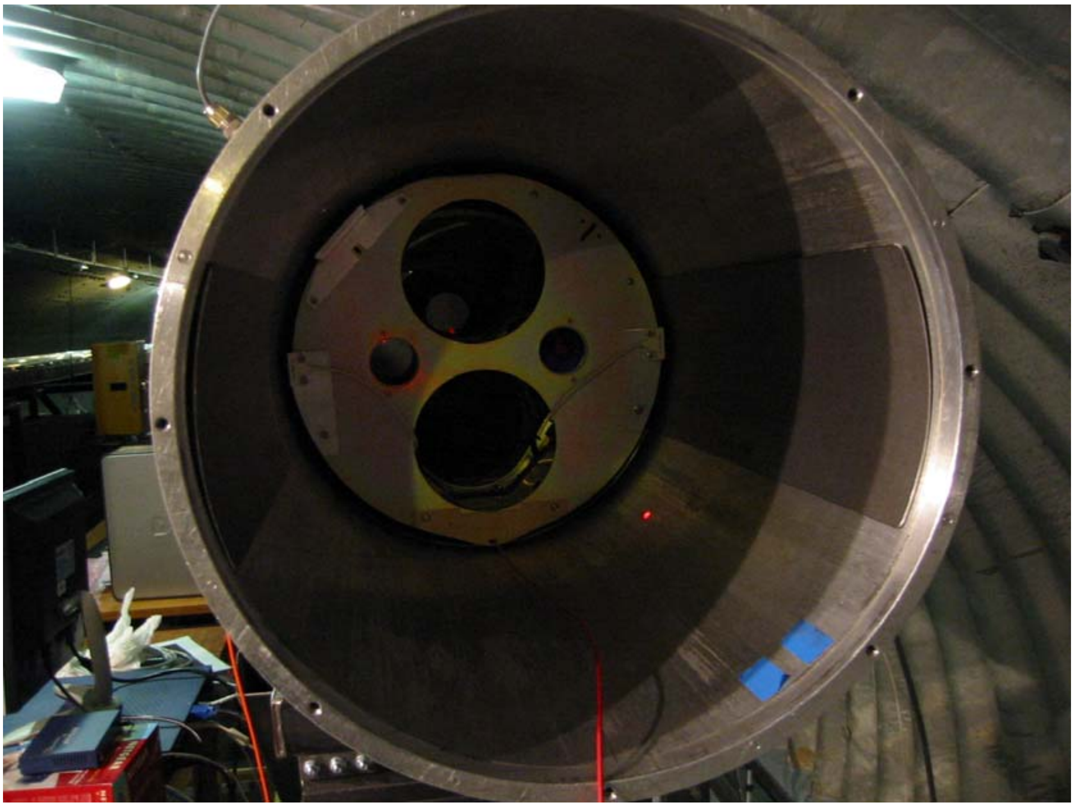

Figure 5 Production trolley in test rig. The velocity limit target plate is on the right and the position limit target plate is on the left. The datum switch target is mounted at the 10:30 position on the trolley and light from the datum switch can be seen on the pipe wall opposite.

2 Relationship of FAT Tests to Requirements

The requirements to be tested fall into two categories: the top-level requirements that impinge on the performance of the delay line and the derived requirements which are directly concerned with the performance of subsystems in the delay line. The relationship of these requirements to the tests to be conducted is described in the following tables.

2.1 Top Level Requirements

Req. No.	Requirement Description	Test Ref. (AD02)	Description
	Delay precision		
	Intra-night repeatability of <10μm rms	2.2.6 test 2 2.2.6 test 3	Acquire datum 10 times from different starting positions: at, near, far. Repeat datum throughout 8 hrs.
	Inter-night repeatability of <100μm rms	2.2.6 test 4	Acquire datum the following day.
	Slew speed		
	Slew 15m in less than 30s	2.2.1 test 1	
	Slew from any position to any other position in less than 5 min	2.2.3 test 1	Calculate from a single slew test
	Sidereal tracking and Jitter		
	Jitter shall be <λ/40 in $2t_o$: For trolley speeds up to 15mm/s For accelerations up to 2.5μm/s	2.2.2 test 1-3 2.2.3 test 2-3	Test tracking at constant accelerations Test reversing direction while tracking
	Dynamic tracking of atmospheric fluctuations: <30ms for steps up to 10μm	2.2.3 test 4	Test response to fringe tracking offsets

2.2 Derived Requirements

The derived requirements, AD01, that are to be verified by test are listed in the following tables. Each table is based on the grouping of requirements which appear in the derived requirements and the first column in the tables relates to the subsection of that document. The second column is a very brief description of the requirement. The third column is a reference to the test which is specified in the List of Tests, AD02, and the fourth column is a very brief description of the test.

2.2.1 Cat's Eye Requirements

Req. No.	Requirement Description	Test Ref. (AD02)	Test Description
2.1.2	**Secondary Mirror**		
2.1.2.2	Tip/Tilt range [±3.9mrad]	2.2.4 test 5	Test range available
2.1.2.3	Tip/Tilt slew rate [4.7mrad/sec each axis]	2.2.4 test 6	Test slew rate
2.1.3	**Focus Stage**		
2.1.3.1	Focus resolution [20μm]	2.1.5 test 1	Test minimum repeatable focus step
2.1.3.2	Focus drift [5μm]	-	Lab test of cat's eye structure

2.2.2 Voice coil drive tests

Req. No.	Requirement Description	Test Ref. (AD02)	Test Description
2.3.1	Peak drive current [9A]	2.1.7 test 2	Stopping by actuation of the pre-limit
3.1	Bandwidth [100 Hz minimum]	-	Lab test during tuning for FDR

2.2.3 Trolley Tests

Req. No.	Requirement Description	Test Ref. (AD02)	Description
2.2.1	Slew speed [0.7m/s]	2.2.1 test 1	16m slew test
2.2.2	Maximum acceleration [0.14m/s^2]	2.2.1 test 1	Repositioning tests
2.4.1	Roll accuracy [±0.3º]	2.2.4 test 1	16m of tracking at 90mm/s
2.5.1	Power dissipation [<50W]	2.2.1 test 1 2.2.1 test 3	Power while tracking at min/max rate Sufficient power while slewing at 0.7m/s

2.2.4 Pipe Requirements

Req. No.	Requirement Description	Test Ref. (AD02)	Description
4.1.1	Maximum air pressure [1mbar]	2.1.8 test 1	Pump down to 0.2 to 0.5mbar
4.1.3	Minimum hold time [16hrs]	2.1.8 test 1	Check pressure a.m. and p.m.

2.2.5 Metrology system requirements

Req. No.	Requirement Description	Test Ref. (AD02)	Description
6.1.1	Minimum power [50µW per delay line]	-	Reduce beam intensity and confirm operation.
6.1.2	Beam pointing stability [0.45 arcsec RMS]	-	Measure beam tilt over a period of time using projection onto a CCD.
5.4.1	Datum switch repeatability [<10µm RMS]	2.1.5 test 1	Test of datum switch in lab
5.4.2	Datum structure stability (intra-night) [<10µm RMS]	2.2.6 test 2 2.2.6 test 3	Repeated test of datum on test rig Test datum during whole day
5.4.3	Datum structure stability (night-night) [<100µm RMS]	2.2.6 test 4	Test datum day to day.

2.2.6 Shear System Requirements

Req. No.	Requirement Description	Test Ref. (AD02)	Description
7.1.1	Closed loop residuals (track)[0.5mm RMS 2-axis]	2.2.4 test 3	2min of tracking at 15mm/s
7.1.1	Closed loop residuals (slew) [3mm RMS 2-axis]	2.2.4 test 2	16m of slewing at 0.7m/s

3 Test Results

3.1 Presentation of Test Results

Because of the volume of data which is required for testing there is too much information to present at a detailed level. Therefore the test results are grouped in sections and shown in tabulated form with a pass or fail and some indication of the nature of the failure.

Each test section states the purpose of the test and whether it addresses specific requirements or demonstrates some functionality that is necessary for the system to work as intended.

Tests which are conducted to show that the OPD performance requirement is met are subject to a set of (conservative) criteria which address different aspects of the requirements. If a test fails on a particular criterion it does not necessarily mean that the performance requirements are not satisfied and so an assessment of the failure is necessary to determine its impact on performance. The test criteria are complex so they are described and justified in section 5.

3.1.1 Test documentation

Test results are produced from logging the status and telemetry of the delay line system by the workstation (see RD2). The logs are saved as FITS files which can be imported into Matlab using a purpose made GUI interface for extracting and plotting the results. Hence most test results are obtained by graphical output but in particular the analysis of OPD error to compare results to the test criteria is automated and plotted as described in section 5.

3.1.2 Test tables

Tests are grouped for convenience of reporting as well as carrying them out but results from one test may be used in more than one table where appropriate data is obtainable from an existing test. The test tables generally consist of seven columns, described below:

1. indicates the filename of the FITS log taken during the test
2. indicates a test parameter, e.g. slew distance
3. the length of the log in seconds
4. indicates, where appropriate, a Pass (P) or Fail (F) on the test criteria
5. a comment.
6. indicates an overall Pass or Fail based on assessment
7. the filename of any graphical output (usually .pdf format). A copy of the output is included in the separate documents which comprise Appendix A

3.2 *Tests at Atmospheric Pressure*

These are a partial set of FATs to establish that the trolley performs in air and to serve as a check for readiness to evacuate the pipe. The test rig is not evacuated. The far end of the test rig is fitted with the end plate carrying the communications aerials and module. For historical reasons, the inductive power line is also terminated at this end and its power module is connected at the other end of the test rig. A special end plate is fitted to the metrology end of the test rig which allows for easy removal of the trolley if necessary.

The optical wedges are fitted to the trolley. It has already been establish from tests in the test track that the wedges do not degrade the performance of the trolley.

3.2.1 Trolley Tracking Tests

These sets of tests are to test the OPD performance while tracking at constant velocities of (plus and minus) 0.1mm/s, 0.2mm/s, 0.4mm/s, 0.6mm/s, 0.8mm/s and then 1 to 15mm/s in increments of 1mm/s. The steering and shear loops are closed.

3.2.1.1 Tracking at constant velocity

The test results are shown in Table 1. The most stringent criterion is 15 nm RMS (the criterion for the 10 ms bin). The results for this criterion are given in the comment column of the table and all are substantially below 10 nm RMS.

Table 1 Results from tracking at constant positive velocities.

File No. dllog_ 20110328	Vel mm/s	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS)	Overall Pass/Fail	Pdf graphical output
_130921	0	30	P	2.7 nm	Pass	
_131132	+0.1	30	P	5.3 nm	Pass	
_131259	-0.2	30	P	5.6 nm	Pass	
_131420	+0.4	30	P	5.7 nm	Pass	
_131543	-1	30	P	5.7 nm	Pass	
_132303	+2	30	P	5.6 nm	Pass	
_132414	-3	30	P	5.4 nm	Pass	
_132540	+4	30	P	5.6 nm	Pass	
_132631	-5	30	P	6.5 nm	Pass	
_132758	+6	30	P	7.0 nm	Pass	
_132854	-7	30	P	5.9 nm	Pass	
_133020	+8	30	P	5.7 nm	Pass	
_133114	-9	30	P	5.7 nm	Pass	
_133241	+10	30	P	7.2 nm	Pass	
_133355	-11	30	P	5.8 nm	Pass	
_133457	+12	30	P	5.6 nm	Pass	
_133625	-13	30	P	5.5 nm	Pass	
_133749	+14	30	P	5.5 nm	Pass	
_133846	-15	30	P	5.5 nm	Pass	

Results

The OPD Jitter of 10 ms bins is <10nm RMS and does not generally increase with velocity.

Conclusions

The tracking performance is substantially better than the requirement. All of the tests pass all criteria.

3.2.1.2 Contiguous Tracking Tests

The purpose of these tests is to track for a typical observing time of 10 minutes and assess the quality of tracking through measurement of the OPD error and applying the test criteria.

The tests are to set continuous tracking at constant velocity for 10 minutes at the following velocities: -1mm/s, +5mm/s, -10mm/s and +15mm/s. To keep the log files to a manageable size each test is composed of five or more 2 minute logs with only a few seconds gap between each log as the operator restarts the logging.

Table 2 Contiguous tracking test results

File No. dllog_ 20110328	Vel mm/s	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS)	Overall Pass/Fail	Pdf graphical Output Mar28_
_142044	-1	6x120	P	5.6 nm	Pass	
_142353			P	5.6 nm	Pass	
_142603			P	5.7 nm	Pass	
_142831			P	5.9 nm	Pass	
_143055			P	6.1 nm	Pass	
_143312			P	5.7 nm	Pass	
_144029	+5	5x120	P	6.8 nm	Pass	
_144328			P	6.7 nm	Pass	
_144551			P	5.9 nm	Pass	
_144820			P	5.9 nm	Pass	
_145043			P	6.5 nm	Pass	
_145858	-10	5x120	P	7.1 nm	Pass	
_150145			P	6.9 nm	Pass	
_150409			F	7.5 [fails pk-pk by 334nm: slope]	Fail	_150409_OPD
_150632			P	6.9 nm	Pass	
_150859			P	7.4 nm	Pass	
_151136	15	5x120	F	6.5 [fails pk-pk by 75 nm: join]	Pass	
_151457			F	6.1 [fails pk-pk by346 nm: slope]	Fail	
_151715			P	6.1 nm	Pass	
_151936			F	6.5 [fails pk-pk by 516 nm: join]	Pass	_151936_OPD
_152200			F	5.8 [fails pk-pk by 2μm: slope]	Fail	

Results

The results are shown in Table 2. The most stringent criterion is the OPD jitter for the 10 ms bin which must be <15 nm RMS. The results for this criterion are given in the comment column of the table; all are substantially below 10 nm RMS. Thus all tests pass the most stringent OPD jitter criterion.

Failures on peak to peak OPD error specifically due to a join event in fact pass the test overall as this is allowed to happen for a join. Failures on peak to peak OPD error due to a substantial slope of the OPD error are caused by sections of pipe which have steep slopes or a rapid change in slope, particularly near the joins. The test rig pipe has several sections which are outside the specifications for delay line pipe. These test failures are due to the slope caused by these pipe sections.

Conclusions

The dynamic tracking performance at all velocities is well within the OPD error criteria, even when crossing joins. Failures of the peak to peak criterion are due to the really bad joins but pass the test overall because failures at joins are allowed for up to 0.5 seconds in every 60 seconds. Failures of the peak to peak criterion due to the slope of bad sections of pipe in the test rig are of no consequence. It is likely that MROI pipe will not lead to this magnitude of deviation of the OPD error, but if it were then the fringe tracker would act to remove it, because the deviation takes place over timescales (10s of seconds) that are much longer than the timescale on which the fringe tracker corrects OPD errors.

3.2.2 Trolley Trajectory Tests

Three tests are grouped under this heading. The results are presented in the following subsections:

- Test trajectory acquisition and time by switching from tracking at one position to tracking at another position for a range of distances e.g. 4mm, 20mm, 100mm, 200mm, 500mm, 2m 5m and 10m.
- Test tracking at constant accelerations of 0.3μms^{-2}, 0.625μms^{-2} and 1.25μms^{-2} including reversing direction while tracking with a realistic trajectory.
- Test response to fringe tracking offsets of 0.5 μm,1μm and 10μm

3.2.2.1 Slew times

The purpose of these tests is twofold:

1. To test the slew time requirement defined by the slew speed and maximum acceleration.
2. To demonstrate the trajectory acquisition and time by switching from tracking at one position to tracking at another position for a range of distances and to e.g. 4mm, 20mm, 100mm, 200mm, 500mm, 2m 5m and 10m.

Most of these tests are performed by setting the trolley tracking and then requiring it to go to another position followed by a command to track. This is not a particularly efficient method of switching from tracking at one position to tracking at another position but is easy to do from the engineering GUI for small distances. It involves additional time for the operator to issue a command to track and for the command to reach the VME system. Therefore the extra time introduced because of this command should be taken into account in assessing the overall time taken to track at the new position. For a change in tracking position of 1m it was easy to do by using the more natural trajectory method.

Table 3 Slew time results

File No. dllog_ 20110328	Slew Dist (mm)	Time (s)	P/F on criteria	Results/Comments Time to reach new position [including command delay]	Overall Pass/Fail	Pdf graphical Output Mar28-
_155114	10	40	P	2.6s [7s]	Pass	
_155357	100	40	P	4.6s [8s]	Pass	
_155606	500	40	P	7.5s [10.4s]	Pass	
_160940	1000	40	P	9.2s (using trajectory method)	Pass	_160940_MET

File No. dllog_ 20110329	Slew rate (m/s)	Time (s)	Results/Comments Velocity and acceleration	Overall Pass/Fail	Pdf graphical output
_111838	0.7	10	Velocity = 0.7m/s Acceleration: 0.7m/s in 1.71s = 0.41m/s^2	Pass	_111838_MOT

Results

The results are shown in Table 3. Slew times are as expected and are the same as FDR tests. The velocity is limited to 0.7m/s but could be increased up to 1m/s if desired. The acceleration is greater than required and could be decreased if the velocity was increased slightly so that the requirement to slew 15m in 30s is still met.

Conclusions

The time taken from tracking at one position to tracking at another position is similar to the FDR test results and meets the requirements for tests undertaken. The velocity and acceleration necessary to meet requirements are met.

3.2.2.2 *Accelerations and reversal*

The purpose of these tests is to demonstrate that the tracking OPD requirements are met over a range of constant accelerations and also through reversal of the trolley under realistic trajectory conditions. The tests are:

1. Test tracking at constant accelerations of 0.3μms^{-2}, 0.625μms^{-2} and 1.25μms^{-2}
2. Test reversing direction while tracking with a realistic trajectory

The test incorporating a reversal has an associated -MET pdf figure showing the trajectory followed.

Table 4 Acceleration and tracking reversal results

File No. dllog_ 20110329	Acc'n μms^{-2}	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS)	Overall Pass/Fail	Pdf graphical Output Mar29
_101742	0.3	30	P	5.4 nm	Pass	
_102001	0.625	30	P	5.4 nm	Pass	
_102310	+1.25	200	P	5.6 nm	Pass	
_103317	-1.25	200	P	6.7 nm [Reversal]	Pass	_103317_OPD _103317_MET

Results

The test results are shown in Table 4. The tracking tests are carried out with an initial velocity of 1mm/s except for the reversal test where the initial velocity is 0.1mm/s.The results are consistent with tracking at constant velocity except that at extremely slow velocity, either side of reversal, there is an increase in jitter which increases the overall RMS.

Conclusions

The requirements to meet the OPD criteria while tracking with acceleration and through reversal have been met.

3.2.2.3 *Fringe tracker offsets (step response)*

The purpose is to test the OPD response to fringe tracking offsets of up to 10µm. The test system is not capable of yet of pre-filtering the offset command and so offsets are applied as a single step in one sample period (200µs).

The offsets applied are ±0.5µm, ±1µm and ±10µm

Table 5 Fringe tracker offset step response results

File No. dllog_ 20110329	Offset µm	Time (s)	Req't	Results/Comments	Overall Pass/Fail	Pdf graphical Output Mar29_
_104612	0.5	30	<30ms	<15ms with 60% overshoot	Pass	
_105222	1	30	"	<15ms with 50% overshoot	Pass	
_105727	10	30	"	<20ms with 50% overshoot	Pass	_105727_MET

Results

The step response times are shown in Table 5 and are better than the FDR results.

Conclusions

The requirements are met for all step sizes. The overshoot can be limited by adding additional functionality to the code in the VME system to ensure that any step requests are pre-filtered.

3.2.3 Trolley Shear Loop Tests

The purpose of these tests is to demonstrate that:

1. the requirements on shear residuals are met
2. the shear deviations can be measured

To demonstrate (1) the trolley is tracked at 15mm/s and also 0.7m/s and the shear residuals are logged.

To demonstrate (2) the trolley is slewed at 90mm/s with the shear loop open and the shear deviations are logged.

Table 6 Shear loop test results

File No. dllog_	Vel (mm/s)	Time (s)	Req't	Results/Comments	Overall Pass/Fail	Pdf graphical Output
20110328 _151936	+15	120	0.5mm rms	Shear residuals <0.05mm pk-pk.	Pass	Mar28 _151936_SHE
20110329 _111838	+700	40	3mm rms	Closed loop residuals: X <3mm & Y <2mm	Pass	Mar29 _111838_SHE _111838_MOT _111838_PRE _111838_STE _111838_VOL
20110329 _112231	90	200	0.5mm rms	Closed loop residuals: X <0.5mm & Y <0.14mm	Pass	Mar29 _112231_SHE _112231_STE
20110329 _112754	-90	200		Open loop		Mar29 _112754_SHE

Results

The results are shown in Table 6. The open and closed loop shear residuals are met even in a pipe run which deviates from its mean axis by more than ±5mm as revealed by the open loop shear test.

Conclusions

The requirements for shear residuals have been met.

3.2.4 Trolley Roll Loop Tests

The purpose of these tests is to demonstrate that:

1. the requirement on roll control of the trolley is met
2. the trolley is stable with steering centred and the steering loop open
3. the trolley is stable with steering at maximum steering angle

To demonstrate (1) the trolley is slewed at 90mm/s and the roll angle is logged

To demonstrate (2) the trolley is slewed for the full length of the test rig at a constant velocity of 90mm/s while logging with steering loop off but centred and the roll logged (this checks trolley's balance about the roll axis).

An FDR test established that the roll of the trolley if the steering mechanism were to fail at maximum deviation was limited to approximately 0.4 radians or 23º, which is perfectly safe. The maximum steering deviation of the production trolley is now half that of the prototype and so the limiting roll will be less.

Table 7 Roll loop test results

File No. dllog_	Vel (mm/s)	Time (s)	Req't	Results/Comments	Overall Pass/Fail	Pdf graphical output
20110329 _112231	90	200	±0.3º (5.2mrad)	Roll -0.007 to +0.015	Fail	Mar29 _112231_STE

Results

The result of the roll loop test is shown in Table 7. The steering accuracy requirement has not been met. The maximum deviations are associated with the bad sections of pipe. However, at higher trolley velocity, well above the maximum tracking rate the trolley has less time to correct roll deviations than would be the case at tracking rates.

The trolley steering, when centred according to its encoded reading, produces a trend in the roll which means that the steering is not actually centred (the trolley was balanced transversely in lab tests). The steering zero position will be set up during vacuum tests.

Conclusions

The steering accuracy has not been met but will be improved during vacuum testing.

3.2.5 Datum Tests

The purpose of these tests is to demonstrate the requirements on datum stability are met.

The test procedure is to acquire datum at least 10 times from different starting positions and note the metrology value at the instant before the datum causes a reset to zero position. The variability of the reset position would be due to a combination of the following:

1. Repeatability of the switch function
2. Stability of metrology table with respect to test rig
3. Position of cat's eye with respect to trolley shell (the datum target is mounted on the trolley)
4. A change in roll angle of the trolley (the edge of the target material may not be exactly normal to the direction of travel of the trolley)

A period of datum testing was undertaken where the trolley was sent to datum from different positions along the pipe. The results are shown in Table 8. Since the datum target is attached to the trolley and not the cat's eye any change in datum position can be partly explained by a change in differential position between the trolley and the cat's eye. Exhaustive testing of the datum was undertaken and reported in the post-FDR tests (AD2) and concluded that there is very little difference between cat's eye and trolley positions when detecting the datum.

Table 8 Tests of datum repeatability from various positions along the pipe. The tests were not conducted in any particular order; the results have merely been presented in groups according to the distance from the datum position.

Seek from 0.2m (μm)	Seek from 2m (μm)	Seek from 5m (μm)	Seek from 10m (μm)	Seek from 15m (μm)
+1.2	+3.2	+0.9	+2.7	-3.6
-1.3	+0.7	+3.3	+1.6	+5.3
-0.3	-2.8	-2.6		
+0.7				
-0.3				
+0.6				
-0.2				
-2.1				
+1.9				
+1.4				

Results

The mean position of the datum is 0.515 μm and the repeatability as set by the trolley (rather than the cat's eye) is < 2.26 μm RMS.

Conclusions

The requirements for datum repeatability of <10μm have been met.

3.2.6 Thermal Results

Temperatures are logged as part of trolley telemetry and so are monitored with every log taken. The initial temperatures (in air) are shown in Table 9. The bunker temperature at this time was 11.5 ºC.

Table 9 Trolley start-up temperatures (in air) and after operating for 3 hrs. The PC104 stack has already been heating up for approximately 5 minutes while the trolley is powered on and the software is booted. Start-up temperatures are from dllog-20110328-130921.fits and operating temperatures are from dllog-20110328-160940.fits

Sensor	**Placement**	**Start-up Temp (ºC)**	**After 3 hrs (ºC)**
Tcarrf	Carriage front (on base)	12.2	12.7
Tfocus	Secondary focus	14.1	14.6
Tmidcarr	Midway along side-wall of the trolley	11.7	12.9
Tpricell	Primary mirror cell	14.1	16.0
Tcarrr	Carriage rear (voice coil bulkhead)	12.9	17.5
Tpower	PC104 stack temperature	19.9	31.5

Conclusions

The temperature of the PC104 stack is well within operating thermal limit of 65 ºC and is cooler than the prototype trolley during FDR tests, taking into account the ambient temperature.

3.2.7 Power consumption

The power consumption of the trolley should be <50W in all operating modes except slew. Five results are available from logs during the testing activity at atmospheric pressure: the power consumption under idling, tracking at 0.1mm/s, 1mm/s and 15mm/s and slewing at 0.7m/s. Power is calculated by multiplying the voltage and current monitored on board the trolley. These results are shown in Table 10.

Table 10 Trolley power consumption under various operating conditions.

File No. dllog_	Vel (mm/s)	Time (s)	Mean Bus Volts (V)	Mean Bus Amps (A)	Results/Comments Power consumption	Overall Pass/Fail
20110329 _145433	Idle	30	47.66	0.75	35.7 W [<50 W]	Pass
20110328 _131132	0.1	30	47.38	0.83	39.3 W [<50 W]	Pass
20110328 _131543	1	30	47.36	0.82	38.8 W [<50 W]	Pass
20110328 _133846	15	30	47.35	0.82	38.8 W [<50 W]	Pass
20110329 _111838	slew	10	46.2	1.41	65.1 W [Power is sustainable}	Pass

Conclusions

The requirements for power consumption are met and also power is sustainable while slewing.

3.3 Tests under Vacuum

The test rig is evacuated to <1.5mb. The far end of the test rig is fitted with the end plate carrying the communications aerials and module. For historical reasons, the inductive power line is also terminated at this end and its power module is connected at the other end of the test rig. See Figure 6.

Figure 6 The end plate of the test rig carries the communications module, as at MROI, but not the inductive power module. The inductive power cable termination is at the bottom of the end plate and a vacuum pumping port is on the left. The low-latency link connects at the centre of the end plate and the wi-fi link connects above it.

An end plate containing two metrology windows and a connector for the inductive power input is fitted to the metrology end of the test rig. The inductive power wire from the connector enters a connector block with screw terminals and is then looped as in a Ω shape with elastic to provide tension at the base.

3.3.1 Trolley slew tests

The purpose of these tests is

1. To demonstrate the repositioning time for the trolley and that the requirement that the trolley can slew 15m in <30s.
2. To demonstrate that the trolley can be continuously slewed with the power that is available to it for sufficiently long distances that it does not impact the operation of the delay line.
3. To ensure that temperature rises are within expectations, to demonstrate that the metrology system does not lose lock and that the received RF signal is stable

The following tests are undertaken:

- Check velocity ramping under VME control by moving fixed distances (plus and minus): 4mm, 10mm, 20mm, 50mm, 100mm, 200mm, 500mm, 2m, 10m and 16m.
- Carry out a ~17m slew with the maximum velocity set to +0.7m/s and -0.7m/s
- Carry out a sequence of slews equivalent to 190m of delay line travel

3.3.1.1 Time taken for a range of slew distances

Check velocity ramping under VME control by moving fixed distances (plus and minus): 4mm, 10mm, 20mm, 50mm, 100mm, 200mm, 500mm, 2m, 10m and 16m.

Table 11 Results of ‘slew time’ tests.

File No. dllog_ 20110330	Slew Dist (mm)	Log time (s)	Slew Time (s)	Comments	Overall Pass/Fail	Pdf graphical Output Mar30-
_095922	4	60	2.5		Pass	_095922_MET
“	10		2.7		Pass	“
“	20		3.3		Pass	“
“	50		4.0		Pass	“
“	100		5.0		Pass	“
_101516	200	60	5.6		Pass	_101516_MET
“	500		6.9		Pass	“
“	1m		7.4		Pass	“
_101739	2m	60	11.3		Pass	_101739_MET
“	10m	30	20.6		Pass	“
_102017	-16m	60	29.8	Includes 1.5s of velocity pre-limit @ 100mm/s	Pass	_102017_MET _102017_MOT

Results

The results are shown in Table 11. The trolley repositions by 16m in less than 30s. The velocity is 0.7m/s for slews long enough to reach that value and the acceleration is $0.41ms^{-2}$ and deceleration is $0.2ms^{-2}$.

Conclusions

The positioning time requirement, velocity and acceleration requirements are met. Therefore the top level requirements on slew velocity are met.

3.3.1.2 Simulation of a long slew

Carry out a sequence of ~16m slews equivalent to at least 190m of delay line travel. This is a conservative test as it also incorporates the acceleration and deceleration of the trolley for each slew, requiring more power than a single 190m slew.

Table 12 Results from simulation of a long slew.

File No. dllog_	Slew Dist (m)	Time (s)	Results/Comments	Overall Pass/Fail	Pdf graphical Output Mar30-
20110330 _102749	192	400	12 slews	Pass	_102749_MET _102749_MOT _102749_POW
20110330 _103641	36	100	3 slews	Pass	
Total	228m		Power is available for at least two slews Metrology lock is maintained Power dissipation meets requirements Temperature rise is acceptable	Pass Pass Pass Pass	
20110413 _140141	200	200	Average RF signal level is stable with a slope of 2.4×10^{-6} over the 16m travelled.	Pass	Apr13 _140141_STE

Results:

The results of the simulated slew tests are shown in Table 12. The supply voltage provided by the super-capacitor dropped from 47.6V to 45.4V and stabilised at that value. This means that the inductive supply is capable of supplying the current necessary to drive the trolley and maintain the super-capacitor in an almost fully charged state. Note that this is a more severe test because of the number of accelerations and decelerations during slewing.

Metrology lock is not lost when the trolley is travelling at a velocity of 0.7m/s and the shear loop is operating.

The average current supplied to the trolley during slewing was 1.5A and the average voltage was 45.5V suggesting a total power dissipation of 61.4W.

The temperature of the rear of the trolley at the voice coil bulkhead increases by only 0.5 ºC and the temperature of the PC104 stack increases by <1 ºC.

The mean RF signal level does not varysignificantly throughout the length of the pipe and has only a small standing wave ripple.

Conclusions

The following conclusions can be drawn from the simulated slew tests:

1. The inductive power supply is capable of delivering sufficient power to the trolley indefinitely.
2. Metrology lock is maintained during slews (even in pipe of poor specification and join quality).
3. The power dissipation during slewing (<62W) is within the capability of the inductive power supply (2A at 45V is 90W).
4. The increase in power dissipation during a long slew does not significantly increase the trolley temperature or the temperature of the PC104 stack.
5. The average RF signal level of the low latency link does not reduce noticeably (<0.5%) over the 17m operating length of the test rig so losses are expected to be <6% for a 200m delay line.

3.3.2 Trolley Tracking Tests

These sets of tests are to test the OPD performance while tracking at constant velocities of (plus and minus) 0.1mm/s, 0.2mm/s, 0.4mm/s, 0.6mm/s, 0.8mm/s and then 1 to 15mm/s in increments of 1mm/s. The steering and shear loops are closed.

3.3.2.1 Tracking positive at constant velocity

The test results are shown in Table 13. The most stringent criterion is 15 nm RMS (the criterion for the 10 ms bin). The results for this criterion are given in the comment column of the table.

Table 13 Results from tracking at constant positive velocities.

File No. dllog_ 20110330	Vel mm/s	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS)	Overall Pass/Fail	Pdf graphical output Mar30-
_153255	0	30	P	2.7 nm	Pass	_153255_OPD
_154144	0.1	30	P	5.3 nm	Pass	_154144_OPD
_154258	0.2	30	P	5.2 nm	Pass	_154258_OPD
_154423	0.4	30	P	5.3 nm	Pass	_154423_OPD
_154553	0.8	30	P	5.4 nm	Pass	_154553_OPD
_154659	1	30	P	5.4 nm	Pass	_154659_OPD _154659_PSD
_155918	2	30	P	5.5 nm	Pass	_155918_OPD
_160357	3	30	P	5.0 nm	Pass	_160357_OPD
_155019	4	30	P	5.8 nm	Pass	_155019_OPD
_155205	5	30	P	6.0 nm	Pass	_155205_OPD
_155305	6	30	P	5.5 nm	Pass	_155305_OPD
_155420	7	30	P	5.8 nm – rear wheels pass joint 1	Pass	_155420_OPD
_155514	8	30	P	4.8 nm	Pass	_155514_OPD
_155615	9	30	P	4.7 nm	Pass	_155615_OPD
_160030	10	30	P	6.0 nm – steering corrections	Pass	_160030_OPD
_160203	11	30	P	5.8 nm	Pass	_160203_OPD
dllog_ 20110331						Mar31-
_155939	12	30	P	5.3 nm	Pass	_155939_OPD
_160123	13	30	P	6.0 nm – steering corrections	Pass	_160123_OPD
_160225	14	30	P	6.6 nm	Pass	_160225_OPD
_160331	15	30	P	7.7 nm	Pass	_160331_OPD

Results

The results for the 10ms bin RMS are given in the comment column of the table and all are substantially below 15 nm RMS. A typical power spectrum is provided in file _154659_PSD.

Conclusions

The tracking performance is substantially better than the requirement. All of the tests pass all criteria.

3.3.2.2 Tracking negative at constant velocity

The test results are shown in Table 14. The most stringent criterion is 15 nm RMS (the criterion for the 10 ms bin). The results for this criterion are given in the comment column of the table.

Table 14 Results from tracking at constant negative velocities.

File No. dllog_ 20110331	Vel mm/s	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS)	Overall Pass/Fail	Pdf graphical Output Mar31-
_160519	0	30	P	3.1 nm	Pass	_160519_OPD
_160608	-0.1	30	P	6.1 nm	Pass	_160608_OPD
_160738	-0.2	30	P	6.0 nm	Pass	_160738_OPD
_160856	-0.4	30	P	6.1 nm	Pass	_160856_OPD
_163423	-0.8	30	P	6.1 nm	Pass	_163423_OPD
_161111	-1	30	P	6.3 nm	Pass	_161111_OPD
_161547	-2	30	P	6.3 nm	Pass	_161547_OPD
_161644	-3	30	P	5.8 nm	Pass	_161644_OPD
_161837	-4	30	P	5.9 nm	Pass	_161837_OPD
_163615	-5	30	P	5.9 nm	Pass	_163615_OPD
_162051	-6	30	P	5.0 nm	Pass	_162051_OPD
_162202	-7	30	P	4.9 nm	Pass	_162202_OPD
_162315	-8	30	P	4.9 nm	Pass	_162315_OPD
_162444	-9	30	P	5.6 nm	Pass	_162444_OPD
_164207	-10	30	P	6.1 nm	Pass	_164207_OPD
_162740	-11	30	P	6.5 nm	Pass	_162740_OPD
_162933	-12	30	P	6.0 nm	Pass	_162933_OPD
_163032	-13	30	P	5.8 nm	Pass	_163032_OPD
_163158	-14	30	P	5.2 nm	Pass	_163158_OPD
_163302	-15	30	P	6.6 nm	Pass	_163302_OPD

Results

The results for the 10ms bin RMS are given in the comment column of the table and all are substantially below 15 nm RMS.

Conclusions

The tracking performance is substantially better than the requirement. All of the tests pass all criteria.

3.3.2.3 Contiguous Tracking Tests

The purpose of these tests is to track for a typical observing time of 10 minutes and assess the quality of tracking through measurement of the OPD error and applying the test criteria.

The tests are to set continuous tracking at constant velocity for 10 minutes at the following velocities: 0.2mm/s, -1mm/s, +5mm/s, -10mm/s and +15mm/s. To keep the log files to a manageable size each log is composed of five 2 minute logs with only a few seconds gap between each log as the operator restarts the logging. Results are shown in Table 15.

Table 15 Contiguous tracking test results

File No. dllog_ 20110401	Vel mm/s	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS)	Overall Pass/Fail	Pdf graphical Output Apr01-
_141126	0.2	5x120	P	5.6 nm	Pass	_141126_OPD
_141431			P	5.6 nm	Pass	_141431_OPD
_141652			P	5.6 nm	Pass	_141652_OPD
_141909			P	5.6 nm	Pass	_141909_OPD
_142130			P	5.7nm	Pass	_142130_OPD
_135622	-1	5x120	P	5.4 nm	Pass	_135622_OPD
_140147			P	5.5 nm	Pass	_140147_OPD
_140416			P	5.4 nm	Pass	_140416_OPD
_140641			P	5.6 nm	Pass	_140641_OPD
_140857			P	5.7 nm	Pass	_140857_OPD
_132741	5	5x120	P	6.1 nm	Pass	_132741_OPD
_133023			P	6.1 nm	Pass	_133023_OPD
_133242			P	5.8 nm	Pass	_133242_OPD
_133506			P	5.1 nm	Pass	_133506_OPD
_133725			P	5.4 nm	Pass	_133725_OPD
_134404	-10	5x120	P	6.0 nm	Pass	_134404_OPD
_134658			P	5.9 nm	Pass	_134658_OPD
_134915			F	6.3 nm [pk-pk (slope) by 166nm]	Fail	_134915_OPD
_135131			P	5.4 nm	Pass	_135131_OPD
_135350			P	6.1 nm	Pass	_135350_OPD
_131212	15	5x120	P	6.8 nm	Pass	_131212_OPD
_131535			P	6.0 nm	Pass	_131535_OPD
_131756			F	7.1 nm [pk-pk (slope) by 164nm]	Fail	_131756_OPD
_132015			P	6.9 nm	Pass	_132015_OPD
_132234			F	6.4 nm [pk-pk (slope) by 891nm]	Fail	_132234_OPD

Results

Three tests fail on the peak-to-peak criterion due to the slope of the pipe. These are due to sections of pipe which have steep slopes or a rapid change in slope, particularly near the joins. The test rig pipe has several sections which are outside the specifications for delay line pipe. These test failures are due to the slope caused by these pipe sections.

Conclusions

The dynamic tracking performance at all velocities is well within the OPD error criteria, even when crossing joins. Failures of the peak to peak criterion are due to the really bad joins but pass the test overall because failures at joins are allowed for up to 0.5 seconds in 60 seconds. Failures of the peak to peak criterion due to the slope of bad sections of pipe in the test rig are of no consequence. It is likely that MROI pipe will not lead to this magnitude of deviation of the OPD error, but if it were then the fringe tracker would act to remove it, because the deviation takes place over timescales (10s of seconds) that are much longer than the timescale on which the fringe tracker corrects OPD errors.

3.3.2.4 Tracking tests across joins

The purpose of these tests is to assess how the trolley copes with bad joins. Some tracking tests include join events which the trolley copes with easily and the tracking criteria are not exceeded. The layout of joins is shown in Figure 7 below.

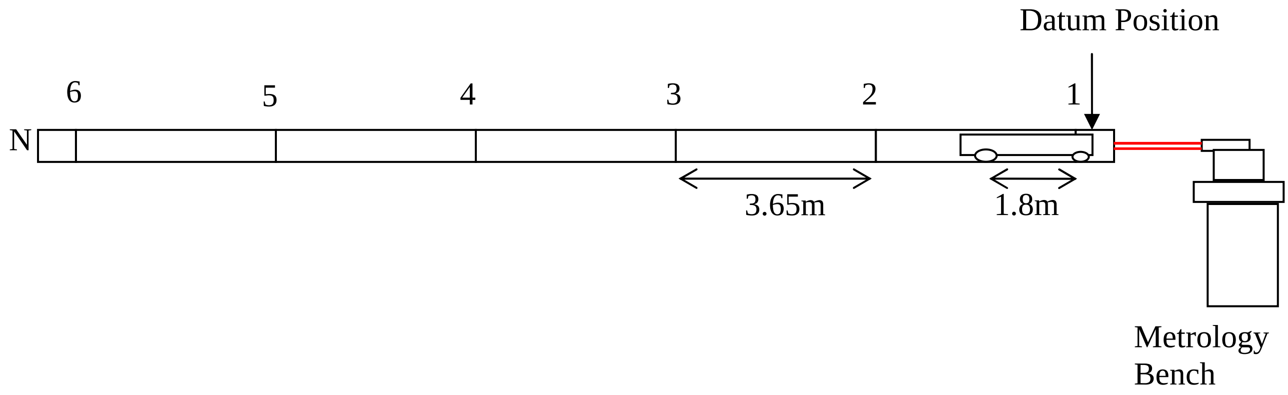

Figure 7 Layout of Delay Line Test Rig in COAST bunker showing join positions.

The trolley wheelbase is almost half the length of a pipe thus a join event would occur every 1.8m or thereabouts. For tracking at 10mm/s an event would occur every 180s whereas at 15mm/s an event can be expected every 120s. A two minute tracking test at 15mm/s is almost certain to contain a join disturbance.

Approximate metrology distances for the passing of front and rear wheels over each join are given in Table 16. The exact position will depend on where the datum target has been fitted and also in which direction the join event is encountered. Information on join quality was obtained from laser displacement measurements of the inner surface of the pipe and this is translated to the event size given in the table (from very small to small, large and very large).

Table 16 Approximate locations of joins for each wheel

Join No. N-S	Rear Wheel (m)	Event size	Front Wheel (m)	Event size
6	16.558	S	-	
5	12.901	S	14.701	VS
4	9.244	VL	11.044	L
3	5.587	L	7.387	VL
2	1.930	S	3.730	VS
1	-		0.073	S

Results from contiguous tracking tests at 15 mm/s over a number of joins are given in Table 17. Two of the tests fail on criteria but pass on overall requirements.

Tracking performance of both front and rear wheels passing over a join at different velocities and in different directions is given in Table 18. One of the worst joins, Join 3, was chosen for these tests. The velocities tested are ±0.2 mm/s, ±1 mm/s, ±5 mm/s and ±10 mm/s (results for ±15 mm/s are already available in Table 17). Travelling in the positive direction produces larger disturbances and so graphical output is only provided for positive velocities. All these tests pass the criteria.

Table 17 Tracking performance over joins 2, 3, 4 and 5 at 15 mm/s

File No. dllog_	Vel mm/s	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS) [pk-pk error of join event]	Overall Pass/Fail (join)	Pdf graphical Output
20110402 _112211	-15	30	P	Front wheel at join 5 6.3 nm	Pass	Apr02_ _112211_OPD
20110402 _112510	-15	30	P	Rear wheel at join 5 7.1 nm	Pass	Apr02_ _112510_OPD
20110402 _112716	-15	30	F	Front wheel at join 4 6.1 nm [1187 nm due to slope]	Fail	Apr02_ _112716_OPD
20110402 _112940	-15	30	F	Rear wheel at join 4 6.4 nm [1422 nm due to slope]	Fail	Apr02_ _112940_OPD
20110328 _151936	+15	30	F pk-pk	Front wheel at join 3 6.5 nm [1016 nm]	Pass	Mar28_ _151936_OPD
20110328 _151715	+15	30	P	Rear wheel at join 3 6.1 nm [491nm]	Pass	Mar28_ _151715_OPD
20110328 _151457	+15	30	P	Front wheel at join 2 6.1 nm [<100 nm]	Pass	Mar28_ _151457_OPD
20110328 _151136	+15	30	P	Rear wheel at join 2 6.5 nm [<300 nm]	Pass	Mar28_ _151136_OPD
20110328 _152200	+15	30	P	Front wheel at join 4 5.8 nm [<200 nm]	Pass	Mar28_ _152200_OPD
20110328 _153256	-15	30	F 120ms	Front and rear wheels at join 3 5.7 nm [<200 nm each event]	Pass	Mar28_ _153256_OPD
20110328 _153807	-15	30	P	Front wheel at join 4 Rear wheel at join 5 6.5 nm [480nm and 454nm]	Pass	Mar28_ _153807_OPD

Table 18 Tracking performance while traversing join 3 at various velocities in each direction.

File No. dllog_ 20110404	Vel mm/s	Time (s)	P/F on criteria	Results/Comments [OPD Jitter of 10 ms bins (RMS)]	Overall Pass/Fail	Pdf graphical Output Apr04-
_105736	+0.2	100	P	Front wheels: [4.9 nm]	Pass	_105736_OPD
_110313	-0.2	100	P	Front wheels: [5.0 nm]	Pass	
_131114	+0.2	100	P	Rear wheels: [5.2 nm]	Pass	_131114_OPD
_132136	-0.2	100	P	Rear wheels: [5.3 nm]	Pass	
_110833	+1	30	P	Front wheels: [5.2nm]	Pass	_110833_OPD
_111929	-1	30	P	Front wheels: [5.3 nm]	Pass	
_132651	+1	30	P	Rear wheels: [5.6 nm]	Pass	_132651_OPD
_132803	-1	30	P	Rear wheels: [5.7 nm]	Pass	
_112222	+5	30	P	Front wheels: [5.4 nm]	Pass	_112222_OPD
_112336	-5	30	P	Front wheels: [5.4 nm]	Pass	
_132907	+5	30	P	Rear wheels: [5.8 nm]	Pass	_132907_OPD
_133128	-5	30	P	Rear wheels: [6.0 nm]	Pass	
_135630	+10	30	P	Front wheels: [5.8 nm]	Pass	_135630_OPD
_135744	-10	30	P	Front wheels: [5.8 nm]	Pass	
_135118	+10	30	F	Rear wheels: [5.7 nm]	Fail	_135118_OPD
_135305	-10	30	P	Rear wheels: [5.6 nm]	Pass	

Results

When tracking at 15mm/s over the worst joins two of the tests fail on slope of the error and two other tests fail on criteria but pass on overall requirements:

(i) one failure on peak-to-peak error of just over 1000nm (the criterion is 500nm) but this is allowed at a join provided the fringe tracker does not loose lock. Failing to meet this criterion will lead to a small momentary loss in fringe visibility.

(ii) one failure of exceeding the number of consecutive 10ms bins for which the OPD error exceeds 15 nm RMS. This happens for only 120ms but is allowed provided the loss of data does not exceed 0.5 seconds in any 60 second period (INT-406-TSP-0002 section 5.2 ‘Sidereal tracking and jitter’).

There are no failures when tracking at velocities from 0.2 mm/s to 10 mm/s over one of the worst joins in either direction for both front and rear wheels.

Conclusions

The dynamic tracking performance at all velocities is well within the OPD error criteria, even when crossing joins. All the tests carried out meet the performance requirements except for two which fail because of the slope of the pipe. Failures of the peak to peak criterion due to the slope of bad sections of pipe in the test rig are of no consequence. It is likely that MROI pipe will not lead to this magnitude of deviation of the OPD error, but if it were then the fringe tracker would act to remove it, because the deviation takes place over timescales (10s of seconds) that are much longer than the timescale on which the fringe tracker corrects OPD errors.

3.3.3 Trolley Trajectory Tests

Three tests are grouped under this heading. The results are presented in the following subsections:

- Test trajectory acquisition and time by switching from tracking at one position to tracking at another position for a range of distances e.g 4mm, 20mm, 100mm, 200mm, 500mm, 2m 5m and 10m.
- Test tracking at constant accelerations of 0.3μms^{-2}, 0.625μms^{-2} and 1.25μms^{-2} including reversing direction while tracking with a realistic trajectory.
- Test response to fringe tracking offsets of 0.5 μm,1μm and 10μm

3.3.3.1 Slew times

The purpose of these tests is twofold:

1. To test the slew time requirement defined by the slew speed and maximum acceleration.
2. To demonstrate the trajectory acquisition and time by switching from tracking at one position to tracking at another position for a range of distances and to e.g 4mm, 20mm, 100mm, 200mm, 500mm, 2m, 5m, 10m and 16m.

Table 19 Slew time results

File No. dllog_ 20110330	Slew Dist (mm)	Time (s)	P/F on criteria	Results/Comments Time to tracking at new position including 3s command delay.	Overall Pass/Fail	Pdf graphical Output Mar30-
_144901	4	20	P	5s	Pass	
_145241	10	20	P	5.4s	Pass	
_145348	20	20	P	7s	Pass	
_150726	50	30	P	8s	Pass	
_150915	100	30	P	10s (2s delay in requesting track)	Pass	
_151017	200	30	P	8s	Pass	
_151218	500	40	P	9s	Pass	
_151458	1000	40	P	11s	Pass	
_151726	2000	40	P	12s	Pass	
_151957	5000	40	P	17s	Pass	
_152438	10000	40	P	24s	Pass	_152438_MET
_152736	16000	60	P	35s	Pass	

Results

Results are shown in Table 19. The slew speed and acceleration of the trolley can be ascertained from the test undertaken at 15:24 i.e. _152438.

(iii) The slew speed is 0.7m

(iv) The acceleration is 0.41ms^{-2}

For a slew of 10m the time taken is 24s. This can be used as a basis from which the time to reposition the trolley through greater distances can be calculated. The slew speed is 0.7 m/s and thus 1.43s can be added for each addition metre of travel. Hence for a 190 m slew the time taken would be 24 + 180 x 1.43s = 281.4s or 4 minutes 21.4 seconds.

Conclusions

The time taken from tracking at one position to tracking at another position meets the requirement up to and including a slew of the length of the delay line i.e. a slew from any position to any other position in less than 5 min.

3.3.3.2 Accelerations and reversal

The purpose of these tests is to demonstrate that the tracking OPD requirements are met over a range of constant accelerations and also through reversal of the trolley under realistic trajectory conditions. The tests are:

3. Test tracking at constant accelerations of 0.3μms^{-2}, 0.625μms^{-2} and 1.25μms^{-2}
4. Test reversing direction while tracking with a realistic trajectory

The results of these tests are shown in Table 20. Some files also have an associated -MET pdf figure showing the trajectory followed.

Table 20 Acceleration and tracking reversal results

File No. dllog_ 20110401	Acc'n μms^{-2}	Time (s)	P/F on criteria	Results/Comments OPD Jitter of 10 ms bins (RMS)	Overall Pass/Fail	Pdf graphical Output Apr01-
_143358	0.3	30	P	5.8 nm	Pass	_143358_OPD
_143651	0.625	30	P	5.7 nm	Pass	_143651_OPD
_143826	-0.625	30	P	6.7 nm	Pass	_143826_OPD
_144421	-1.25	30	P	7.7 nm	Pass	_144421_OPD _144421_MET _144421_MOT _144421_PRE _144421_PSD
_144610	+1.25	30	P	8.0 nm	Pass	_144610_OPD _144610_MET _144610_MOT _144610_PRE _144610_PSD
_145230	+1.25	100	P	8.1 nm [Through reversal]	Pass	_145230_OPD _145230_MET _145230_MOT _145230_PSD
_145631	-1.25	200	P	7.8 nm [Through reversal]	Pass	_145631_OPD

Results

The tracking tests are carried out with an initial velocity of 1mm/s except for the reversal test where the initial velocity is 0.1mm/s. The results are consistent with tracking at constant velocity except that at extremely slow velocity, either side of reversal, there is an increase in jitter which increases the overall RMS.

Conclusions

The requirements to meet the OPD criteria while tracking with acceleration and through reversal have been met.

3.3.3.3 Fringe tracker offsets (step response)

The purpose is to test the OPD response to fringe tracking offsets of up to 10μm. The test system is not capable of yet of pre-filtering the offset command and so offsets are applied as a single step in one sample period (200μs).

The offsets applied are ±0.5μm, ±1μm and ±10μm and the results are shown in Table 21.

Table 21 Fringe tracker offset step response results

File No. dllog_ 20110402	Offset μm	Time (s)	Settling Time (ms)	Results/Comments	Overall Pass/Fail	Pdf graphical Output Apr02-
_110727	0.5	30	<20	60% overshoot	Pass	_110727_MET
"	1	30	<20	"	Pass	"
_111533	5	30	<20	"	Pass	_111533_MET
"	10	30	<20	"	Pass	"
_110727	-0.5	30	<20	"	Pass	_110727_MET
"	-1	30	<20	"	Pass	"
_111533	-5	30	<20	"	Pass	_111533_MET
"	-10	30	<20	"	Pass	"

Results

The step response overshoots slightly more than is the case when the trolley is at atmospheric pressure. This is expected because there is no element of air damping acting on the cat's eye in vacuum. Consequently the settling times are longer but all are still less than 20 milliseconds, well within the requirement.

Conclusions

The requirements are met for all step sizes. The overshoot can be limited by adding additional functionality to the code in the VME system to ensure that any step requests are pre-filtered.

3.3.4 Trolley Shear Loop Tests

The purpose of these tests is to demonstrate that:

1. the requirements on shear residuals are met
2. the shear deviations can be measured

To demonstrate (1) the trolley is tracked at 15mm/s and also 0.7m/s and the shear residuals are logged.

To demonstrate (2) the trolley is slewed at 90mm/s with the shear loop open and the shear deviations are logged.

The results of these tests are shown in Table 22.

Table 22 Shear loop test results

File No. dllog_	Vel (mm/s)	Time (s)	Req't	Results/Comments Shear residuals (mm RMS)	Overall Pass/Fail	Pdf graphical Output
20110401 _131212	+15	120	0.5mm rms	x = 0.023; y = 0.046	Pass	Apr01 _131212_SHE _131212_OPD
20110404 _142114 _141205	 +700 -700	 30 30	 3mm rms	Calculated over actual motion: x = 0.675; y = 0.754 x = 0.683; y = 0.798	 Pass Pass	Apr04- _142114_SHE _142114_MOT _141205_SHE _141205_MOT _141205_PRE
20110330 _105401	-90	200	-	Open shear loop Deviations do not saturate	Pass	Mar30- _105401_SHE

Results

The shear residuals for tracking at 15mm/s are calculated from one of the contiguous tracking tests. The residuals are more than a factor of ten better than the requirement.

The shear residuals for slewing at 0.7 m/s are calculated over the actual motion and do not include residuals while the trolley is stationary. The residuals are more than a factor of three better than the requirement.

The open loop shear measurements in X indicate pipe deviations of ~10 mm peak to peak and those in Y are ~13mm peak to peak. The return beam from the trolley is distorted and vignetted and so the actual pipe deviations will be somewhat greater. The shear system can be used to measure deviations of the pipe up to ±5mm of the nominal centreline and can indicate deviations greater than this without completely saturating.

Conclusions

The requirements for shear residuals during slewing and tracking have are met. The shear deviations can be measured and pipe deviations greater than ±5mm are also indicated.

3.3.5 Trolley Roll Loop Tests

The purpose of these tests is to demonstrate that:

1. the requirement on roll control of the trolley is met
2. the trolley is stable with steering centred and the roll loop open

To demonstrate (1) the trolley is slewed at 90mm/s and the roll angle is logged

To demonstrate (2) the trolley is slewed for the full length of the test rig at a constant velocity of 90mm/s while logging with steering loop off but centred and the roll logged (this checks trolley's balance about the roll axis).

The test results are shown in Table 23.

Table 23 Roll loop test results

File No. dllog_	Vel (mm/s)	Time (s)	Req't	Results/Comment	Overall Pass/Fail	Pdf graphical Output
20110401 _104038	200	200	-	Open loop steering angle 0 rad gives <1 mrad/m.	Pass	Apr01 _104038_STE _104038_MOT
20110413 _134447	+90	200	±0.3º (5.2mrad)	+11.4 to -4.8 mrad	Fail	Apr13 _134447_STE
20110413 _140141	-90	200	±0.3º (5.2mrad)	+5.7 to -7.6 mrad	Fail	Apr13 _140141_STE

Results

The steering zero point was adjusted so that the overall slope of the steering error when the roll loop is open is less than 10mrad in the length of the test rig. This is shown in the test at 200 mm/s.

The roll deviations of the trolley measured in the second and third tests fail to meet requirements. The reason for this is the poor straightness of some pipes in the test rig and the rate of curvature of the pipe close to some joins. This is evident when comparing the roll performance in each direction: roll performance when travelling in the negative direction almost meets specification.

Note the action of the velocity limit in the motor velocity at either end of the pipe in the first test.

Conclusions

The steering accuracy requirement has not been met. The maximum deviations are associated with the bad sections of pipe. The responsiveness of the steering servo is at maximum but the range of steering angle could be easily increased further. MROI pipe is much straighter than the test rig and it is unlikely that further action would be needed.

Note that the roll requirement is based solely on the perceived need to track the trolley accurately across the joins so that the OPD requirements are met. It has been shown in the tracking tests that the joins themselves do not cause failure to meet the OPD requirements and so such stringent roll control is not necessary.

3.3.6 Secondary Tip/tilt Tests

The purpose of these tests is to demonstrate that:

1. the tip/tilt range provides for ±5mm of shear
2. the tip/tilt slew rate meets the 4.7mrad/s minimum requirement

To demonstrate both (1) and (2) the tip/tilt actuator is switched between its positive and negative extremes in each axis and the resulting deflections of the metrology beam are measured by the shear system and logged. The results are shown in Table 24

Table 24 Secondary tip/tilt test results

File No. dllog_ 20110405	test	Req	Result	Comment	Overall Pass/Fail	Pdf graphical Output Apr05-
_090306	Tip/tilt range X	±5 mm	+8.5 mm -4.7 mm	A range of 13.2mm about chosen zero point	Pass	_090306_SHE
_090714	Tip/tilt range Y	±5 mm	+7.3 mm -6.7 mm	A range of 14mm about chosen zero point	Pass	_090714_SHE
_090306	Tip/tilt slew rate X	> 4.7 mrad/s	38.2 mrad/s 10.4 mrad/s	To 63% of maximum To 95% of maximum	Pass	_090306_SHE
_090714	Tip/tilt slew rate Y	> 4.7 mrad/s	46.6 mrad/s 8.4 mrad/s	To 63% of maximum To 95% of maximum	Pass	_090714_SHE

Results

The range of the tip/tilt actuator is measured with the trolley closest to the metrology system. This is still an arbitrary tip/tilt position in the pipe (i.e. there is already some shear) and therefore only the span is meaningful in this test. The actual range of tip/tilt is >30% bigger, in both axes, than the requirement.

The slew rate of the tip/tilt actuator is calculated for one time constant, i.e. 63% of the maximum deviation, and also the time to reach 95% is used to give a indication of response time.

Conclusions

The range and slew rate of the tip/tilt actuator meets the requirements.

3.3.7 Secondary Focus tests

The purpose of these tests is to demonstrate that focus actuator meets the 20µm minimum resolution requirement.

To demonstrate this, the focus actuator is moved in increments of 5µm, 10µm and 20µm and the encoded value is logged. This will establish the effective resolution of the mechanism.

An addition test is carried out to test that the focus range available is sufficient to cover the uncertainty in the actual focus position due to manufacturing tolerances of the primary mirror.

Test results are shown in Table 25.

Table 25 Secondary focus test results

File No. dllog_ 20110407	Test	Req't	Results/Comments Focus encoder readings in mm	Pass Fail	Pdf graphical Output Apr07-
_135129	±5µm ±10µm ±20µm	20µm	-1.051→ -1.055→ -1.049→ -1.044→ -1.051 -1.051→ -1.061→ -1.048→ -1.038→ -1.051 -1.051→ -1.071→ -1.051→ -1.031	Pass	_135129_FOC
_135912	range	1mm	-0.3 mm → -1.3 mm in 100 µm steps	Pass	_135912_FOC

Results

The resolution and repeatability of the focus actuator is ~3µm for 5 µm and 10 µm steps and rather better for 20 µm steps.

The range of the focus actuator is determined by withdrawing the focus actuator until no change in position is measured on the focus encoder; this occurred at -1.368 mm. The focus drive was then positioned to -0.3 mm and stepped in 100 µm steps to -1.3 mm

Additional tracking tests were conducted to check that the OPD criteria are met at the extremes of the range.

Conclusions

The range and resolution of the focus drive meets the requirements.

3.3.8 Datum Tests

The purpose of these tests is to demonstrate the requirements on datum stability are met.

The test procedure is to acquire datum at least 10 times from different starting positions and note the metrology value at the instant before the datum causes a reset to zero position. The variability of the reset position may be due to:

1. Repeatability of the switch function
2. Stability of metrology table with respect to test rig
3. Position of cat's eye with respect to trolley shell (the datum target is mounted on the trolley)
4. A change in roll angle of the trolley (the edge of the target material may not be exactly normal to the direction of travel of the trolley)
5. A change in vacuum/atmospheric pressure (the datum switch is located on the end stub of pipe and so is not related directly to the anchor position).

Items 1 to 4 in the above list have been directly tested at atmosphere in section 3.2.5 where a set of datum 'seeks' were carried out from different positions in the pipe. A similar test was carried out in vacuum and is presented in Table 26 Test of datum repeatability from various distances. Here the data are presented in more detail and in order of the sequence of datum moves performed. The repeatability of the datum positions is 3.65 μm RMS.

Table 26 Test of datum repeatability from various distances.

Datum move	Distance (m)	Datum Position (μm)	Differential Position (μm)	Trolley Roll (mrad)
1	0.2	-1.7	-10.8	-2.4
2	1	-0.3	-10.8	-4.9
3	0.4	0.0	-9.9	-5.0
4	2	+1.6	-11.6	-4.9
5	0.2	+4.6	-10.8	-
6	5	+4.9	-11.2	-1.8
7	5	+4.0	-10.8	-1.8
8	4	+7.9	-10.3	-5.8
9	0.5	-4.2	-10.3	-2.6
10	1	-1.3	-11.2	-5.0
11	6	+1.5	-11.2	-5.1
12	10	+2.5	-10.8	-5.5
13	15	+1.9	-11.2	-5.9
14	0.3	-5.5	-10.3	-1.7
RMS		3.65		

Tests of the repeatability of the datum position over each day throughout the testing period are presented in Table 27 Datum repeatability throughout each day during testing period.. There are several comments worth noting:

1. Between April 2nd and April 4th the datum was not reset and only changed by 17.4 μm..
2. On April 7th the datum was set at atmospheric pressure and was 852μm different at 2 millibar.
3. Test spans of five hours and six hours were achieved on April 1st and April 4th respectively
4. The overnight datum test April 12th/13th gave a +168 μm difference which then recovered by 116 μm

after pumping is probably due to some hysteresis in the test rig anchor.

Table 27 Datum repeatability throughout each day during testing period.

Date	Time	Vacuum state: Atmosphere or Vacuum (mb)	Datum Position (μm)	Differential Position (μm)	Trolley Roll (mrad)	Comments
Apr01	10:50					Datum set
	10:55	1.5 mb	+1.8	-10.5	-6.0	(pumping)
	14:00	(pumping)	+16.8	-11.2	-6.0	After reversing 2 m
	14:28	1.0 mb	-8.4	-10.8	-6.0	After tracking tests
	15:29	"	+7.8	-11.2	-4.0	After tracking tests
	16:11	"	+3.0	-11.6	-6.7	
Apr02	10:30	8.6 mb				Datum set
	12:20	1.1 mb	+8.1	-10.3	-	From 1 m
	12:35	"	-9.1	-9.9	-8	
Apr04	09:45	11.2 mb	+17.4	-9.9	-1.0	(over 2 nights)
	12:00	0.7 mb	+9.8	-10.3	-2.0	From 0.5 m
	12:35	"	-15.4	-10.8	-5.5	From 7 m
	14:07	"	+17.3	-11.2	-6.9	From 1 m
	14:35	"	-15.4	-11.2	-6.0	After join tests & from 5.4 m
	15:00	"	+0.7	-11.2	-6.0	From 7.35 m
	15:21	"	+3.1	-10.3	-1.3	From 0.5 m
	15:55	"	-4.0	-9.9	-5.5	After slew test & from 7.6 m
Apr05	10:55	4.2 mb				Datum set
	11:22	"	-6.5	-11.2	-5.0	After tests
Apr06	0950	Atm				Datum set
	1210	Atm	-1.2	-11.2	-2.4	After tests
Apr07	11:00	Atm				Datum set
	14:15	2.1 mb	-852	-9.9	-	After pumping down
	14:18	"	+4.3	-9.9	-5.0	From 0.7 m
	15:10	"	-0.9	-10.8	-5.5	From 0.3 m
Apr08						Power cuts to site
	09:30	8.2 mb				Datum set, pumping down
	11:00	1.5 mb	+4.4	-9.9	-4.3	
	12:25	"	+7.8	-10.8	-4.6	After tracking tests
Apr11	~14:00					Datum set
Apr12	15:05	6.6 mb	-25.8	-10.3	-	
	16:20	0.44 mb	+62.1	-10.8	-	
	17:10	"	+12.5	-10.8	-	
Apr13	14:50	6.7 mb	+168.5	-9.9	-	Pumping down
	15:50	0.75 mb	-116.2	-9.9	-	

Results

Based on these results the repeatability of the datum position throughout a day of testing is <10 μm RMS and the repeatability of the datum from night to night is <100 μm RMS.

Conclusions

The performance of the datum facility meets the requirements.

3.3.9 Thermal test results

This section gathers together data from tests made throughout the testing period. During this period, the trolley was left powered over several days and nights. Temperature results are shown in Table 28 and a diagram of the position of trolley sensors is shown in Figure 8.

The trolley was powered continuously for five days, from March 30th to April 5th. It can be seen that the trolley took approximately 24 hrs to reach its maximum temperature of about 43.5ºC in the PC104 stack. The maximum temperature reached in the PC104 stack after sitting idle overnight was 44.4 ºC and the ambient temperature at this time was 13 ºC. At atmospheric pressure, the temperature of the PC104 stack reaches only 27 ºC when the trolley is on the gurney (April 5th to April 7th) and about 33 ºC when in the pipe (March 30th).

Table 28 Trolley temperatures throughout the period of FATs testing

Date	Time	Front chassis	Secondary frame	Mid chassis	Primary cell	Rear bulkhead	PC104 stack	Amb	Comments
Mar30	12:21	12.5	14.5	12.2	14.5	12.5	18.2	12.0	At atm.
	14:19	13.1	14.6	13.0	14.6	15.8	33.5	“	pumping
	16:45	14.2	15.9	14.1	17.3	19.5	38.2	“	~3 mb
Apr01	10:10	16.4	18.7	17.8	23.5	25.0	41.0	“	5.2 mb
	11:21	16.6	18.6	17.6	23.8	25.2	41.3	“	1.5 mb
	11:40	16.4	18.7	17.6	23.7	25.4	42.5	“	“
	12:25	16.1	18.5	16.8	23.4	25.0	42.8	“	“
	14:03	16.2	18.3	17.0	23.2	25.1	43.5	“	“
	15:52	16.2	18.4	17.1	23.3	24.9	43.1	“	“
Apr02	11:37	16.7	18.9	17.6	24.2	25.7	42.9	“	8.6 mb
	12:29	16.8	18.9	17.7	24.0	25.9	43.9	“	2.3 mb
Apr04	09:49	16.9	18.8	17.9	23.8	25.6	41.8	12.5	pumping
	11:57	16.6	19.1	17.9	24.1	25.9	44.3	“	0.7 mb
	14:11	16.7	18.9	17.7	23.8	26.0	44.1	“	“
	14:51	16.5	18.8	17.4	23.9	25.8	43.9	“	“
	15:21	16.5	18.7	17.4	23.9	25.6	43.8	“	0.8 mb
	16:10	16.5	18.5	17.3	23.7	25.2	43.5	“	“
Apr05	10:03	17.0	19.2	18.1	24.3	26.0	42.9	“	5.8 mb
	11:22	17.3	19.4	18.2	24.2	26.0	42.6	“	“
	Brought test rig up to atmosphere & powered off trolley for removal								
	14:22	17.1	17.1	14.8	20.0	14.8	21.2		Power-up
	16:10	14.3	16.5	14.4	18.5	16.5	25.1		On gurney
	17:10	14.6	16.8	14.5	18.5	17.4	26.7		“
	Trolley powered off overnight – on gurney								
Apr06	10:16	13.2	14.5	12.5	14.9	13.0	21.3	13.0	Power-up
	16:26	14.8	17.2	14.8	17.8	18.0	27.1	“	On gurney
	Trolley powered off overnight – on gurney								
Apr07	10:46	13.5	14.9	13.0	15.5	14.2	25.2	“	
	12:21	13.7	15.5	13.4	15.5	15.5	27.1	“	
									Pumping
	13:20	14.1	15.6	14.2	16.8	18.4	36.2	“	2.1 mb
	15:10	14.2	16.0	14.3	17.5	19.5	37.7	“	
Apr08	11:09	17.8	19.7	18.6	24.9	26.8	44.4	“	Idle
	12:20	17.9	19.9	18.8	24.9	26.6	44.1		After tests

The FDR tests showed that the highest temperatures on the trolley were reached after 24 hours with the trolley stationary. The reason that temperatures reach their highest is that the delay line pipe has also warmed due to conduction and radiation from the trolley wall to the pipe wall. As soon as the trolley moves to a new section of pipe wall its temperatures start to fall by ~ 2ºC.

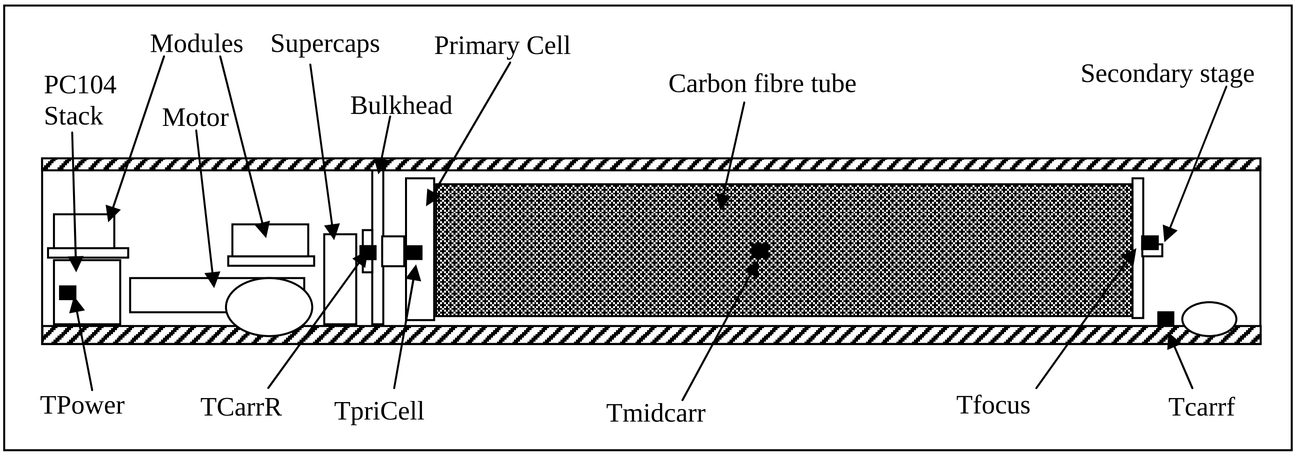

Figure 8 Standard placement of the trolley temperature sensors

The position of the temperature sensors is described here:

- Tpower is mounted on the heat sink of the PMAC board and close to the PC104 power supply heat-sink. It is at the hottest part of the stack but is not necessarily at the hottest component.
- TCarrR is mounted on the rear of the voice coil bulkhead, inside the electronics compartment.
- TpriCell is mounted on the back plate of the primary mirror cell.
- Tmidcarr is mounted on the inside of the trolley chassis opposite a point which is mid-way along the length of the cat's eye.
- Tcarrf is mounted on the trolley chassis between the front cat's eye flexure and the front wheel assembly.
- Tfocus is mounted on the centre-piece of the secondary structure close to the focus mechanism.

Results

The temperatures in the trolley take about 24 hrs to stabilise from power-up. This is consistent with the results obtained during the FDR tests.

The maximum temperature of the PC104 stack reached 44.4 ºC when the ambient temperature was 13 ºC in the bunker. This suggests that a temperature difference of 31.4 ºC from the maximum DLA temperature which is 25 ºC at MROI will produce a peak PC104 stack temperature of 56.4ºC which is well below the 65ºC recommended by component manufacturers.

From power-up the temperature of the cat's eye secondary structure increases by 5 ºC while the primary cell increases by <10 ºC. Whilst operating (slewing or tracking to different parts of the pipe) these temperatures change by <1 ºC. Since the CTE of the cat's eye assembly is expected to be <1 part in 10^6 and the tolerance on focussing the cat's eye is 5 μm there should be no need to refocus the cats eye during normal operations on a day to day basis, even from power-up.

Conclusions

The trolley temperature performance is within requirements both for maximum permissible temperature and for focus stability. This means that the trolley can be operated with a DLA temperature of up to 25 ºC and focus variations will be less than 5 μm during night time operation. In fact it is unlikely that re-focussing will be required for several weeks unless there is a large (>4 ºC) variation in DLA temperature.

4 Summary of factory acceptance test results

In this section the factory acceptance test results are summarised in tables which are based on the layout of the Production Trolley Factory Acceptance Tests (AD02).

4.1 Test at atmosphere

4.1.1 Trolley slew tests

Test No.	Test Description	Primary objective	Subordinate objectives	Results
1	Check velocity ramping under VME control by moving fixed distances (plus and minus): 4mm, 10mm, 20mm, 50mm 100mm 200mm 500mm 2m.	Test repositioning time Delay precision	Check track/slew switching	**Pass** **Pass**
2	Carry out a 17m slew with the maximum velocity set to +0.7m/s	Check metrology lock	Check time Check power	**Pass**
3	Carry out a 17m slew with the maximum velocity set to -0.7m/s	Check metrology lock	Check time Check power	**Pass**

4.1.2 Trolley tracking tests

Test No.	Test Description	Primary objective	Subordinate objectives	Results
1a	Test tracking at rates of (plus and minus) 0.1mm/s, 0.2mm/s, 0.4mm/s, 0.8mm/s and then 1 to 15mm/s in increments of 1mm/s. Steering loop closed.	Test of OPD performance		**Pass**
1b	If necessary, repeat a constant velocity tracking test where steering is actuated.	Test of steering influence on OPD		**Pass**
2	Continuous tracking for 10 minutes at the following velocities: 0.2mm/s, -1mm/s, +5mm/s and -10mm/s. (log in sections 120s to limit the size of log files)	Test of OPD performance over typical observation time		**Pass**[1]
3	If necessary repeat tracking tests across joins – position trolley so as to cross join.	Test of performance over join		**Pass**

Notes:

[1] Failures on peak to peak OPD error specifically due to a join event in fact pass the test overall as this is allowed to happen for a join. Failures on peak to peak OPD error due to a substantial slope of the OPD error are caused by sections of pipe which have steep slopes or a rapid change in slope, particularly near the joins. The test rig pipe has several sections which are outside the specifications for delay line pipe. These test failures are due to the slope caused by these pipe sections. Failures of the peak to peak criterion due to the slope of bad sections of pipe in the test rig are of no consequence. It is likely that MROI pipe will not lead to this magnitude of deviation of the OPD error, but if it were then the fringe tracker would act to remove it, because the deviation takes place over timescales (10s of seconds) that are much longer than the timescale on which the fringe tracker corrects OPD errors.

4.1.3 Trolley trajectory tests

Test No.	Test Description	Primary objective	Subordinate objectives	Results
1	Test trajectory acquisition and time by switching from tracking at one position to tracking at another position for a range of distances e.g 4 mm, 20 mm, 100 mm, 200 mm, 500 mm, 1 m and 10 m	Check re-acquisition time & delay precision		**Pass**
2	Test tracking at constant accelerations 0.3 μms^{-2}, 0.625 μms^{-2}, 1.25 μms^{-2}.	Test of OPD performance		**Pass**
3	Test reversing direction while tracking with a realistic trajectory.	Test of OPD performance		**Pass**
4	Test response to fringe tracking offsets of 0.5µm and 1µm (also 10µm if can be rate limited)	Test offset response		**Pass**

4.1.4 Trolley roll and shear loop tests

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
1	Slew the trolley for the full length of the test rig at a constant velocity of 90 mm/s With steering and tip/tilt loops closed	Check tip/tilt	Check steering performance Check shear residuals	**Fail**[1] **Pass**
2	Slew the trolley at 0.7 m/s	Check tip/tilt range	Check shear residuals	**Pass**
3	Track the trolley at 15mm/s	Check shear residuals	-	**Pass**
4	Slew the trolley for the full length of the test rig at a constant velocity of 90 mm/s while logging with steering loop off but centred and check roll.	Check centre position of steering	-	**Pass**
5	Operate the tip/tilt actuator between its limits in both axes and measure the resulting shear of the metrology beam using the shear sensor.	Check tip/tilt range	-	**Pass**
6	Using the same results gathered in (4) obtain the slew rate of the tip/tilt device in both axes.	Check tip/tilt slew rate	-	**Pass**

Notes:

[1] The steering accuracy requirement has not been met. The steering servo is improved during vacuum tests but is still not meeting the derived requirement. The maximum deviations are associated with the bad sections of pipe. The responsiveness of the steering servo is at maximum but the range of steering angle could be easily increased further. MROI pipe is much straighter than the test rig and it is unlikely that further action would be needed.

Note that the roll requirement is based solely on the perceived need to track the trolley accurately across the joins so that the OPD requirements are met. It has been shown in the tracking tests that the joins themselves do not cause failure to meet the OPD requirements and so such stringent roll control is not necessary.

4.1.5 Datum tests

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
1	Acquire datum 10 times from close range and check the deviation from zero at the instant before the reset.	To check datum switch repeatability		**Pass**
2	Acquire datum 10 times from different starting positions: at, near, far. Check deviation as for test 1	To check datum stability		**Pass**
3	Acquire datum at various times through testing phase. Check deviation as for test 1	To check intra-night stability		**Pass**
4	Acquire datum the following day. Check deviation as for test 1	To check inter-night stability		**Not tested**

4.1.6 Focus mechanism tests

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
1	Request a range of focus positions to demonstrate the positioning resolution and repeatability (±5 μm, ±10 μm & ±20 μm)	Test focus resolution	Test repeatability	**Not tested**

4.1.7 Trolley limits tests

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
1	Drive trolley into each velocity pre-limit and check that velocity is limited to 100 mm/s	Test velocity limit functionality		**Pass**
2	Drive trolley into each final limit, check that trolley stops within allowed distance and will not drive further but will drive out of limit	Test final limit functionality	Check cat's eye current limit.	**Pass**

4.1.8 Vacuum integrity test

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
1	Pump down to 3 mbar and check pressure over next few hours.	Test of vacuum seals		**Holds**[1]

Notes:

[1] The test rig is not being tested and so small leaks were not tracked down. The pressure held sufficiently well that pumping was only necessary once per day.

4.2 Tests under vacuum

4.2.1 Trolley slew tests

Test No.	Test Description	Primary objective	Subordinate objectives	Results
1	Carry out a 17m slew with the maximum velocity set to +0.7m/s	Check metrology lock	Check velocity Check acc'n	**Pass** **Pass**
2	Carry out a 17m slew with the maximum velocity set to -0.7m/s	Check metrology lock	Check time Check power	**Pass** **Pass**
3	Carry out a sequence of slews at maximum velocity equivalent to 380m of delay line travel	Check power	Check temps Check RF	**Pass** **Pass** **Pass**

4.2.2 Trolley tracking tests

Test No.	Test Description	Primary objective	Subordinate objectives	Results
1	Test tracking at rates of (plus and minus) 0.1, 0.2, 0.4, 0.8 and 1mm/s, then 2 mm/s to 15 mm/s in 1 mm/s steps. Roll & shear loops closed.	Test of OPD performance		**Pass**
2	Continuous tracking for 10 minutes at the following velocities: 0.2mm/s, -1mm/s, +5mm/s -10mm/s & +15mm/s. (log in sections 120s to limit the size of log files)	Test of OPD performance over typical observation time		**Pass**[1]
3	Conduct tracking tests across selected joins at ±0.2 mm/s, ±1 mm/s ±5 mm/s, ±10mm/s and ±15mm/s for both front and rear wheels.	Test of performance over join	Check that specifications are not exceeded for >0.5s in 60s	**Pass**

Notes:

[1] These are due to sections of pipe which have steep slopes. See explanation in 4.1.2

4.2.3 Trolley trajectory tests

Test No.	Test Description	Primary objective	Subordinate objectives	Results
1	Test trajectory acquisition and time by switching from tracking at one position to tracking at another position: 4 mm, 10 mm, 20 mm, 50 mm, 100 mm, 200 mm, 500 mm, 1 m , 2m, 10 m and 15 m.	Check re-acquisition time		**Pass**
2	Test tracking at constant accelerations 0.3 μms^{-2}, 0.625 μms^{-2}, 1.25 μms^{-2}.	Test of OPD performance		**Pass**
3	Test reversing direction while tracking with a realistic trajectory.	Test of OPD performance		**Pass**
4	Test response to fringe tracking offsets of ±0.5 µm ±1 µm and ±10 µm	Test step response		**Pass**

4.2.4 Trolley roll and shear loop tests

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
1	Slew the trolley for the full length of the test rig at a constant velocity of 90 mm/s With steering and tip/tilt loops closed	Check tip/tilt	Check steering performance Check shear residuals	**Fail**[1] **Pass**
2	Slew the trolley at 0.7 m/s	Check tip/tilt range	Check shear residuals	**Pass**
3	Track the trolley at 15mm/s	Check shear residuals	-	**Pass**
4	Slew the trolley for the full length of the test rig at a constant velocity of 90 mm/s while logging with steering loop off but centred and check roll.	Check centre position of steering	-	**Pass**
5	Operate the tip/tilt actuator between its limits in both axes and measure the resulting shear of the metrology beam using the shear sensor.	Check tip/tilt range	-	**Pass**
6	Using results gathered in (4) obtain the slew rate of the tip/tilt device in both axes.	Check tip/tilt slew rate	-	**Pass**

Notes:

[1] The roll deviations of the trolley measured in the second and third tests fail to meet requirements. The reason for this is the poor straightness of some pipes in the test rig and the rate of curvature of the pipe close to some joins. This is evident when comparing the roll performance in each direction: roll performance when travelling in the negative direction almost meets specification. The responsiveness of the steering servo is at maximum but the range of steering angle could be easily increased further. MROI pipe is much straighter than the test rig and it is unlikely that further action would be needed. Note also that the roll requirement is based solely on the perceived need to track the trolley accurately across the joins so that the OPD requirements are met. It has been shown in the tracking tests that the joins themselves do not cause failure to meet the OPD requirements and so such stringent roll control is not necessary.

4.2.5 Focus tests

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
1	Request a range of focus positions to demonstrate the positioning resolution and repeatability (±5 μm, ±10 μm & ±20 μm)	Test focus resolution	Test repeatability	**Pass**
2	Step through focus range in 100 μm increments and back.	Check the focus range	Check repeatability	**Pass**
3	Tracking test at 1mm/s at either end of focus range	Check focus mechanism		**Pass**

4.2.6 Datum tests

Test No.	Test Description	Primary objective	Subordinate Objectives	Results
2	Acquire datum 10 times from different starting positions: at, near, far. Check deviation as for test 1	To check datum stability		**Pass**
3	Acquire datum at various times through testing phase. Check deviation as for test 1	Intra-night stability		**Pass**
4	Acquire datum the following day. Check deviation as for test 1	Inter-night stability		**Pass**

4.3 Conclusions

The factory acceptance tests of production trolley #1 are successful in every respect if it is accepted that the few failures to meet requirements are due to poor quality pipe. It can also be concluded that the trolley can be operated successfully in such pipe for these reasons:

(i) The trolley will successfully track across joints which are known to be bad and still meet all requirements.

(ii) The peak to peak error which occurs when traversing bendy pipe at velocities of 10 mm/s to 15 mm/s will be removed by the action of the fringe tracker. It can also be removed by including an ‘integral of error’ term in the calculations undertaken by the VME system to provide the low-latency correction signal. This has been demonstrated successfully in the last two days by modifying the prototype VME code.

(iii) The roll control of the trolley can be improved if necessary but in any case the derived requirement on roll error (conceived to ensure that the trolley crosses where the joins are good) has been shown to be unnecessarily small. The trolley has been able to meet the tracking requirements when crossing joins which are particularly bad.

5 Trolley OPD Test Criteria

5.1 Introduction

This section describes the test criteria which have been used to assess the performance of the delay line trolley in the acceptance tests undertaken at Cambridge and which will be used on the NMT campus. The data to be analysed are the OPD errors reported by the metrology system, which are sampled at a rate of 5 kHz. Since the metrology system provides trolley distance the OPD error is equal to twice the metrology value.

5.1.1 Definitions

Because of the potentially unfamiliar way in which the raw 5 kHz OPD error data are handled to determine whether the performance criteria have been met, it is important that there are clear definitions of the datasets referred to in this document. There are four key definitions the reader should be aware of:

"Observation":

This is the length of time the delay line has spent tracking and taking data. In a typical astronomical scenario, an "observation" is expected to last between 60 and 180 seconds.

"Signal":

This is the term used to describe the contiguous stream of 5 kHz samples of the OPD error for the whole or some defined part of an observation.

"Segment":

This is a small time-slice of the signal of a specific length. For the purposes of the delay line performance evaluation, there are three important segment lengths of 10ms, 35ms and 50ms. These correspond to the typical coherent integration time expected for interferometric measurements undertaken at 600nm, 1650nm and 2200nm respectively under good seeing conditions (0.75 arcseconds).

"Sequence":

This refers to the set of values of the RMS of the 5 kHz OPD error for a contiguous set of segments of the signal.

For example, an "observation" of 100s can be considered as consisting of 10^4 consecutive 10ms "segments". If the RMS value of the OPD error is computed for each consecutive segment, then the time sequence of these values is what we refer to as a "sequence".

5.1.2 Timescales

There are five timescales over which the OPD error must meet specific test criteria. These timescales are as follows:

(i) the whole signal length;

(ii) segment lengths of 10 milliseconds (associated with interferometric measurements at 600 nm);

(iii) segment lengths of 35 milliseconds (associated with interferometric measurements at 1650 nm);

(iv) segment lengths of 50 milliseconds (associated with interferometric measurements at 2200 nm);

(v) multiple consecutive segment lengths within the signal.

The test criteria for each of these timescales are defined in detail below.

5.2 *Test Criteria*

5.2.1 The signal

There are two criteria that need to be met:

(a) The mean value of the error must be less than 10 µm. This ensures that any mean offset between the commanded OPD and the actual OPD introduced by the delay line will be small compared to the expected instantaneous atmospheric OPD of approximately 60 µm peak-to-peak (i.e. 10 µm RMS). A figure of 10µm is also consistent with the expected intra-night baseline length stability of order 10 µm.

Failing to meet this criterion will impact the amount of time needed to find fringes before the fringe-tracking subsystem can "lock-up".

(b) The peak-to-peak deviation of the error must be less than 500 nm (i.e. roughly 83 nm RMS). This ensures that any contribution to the error in position of the "white light" fringe about a mean offset will be insignificant compared to the ~ 1 µm contribution resulting from residual atmospheric piston fluctuations above the 1 Hz fringe-tracker closed loop bandwidth.

Failing to meet this criterion will lead to a small reduction in fringe visibility. For example, a *fixed* error in the white light fringe position of ×4 the desired criterion will give a 0.7% reduction in fringe contrast for R = 30 in the J band.

5.2.2 The segments

The specified threshold value for the RMS of the error in a segment depends upon the segment length. The threshold values for each segment length are:

(i) 15nm for a 10ms segment length;
(ii) 41nm for a 35ms segment length;
(iii) 55nm for a 50ms segment length.

In each of these cases, the specified threshold arises directly from the top-level requirements that the OPD jitter be less than $\lambda/40$ at the wavelength of observation, giving no more than a 2.5% loss in fringe contrast over the specified segment length.

There are three criteria applied for each segment length:

(a) The RMS of the sequence must be less than the threshold. This ensures that the top-level visibility loss budget is satisfied.

(b) The number of segments for which the RMS error exceeds twice the threshold must be less than 1% of the total number of segments in the sequence. This ensures that even if the instantaneous threshold is exceeded, the resulting visibility loss in an observation will be less than 0.05% (as long as the standard deviation of the sequence under consideration is less than the threshold).

(c) The threshold must not be exceeded for 10 or more consecutive segments within the sequence. This ensures that the "dropouts" of the fringe-tracker will not occur due to long time periods of OPD jitter.

5.3 *Test analysis*

The test analysis we have reported encompasses all the test criteria and also provides other useful information. It is performed on the OPD error which is twice the value of metrology error returned with the telemetry data from the VME system and embedded in the FITS log files. The analysis scripts carry out the following computations on the OPD error signal:

(1) The mean value and the peak-to-peak value of the signal are computed and compared to the requirements. The tests are:

(i) S_{mean} < 10 µm
(ii) $S_{pk\text{-}pk}$ <0.5 µm

(2) The OPD error signal is divided into consecutive *x* ms segments (where *x* = 10 ms, 35 ms and 50 ms).

(3) For each *x* ms segment, the RMS of the OPD error is computed. This produces sequences of RMS's, hereafter referred to as sigmas, which we denote by the notation: *x*10-sigmas, *x*35-sigmas, and *x*50-sigmas.

(4) For each sequence, the histogram of values is plotted and the mean, median, and modal values are computed for information. The test for each sequence is:

(i) Are any members of *x*10-Sigmas > 15nm?
(ii) Are any members of *x*35-Sigmas > 41nm?
(iii) Are any members of *x*50-Sigmas > 55nm?

(5) For each sequence, the number times the sigma value is greater than the "threshold" is computed and represented as a percentage of the total number in the sequence. This is provided for information.

(6) For each sequence, the square root of the mean squared value is computed for assessing the validity of the subsequent test described below. The test outlined below will be valid as long as the following criteria are met:

(i) RMS(*x*10-Sigmas) < 15nm
(ii) RMS(*x*35-Sigmas) < 41nm
(iii) RMS(*x*50-Sigmas) < 55nm

(7) For each sequence, the number of times, N, that any sigma value is greater than twice the "threshold" is computed and represented as a percentage of the total number, L, in the sequence. The test for each sequence is:

(i) 100*N(*x*10-Sigmas) /L(*x*10-Sigmas) < 1%
(ii) 100*N(*x*35-Sigmas) /L(*x*35-Sigmas) < 1%
(iii) 100*N(*x50*-Sigmas) /L(*x*50-Sigmas) < 1%

(8) The number of times, N, there are M or more consecutive values in any sequence that exceed the threshold is computed together with the total time the threshold is exceeded for

these events. The value of M has currently been chosen as 10 and is based on the expected performance of the fringe-tracker. The tests are:

(i) For *x*10-Sigmas: N = 0
(ii) For *x*35-Sigmas: N = 0
(iii) For *x*50-Sigmas: N = 0

5.4 Test Results

These are presented in annotated plots on one sheet per test run. For long tests the FITS log files may be split into sequential files to be analysed separately in which case the results for each test run are tabulated on a title sheet. The individual plots are described below.

Each plot sheet contains:

1. A super-title giving the log filename and the conditions of the test run.
2. A plot of the OPD error with a title including the mean and peak-to-peak values and whether these have passed the test criteria.
3. A histogram of the de-trended error spread over one hundred bins.
4. A plot of the sequence of 10ms segment RMS values incorporating:
    a. a horizontal line indicating the threshold (or 1σ value) and with a title including: the mean, median and mode values;
    b. the mean-subtracted RMS of the sequence and the result of applying the test criteria;
    c. the number of times the threshold has been exceeded for 10 or more consecutive values, the total time whilst exceeded, and the result of applying the test criterion.
5. A histogram of the 10ms RMS values in 1nm bins incorporating vertical lines indicating the threshold (1σ value) and twice the threshold (2σ value) and with a title including the percentage of values exceeding the 1σ threshold and 2σ threshold, and the result of applying the test criterion.
6. A plot of the sequence of 35ms segment RMS values (as described in (4)).
7. A histogram of the 35ms RMS values (as described in (5)).
8. A plot of the sequence of 50ms segment RMS values (as described in (4)).

A histogram of the 50ms RMS values (as described in (5)).

Appendix A

CONTENTS

Appendix A consists of separate documents for reasons of convenience and file size. The documents are groups of Matlab figures from the analysis GUI converted to PDF form. A list of the available documents is given below.

Production Trolley #1 FATS Results INT-406-VEN-0301 Appendix A: Trolley #1 FAT Mar28 - Mar29.pdf

Production Trolley #1 FATS Results INT-406-VEN-0301 Appendix A: Trolley #1 FAT Mar30 - Mar31.pdf

Production Trolley #1 FATS Results INT-406-VEN-0301 Appendix A: Trolley #1 FAT Apr01.pdf

Production Trolley #1 FATS Results INT-406-VEN-0301 Appendix A: Trolley #1 FAT Apr02 - Apr07.pdf