MRO Delay Line

Derived Requirements

The Cambridge Delay Line Team

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Change Record

Revision	Date	Authors	Changes
0.1	2007-07-16	DFB	Initial version
0.2	2008-01-16	DFB	Clean up tables
0.3	2008-01-29	DFB	Version for comment
1.0	2008-01-31	DFB	Released version

Objective

To present requirements on the subsystems of the MROI delay line that can serve to guide the design and testing of the subsystems of the delay line and to guide the verification that the top-level delay-line requirements have been met.

Scope of this document

This document is concerned with meeting the performance requirements in all of the subsystems of the MROI delay line. It does not address requirements to do with cost or maintenance.

1 Introduction

The top-level functional and performance requirements for the MROI delay lines (DLs) presented in INT-406-TSP-0002 present requirements on the DLs which are independent of the particular implementation adopted. This document derives, for the implementation that has currently been adopted, the requirements that these top-level requirements impose on all subsystems of the chosen design (for the purpose of this document, the DL subsystem of the MROI system is called a "system" and the next-level components of the DLs are called "subsystems"). These derived requirements can then be used (a) in the detailed design of these subsystems and (b) as part of the verification that the proposed design meets the top-level requirements, either by indicating which subsystem-level tests will be necessary, or by indicating design requirements which can be verified by inspection.

This document is organised on a subsystem-by-subsystem basis. At the end, a number of critical error budgets are presented which show that the requirements are satisfied across the system as a whole.

For each requirement, a brief rationale for the requirement is given, including all assumptions but without giving the full derivation: in most cases the derivation is straightforward given the assumptions.

2 Trolley requirements

2.1 Catseye

2.1.1 Primary mirror

Clear aperture: Minimum 300 mm. The science beams are separated by 165 mm (centre-to-centre) and the clear aperture for each beam is 125 mm diameter plus an additional 10 mm to allow for a shear of the beams with respect to the trolley of ±5 mm.

Focal length: 1295 mm±6.5 mm. Tolerance is within range of secondary focussing stage.

Surface error: $\lambda/25$ (25.3 nm) RMS wavefront error (single pass) over clear aperture. From the science beam optical error budget.

Support error: 10 nm WFE single pass. From the science beam optical error budget.

Thickness: 50mm±1mm. Aspect ratio of 6:1 simplifies support requirements.

Material: Zerodur. CTE of 10^{-7}/K implies a wavefront error of 10nm for a 1K temperature differential across the mirror.

Centration: 3mm wide chamfer on front outside diameter edge normal to within 2 arc minutes of optical axis. Optical axis to be within 1 mm of mechanical axis (as defined by chamfer and mirror circumference). Required to keep the spot in the centre of the secondary mirror.

2.1.2 Secondary mirror

Diameter: >8 mm to allow ±3.3mrad pitch and yaw of catseye.

Tip/tilt range: ±3.9 mrad, to allow for ±5 mm of pipe non-straightness. A ±5 mrad actuator allows for ±1 mrad of static alignment error to be taken out electronically.

Tip/tilt slew rate: 4.7 mrad/sec per axis, assuming a trolley travelling at 0.7 m/s along a pipe with a a ±5 mm sinusoidal oscillation at a wavelength of 12 ft.

2.1.3 Focus stage

Focus resolution: 20μm. From the science beam optical error budget

Focus drift: 5μm after focussing. From the science beam optical error budget

2.1.4 Tube

Tube CTE: Absolute value $<0.77\times10^{-6}$/K. Allows a 5K temperature change before requiring refocusing.

2.2 Drive system

Slew speed 0.7 m/s, to meet slew time requirements.

Maximum acceleration 0.14 m/s^2 (0.014 g), to meet slew time requirements.

2.3 Voice coil

Drive current: Continuous current $>$ 0.13 A, peak current $>$ 9 A. Required to hold catseye in position against 0.14 m/s^2 trolley acceleration and against an emergency deceleration of 1 g respectively, assuming 20 kg catseye mass and 22 Newtons/Ampere voice-coil response.

2.4 Roll control

Roll accuracy while in track mode: $\pm0.3^\circ$, in order to pass over the pipe joints to within ±1 mm of the nominal track. This minimises the effects of mismatches in the pipe circularity causing "bumps" at the pipe joints.

2.5 Thermal

Power dissipation: Average $<$50 W over thermal time-constant of trolley. Assumes a trolley shell temperature rise of no more than 25° above pipe temperature and a thermal resistance between the shell and the pipe of 0.5°C/W .

3 OPD control loop requirements

Control loop bandwidth: 3dB frequency $> 100\,\text{Hz}$. To meet OPD stability criteria and step response requirements, from system simulation and analysis of COAST trolley data.

Control loop latency: Less than 40 microseconds. To achieve control loop bandwidth requirements, from system simulation.

4 Pipe requirements

4.1 Vacuum

Maximum air pressure: 1 millibar. To meet chromatic dispersion requirements and internal seeing requirements.

Minimum air pressure: 0.05 millibar. To keep air thermal conductivity within 30% of atmospheric for air gaps of less than 1 cm.

Minimum hold time: 16 hours. To allow for 12 hours of observation plus 4 hours of pre-observation alignment without requiring the vacuum pumps to be switched on.

4.2 Windows

Science exit window clear aperture: Minumum 135 mm. To meet 125 mm clear aperture requirements and to allow ± 5 mm of additional alignment tolerance.

Science exit window thickness: Minimum 15 mm. This thickness of silica window introduces $<$12 nm wavefront distortion under vacuum load (note that the differential distortion between different delay lines will be much less than this).

Science window thickness tolerance: ± 0.5 mm, to meet differential dispersion requirements.

Metrology window clear aperture: Minumum 43 mm. To transmit $>$99% of the power from a 21 mm diameter ($1/e^2$) Gaussian beam, when the beam is ± 5 mm from the nominal axis.

Metrology window thickness: Minimum 3.4 mm. Safety factor of 7 against rupture under vacuum for a 50mm silica plate supported at its edges.

4.3 Pipe sections

Material: Aluminium (nominally 6061-T6). High electrical conductivity for inductive power supply. Light weight for a given pipe thickness (thickness required for dowelling).

Nominal length: 16.4 feet (5000 mm). Balance between achievable straightness per section, transportability and requirements for number of supports and joints.

External diameter: 16 in. (406 mm) $\pm$ 0.085 in. (2.16mm). ASD standard dimensions and tolerances.

Wall thickness: 0.5 in. (12.5 mm) $\pm$ 0.045 in (1.16mm). ASD standard dimensions and tolerances.

Eccentricity: $\leq$ 0.06 in (1.27mm). ASD standard tolerance.

Straightness: $\leq$ 0.0158 in./ft for any measured length over 1 foot. This amounts to 6.6 mm maximum deviation for a 5 m-long pipe. Assuming that the worst-case deviations from straightness are sinusoidal with either (a) a pipe length being equal to a half-period of the sinusoid or (b) a pipe length being a full period, then we fulfill the following conditions as shown in Figure 1:

- Assuming that we can rotate the pipes to minimise the deviation about the best-fit straight line, we get a worst-case deviation of the trolley of $\pm$5 mm which is within the range of correction of the shear-correction system.
- To avoid "grounding" on the bottom of the pipe, the carriage needs a minimum clearance of 3.6 mm.
- The worst-case pitch or yaw of the catseye is $\pm$3.3 milliradians for a 1.8 m wheelbase, which is within the allowed range for the catseye.

Circularity: $\leq$ 0.2 in. (5.1mm). ASD standard tolerance. Two elliptical pipe ends with orthogonal major axes can be dowelled to cross at the nominal centrelines of the trolley path as shown in Figure 2. There will then be "steps" between the pipes of height $< 50\,\mu$m a distance of $\pm$1 mm from this centreline, which, according to our test results, is undetectable.

Surface quality $\leq$ 0.012 inches (0.3mm). Conforms to the ASD spec. This level of roughness can easily be removed at the ends where needed for sealing the pipes.

5 Pipe support requirements

Longitudinal expansion range: 18.4 cm. To cope with thermal expansion over the survival temperature range of -10°C to +32°C, assuming a pipe length of 190 m.

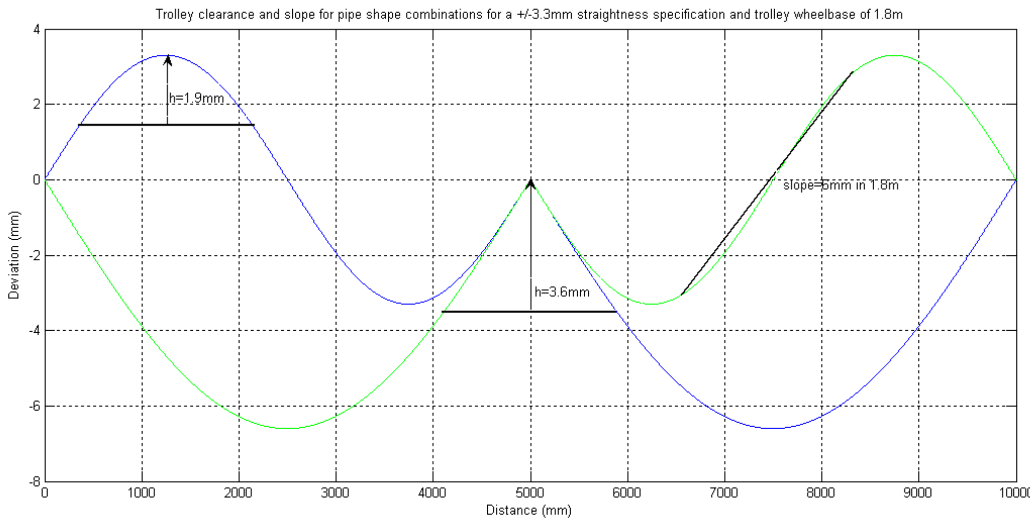

Figure 1: Exaggerated profiles of the worst-case deviations from straight of the pipe. It can be seen that the peak-to-peak deviation of the worst-case sequence of pipes is 10 mm (we assume that the pipes can be rotated by 180° to minimise the deviation). Also shown are the worst-case clearance with respect to grounding of the trolley and the worst-case pitch/yaw of a 1.8-m wheelbase trolley.

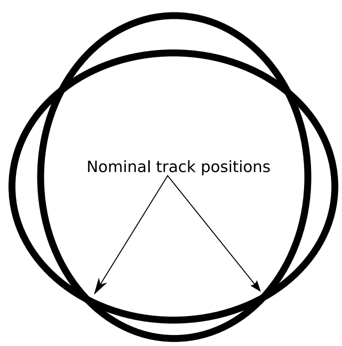

Figure 2: Exaggerated view of the worst-case joining of two out-of-round pipes. The pipe is dowelled at the nominal track to minimise any change in level at the joins. A small step will be present either side of the join.

Support leg minimum length: 1 m between flexures. Means that flexure of legs causes a sag of less than 0.5 mm over a ±20 °C change in temperature from the temperature at which the legs are vertical.

Support leg angular range: ±5°. To cope with longitudinal expansion, assuming a leg length of 1.05 m.

6 Metrology system requirements

The metrology system is subdivided into the metrology laser, the system of beamsplitters and mirrors which split the light between delay lines, the interferometer which splits and recombines the beams to form the heterodyne fringe signal, the pair of adjustment mirrors which adjust the launch direction and shear of the beam, the launch beam expander, the receiver beam compressor, the pair of adjustment mirrors which adjust the direction and shear of the return beam to feed the interferometer and the shear camera.

6.1 Laser

Minimum power: See the Metrology Laser Choice document (INT-406-VEN-0114).

Beam pointing stability: 0.45 arcsec RMS two-axis wavefront tilt over ±0.1°C ambient temperature change. From the shear stability error budget.

6.2 Mirrors and beamsplitters

Beam splitting system angular stability: 0.45 arcsec RMS two-axis wavefront tilt over ±0.1°C ambient temperature change. From the shear stability error budget.

Interferometer angular stability: 0.45 arcsec RMS two-axis wavefront tilt over ±0.1°C ambient temperature change. From the shear stability error budget.

Launch mirror adjustment resolution : wavefront tilt of <1.8 arcsec per axis. Allows metrology beam to be aligned to within 0.5 mm of the optimum axis over a 200 m stroke.

Launch mirror tilt stability: 0.90 arcsec RMS wavefront tilt (net two-axis motion for the combination of 2 mirrors) over ±0.1°C temperature change. From the shear stability error budget.

Receiver mirror adjustment resolution : wavefront tilt of <2.7 arcsec per axis. Allows the metrology return beam to be aligned to better than $\lambda/8$ across a 6 mm beam.

Receiver mirror stability: 1.96 arcsec RMS wavefront tilt (net 2-axis motion for 2 mirrors) over ±0.1°C temperature change. From the shear stability error budget.

6.3 Beam expanders and compressors

Focus resolution: 60μm. From the metrology wavefront quality error budget.

Focus stability: 60μm. From the metrology wavefront quality error budget.

Beam expander tilt stability: 0.13 arcsec RMS output wavefront tilt (two-axis) over ±0.1°C temperature change. From the shear stability error budget.

Beam compresser tilt stability: 1.96 arcsec RMS output wavefront tilt (two-axis) over ±0.1°C temperature change. From shear stability error budget.

7 Shear camera requirements

Shear system closed-loop shear residuals (track mode): 0.5 mm two-axis RMS residual motion (referred to the expanded metrology beam). From the shear stability error budget.

Shear system closed-loop shear residuals (slew mode): 3 mm two-axis RMS residual motion (referred to the expanded metrology beam). Maintains metrology fringe visibility loss due to beam shear at less than 5% for a $1/e^2$ beam radius of 10 mm.

Shear camera frame size: Minimum 180×180 pixels. Samples a 45 mm×45 mm region (referred to the expanded metrology beam) with at least 4 pixels/mm. Can cope with a 35 mm diameter beam (encloses $>$ 99% of the beam energy for a $1/e^2$ beam radius of 10 mm) which moves by ±5 mm due to pipe non-straightness.

Shear camera frame rate: Minimum 20 Hz. To allow a 2 Hz closed-loop bandwidth in the shear control loop.

8 Error budgets

Table 1 gives the error budget to meet the top-level optical wavefront quality requirements for the science beam. Table 2 gives the error budget required to meet the top-level requirement of 1 mm RMS beam shear for the science beam. Note that these requirements do not need to be met while the delay line is slewing, only when it is tracking at a sidereal rate. Table 3 gives the wavefront error budget for the metrology laser, allowing an overall fringe signal loss equivalent to loss of 5% of the metrology laser intensity.

Table 1: Wavefront quality error budget for the science beam.

Item	Aberration (nm)	Tilt drift (arcsec)
Exit window figure	13	
Exit window support error	10	
Primary mirror figure[1]	22	
Primary mirror support error[1]	14	
Primary mirror thermal deformation (1 °C gradient)[1]	14	
Secondary mirror figure	0[2]	
Secondary mirror 20 μm static defocus	9	
Secondary mirror 5 μm focus drift	3	0.12
Secondary mirror pivot point error[3]	2	0.10
Catseye pitch and yaw (3.33 mrad)	3	0.14
Contingency	48	0
RSS total	60	0.21

[1] Double pass
[2] Beam only illuminates a few microns of the surface
[3] Assumes 1 mm decentre of the pivot point and 4.2 mrad tilt of the secondary.

Table 2: Shear stability error budget. Values are for stability over 1 night.

Item	RMS tilt (arcsec)	Demagnification	Distance (m)	Shear (mm)
Laser pointing	0.45	3.5	400	0.25
Beam splitting system	0.45	3.5	400	0.25
Interferometer	0.45	3.5	400	0.25
Launch mirrors	0.90	3.5	400	0.50
Beam expander	0.13	1	400	0.25
Beam compressor	1.96	0.29	3	0.10
Receiver mirrors	1.96	0.29	3	0.10
Closed-loop residuals				0.50
Contingency				0.48
RSS total				1.00

Table 3: Wavefront error budget for the metrology system

DOF	WFE (nm RMS)
Beam expander 60 micron static defocus	15
Beam expander 60 micron defocus drift	15
Beam compresser 60 micron static defocus	15
Beam compresser 60 micron defocus drift	15
Figure errors, 4 lenses	63
Figure errors, 4 flats	32
Figure errors, 1 beamsplitter	16
Figure error, catseye (2 reflections)	31
Figure error, 2 windows	16
Figure error, 2 wedges	16
Tilt error	30
Contingency	100
RSS total	136