MRO Delay Line

System Overview

The Cambridge Delay Line Team

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Objective

To outline the components of the delay line system and their functions, and to provide pointers to other FDR documents. To explain how the designs submitted for FDR relate to what will ultimately be commissioned at the MROI site.

Scope

This document aims to provide a context for the design drawings and design description documents submitted for FDR. There are several aspects to this:

- The physical layout of the major delay line components
- How the various delay line sub-systems (described individually in separate documents) interact with each other. In particular we describe the aspects of the delay line functionality which span several sub-systems
- How the submitted designs relate to what will ultimately be installed on the Magdalena Ridge, and to the setup used for initial tests at Cambridge

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1 Introduction

The Cavendish Laboratory of the University of Cambridge is designing and prototyping delay lines for the Magdalena Ridge Observatory Interferometer (MROI).

The Cavendish Laboratory is contracted to undertake the design of all components of the delay line system as well as delivery of the first production trolley and its associated control electronics. New Mexico Tech (NMT) will be responsible for fabrication/procurement of delay line components and further trolleys.

The concept for the MROI delay lines has several novel features. To mitigate the risks associated with these, the design phase of the delay line activity was structured to include a set of risk mitigation experiments carried out in Cambridge and subsequently reviewed by NMT (see “Results of the Risk Reduction Experiments”, July 2005), followed by a prototyping phase. In this phase a prototype trolley would be built and tested both in an open test track and in a 20m-long vacuum test rig.

This document forms part of the Cavendish submission to the Final Design Review, which will review the design of the delay line, the accompanying analysis, and test results obtained with the prototype trolley. The principal aim of the review is to assess whether the top-level requirements for the delay lines (see INT-406-TSP-0002) can be met with the proposed designs.

Our submission includes detailed mechanical and electronic designs for the delay line trolley, metrology system, and pipes and supports. Build-to drawings will be supplied later in the contract.

Please note that some of the components used for the prototype tests do not correspond to the final design drawings. Hence the test system need not itself meet all of the requirements; rather the reviewers must assess whether the submitted designs and analysis, supported by appropriate test results, demonstrate that the probability of meeting the requirements at the Magdalena Ridge is sufficiently high.

The setup used for the tests of the prototype trolley consists of:

- The prototype trolley described in the documents “Trolley Mechanical Design Description” and “Trolley Electronics Design Description”
- The prototype metrology system described in “Metrology and VME Hardware Design Description”
- The shear camera system described in “Shear Camera Software Functional Description”
- Trolley tests are performed in both of the following:
    - The open test track described in the Test Results document.
    - The 20m vacuum test rig described in “Delay Line Pipes and Supports Design Description”
- The test software and control computers described in “Control Software Architecture” and the documents referenced therein

This should be compared with the delay line system that will be installed at the Magdalena Ridge, which is described in Sec. 2 below. These differences and any potential impacts on the test results are discussed in more detail in the Test Results document.

1.1 Submitted Documents

We are submitting the (new) documents listed below for consideration at the Final Design Review. Delivery of the documents will be phased as indicated below:-

Initial document set (trolley and software design descriptions):

- System Overview (this document)
- Trolley Mechanical Design Description
- Trolley Design Drawings
- Trolley Electronics Design Description
- Limits Design Description
- Control Software Architecture (for information only)
- Trolley Software Functional Description (for information only)
- Workstation Software Functional Description (for information only)
- VME Software Functional Description (for information only)
- Shear Camera Software Functional Description (for information only)

Documents to follow:

- Schedule for delivery of first production trolley
- Schedule for Campus Acceptance Tests
- Contract Deliverables List, including tables of contents for deliverable documents
- Production Phase Budgets
- Derived Requirements
- Delay Line Pipes and Supports Design Description
- Delay Line Pipes and Supports Design Drawings
- Metrology System and VME Hardware Design Description
- Metrology Layout Drawings
- Component Lists
- List of tests performed with prototype trolley
- Test results document
- Production trolley Acceptance Test Plan
- Risk and Hazard document
- ICD: Delay line to ICS (INT-406-ENG-0002)
- ICD: Delay line to Beam Relay system (INT-406-VEN-0008)
- ICD: Delay line to BCF infrastructure (building) (INT-406-VEN-0009)
- ICD: Delay line to metrology system (INT-406-VEN-0010)
- ICD: Delay line to vacuum system (INT-406-VEN-0011)
- ICD: Metrology System to BCF (INT-406-VEN-0012)
- ICD: Metrology System to Beam Relay System (INT-406-VEN-0013)

2 Scope of Final System

The delay line system to be installed at MROI on the Magdalena Ridge will consist of:

- Up to ten production trolleys, which will be reworked versions of the trolley described in the documents “Trolley Mechanical Design Description” and

“Trolley Electronics Design Description”

- A metrology system for up to ten delay lines, incorporating the laser interferometer described in “Metrology and VME Hardware Design Description”, with an optical design based on the layout presented in “Metrology Layout Drawings”
- Up to ten shear camera systems, as described in “Shear Camera Software Functional Description”
- Pipes and supports conforming to the designs presented in “Delay Line Pipes and Supports Design Description” and the accompanying design drawings
- Production control software written by NMT

2.1 Design Caveats

The Workstation, VME system, Shear system and Trolley software written to control the prototype trolley is deliverable as “example software”. The control software will be re-implemented by NMT, but it is expected that the software **functionality** will be substantially the same as that described in the submitted documents, except that the “production” software written by NMT will incorporate suitable interfaces to the MROI supervisory control system.

It is likely that there will be some design changes as a result of experience gained during prototype testing but also due to comments and recommendations received from the review team. Therefore the hardware designs described in the referenced documents may be reworked for production depending upon the FDR outcome after gaining design change approval from NMT. Design changes will be incorporated into the first production trolley and fully incorporated in the final deliverable documentation.

There are some design uncertainties whose resolution will be NMT's responsibility. These are mostly to do with delay line pipe procurement and installation, interface details and the provision of preferred items e.g. metrology optics or modules.

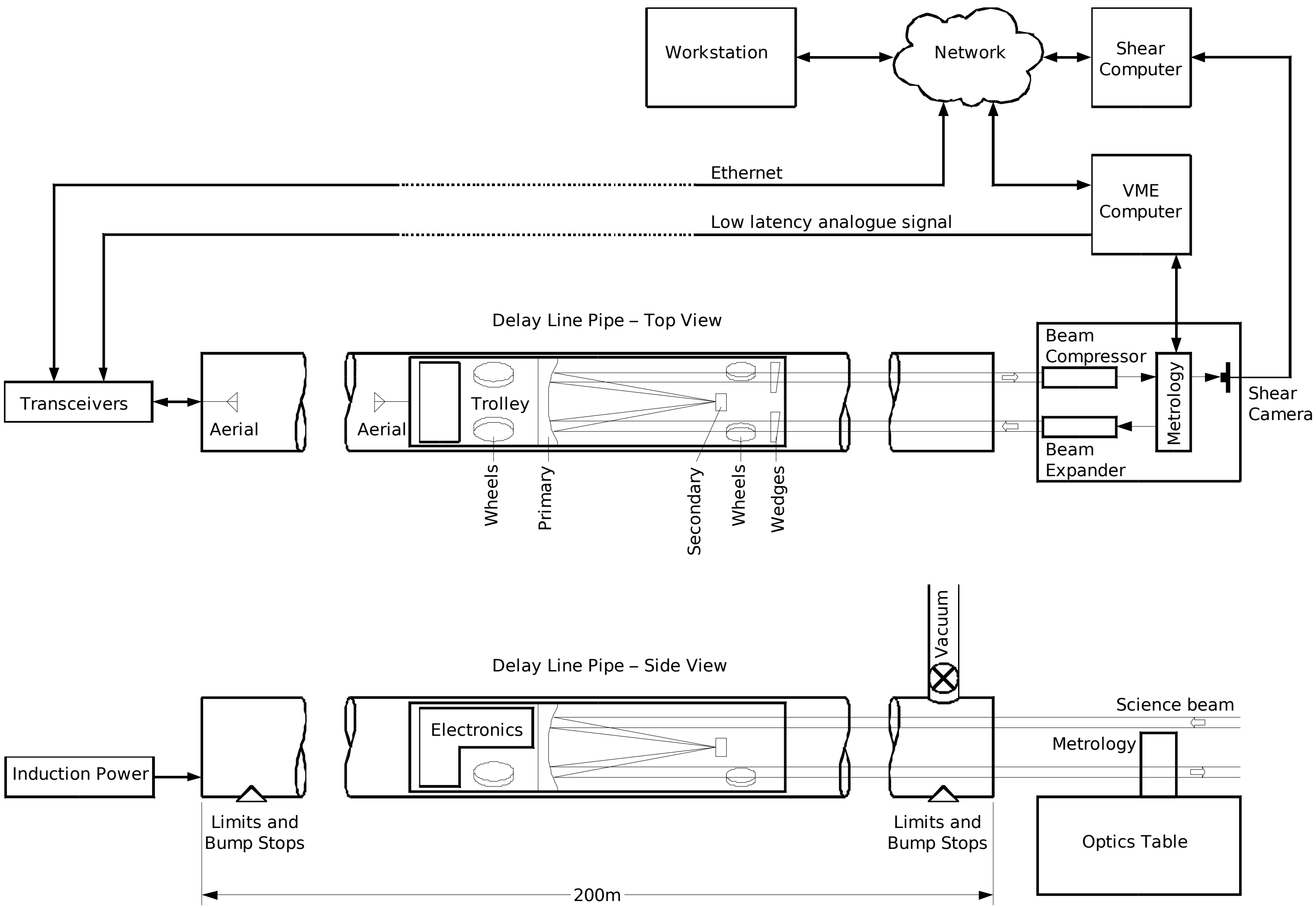

Illustration 1: Schematic top and side views of a complete delay line system, showing the physical locations of the major components.

3 System Components

Each of the delay lines installed at the Magdalena Ridge will incorporate the components listed below. The relative physical locations of these components are shown schematically in Illustration 1.

- A "trolley" consisting of a cylindrical "carriage" supporting and enclosing the cylindrical cat's-eye retroreflector.
- 200 m of vacuum pipe to support and guide the trolley, supported on flexure legs to accommodate thermal expansion.
- A laser metrology system to measure the position of the cat's-eye by bouncing a laser beam off it. The laser is passed through a beam expander before entering the "near" end of the vacuum pipe (see Illustration 1). The beam is reflected from the cat's-eye and returns out of the near end of the pipe, whereupon it is re-compressed. Each laser head is used for multiple trolleys.
- A shear sensor, which uses a small fraction of the metrology light to sense the position of the metrology beam after it has returned from the cat's-eye, and hence the shear of the science beam.
- An inductive power supply to deliver electrical power to the trolley, via a wire lying in the bottom of the vacuum pipe. The wire slides through a long thin transformer on the trolley which inductively couples high-frequency electrical power from the wire to the trolley.
- A distributed control system involving the following components:
  - A "workstation" PC (shared between all trolleys) to act as a supervisor, and provide a user interface for testing the delay line and interrogating delay line telemetry.
  - A VME-bus CPU (shared between all trolleys) to read the metrology signal and hence control the cat's-eye.
  - A low-power PC104 single-board micro on each trolley, to control on-board functions with undemanding timing requirements, and to send telemetry to the workstation.
  - Two separate radio-frequency (RF) links between the trolley and the external control system, transmitted via aerials mounted at the "far" end of the pipe:
    - A low-latency 900 MHz link used to close the Metrology Loop in Track Mode.
    - A standard 2.4 GHz wireless Ethernet link used for communication between the on-board micro and external control computers.
- A "datum" switch, to act as a fixed fiducial point on the pipe from which to reference the laser metrology measurement.
- Limit switches and bump stops, to ensure the trolley slows down and then stops when it approaches either end of the pipe.

4 System Modes

At the highest level of operation from the workstation there are three "system modes" that can be commanded. These are: FOLLOW, STOP/IDLE and DATUM. The system modes are initiated from the control GUI running on the workstation and configure or initiate high-level modes of operation of the delay line described below.

The reader should note that these system modes are distinct from the lower-level Track and Slew Modes. Track and Slew Modes are labels for different behaviours of the delay line axial control loops (described in Sec. 5.4), which are used by certain sub-systems in their implementation of the system modes. For example, in FOLLOW mode the VME system selects either Track or Slew Mode depending upon how far the cat's-eye is from the desired position, whereas DATUM only uses Slew Mode.

4.1 FOLLOW system mode

In this system mode the workstation commands the VME system to cause the trolley to follow the trajectory defined by the position and velocity data the workstation is currently sending. The VME system decides whether or not the trolley must be in Slew Mode in order to reach the condition when Track Mode can be entered so that the trajectory can then be followed precisely. It is possible to command FOLLOW with a velocity of zero in which case the trolley is said to be "holding station".

4.2 STOP/IDLE system mode

In this system mode the workstation directly commands the trolley to enter Slew Mode with a velocity of zero. In this situation the trolley is stationary but the Metrology Loop is not closed.

4.3 DATUM system mode

In this system mode the VME system is commanded to initiate a sequence that will drive the trolley in a safe way so as to eventually reach the datum position and then acquire datum in a consistent fashion.

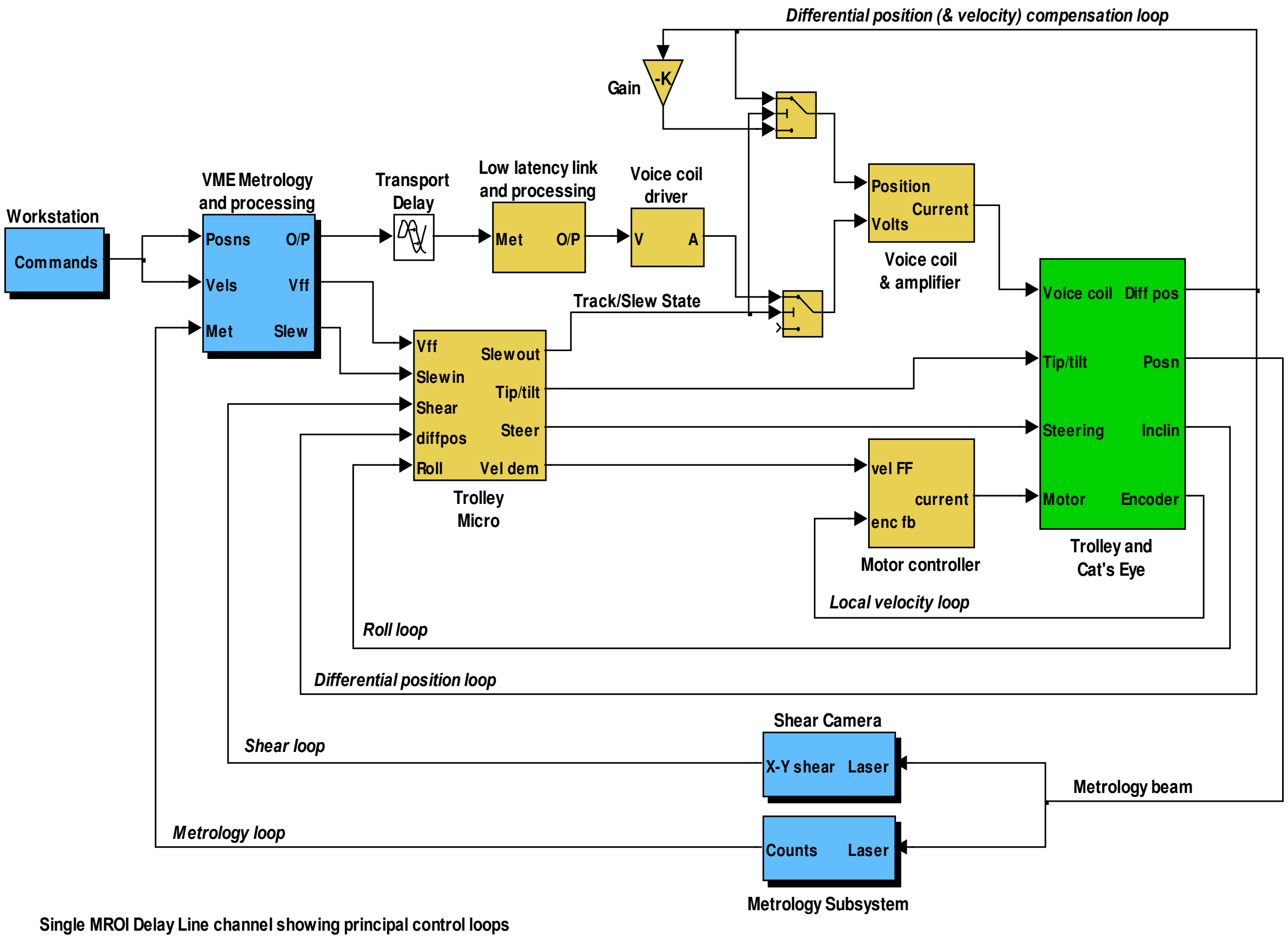

Illustration 2: Conceptual diagram of the delay line servo loops. Blocks with drop-shadows are individual subsystems not on the trolley. Not all links between subsystems are shown, only those which are relevant to the servo loops.

5 Control Loops

There are several servo loops involved in the operation of the trolley. These are shown conceptually in Illustration 2 which includes the loops entirely contained on the trolley and those relying on signals from external components, transmitted to the trolley via the RF data links. The servo loops may be re-configured for different modes of operation, and in general this is done by the onboard microprocessor in response to commands via the ethernet link. The principal servo loops are listed below together with a reference to the documents which describe their function in more detail:

1. The Metrology Loop.
    - Trolley Electronics Design Description
    - Trolley Software Functional Description
    - VME Software Functional Description
2. The Differential Position Loop.
    - Trolley Electronics Design Description
    - Trolley Software Functional Description
3. The Cat's-eye Local Loop.
    - Trolley Electronics Design Description
4. The Shear Loop.
    - Shear Camera Software Functional Description
5. The Roll Loop.
    - Trolley Electronics Design Description
    - Trolley Software Functional Description

The purpose and operation of each of these servo loops is explained in the following subsections and reference should be made to Illustration 2 while reading each description.

5.1 The Metrology Loop

The purpose of the metrology system is to measure the path length between the metrology bench and the cat’s eye on board the delay line trolley. The Metrology Loop uses this measurement to position the cat’s eye so that the required optical delay is produced and maintained with sufficiently low error.

The metrology system, in combination with the VME system, measures the position of the cat’s eye with respect to the laser interferometer and produces an error signal by comparing it with the current demanded position (interpolated from positions sent from the workstation). The magnitude of the error determines which mode the Metrology Loop operates in: Track Mode or Slew Mode. If the error signal is larger than a pre-defined amount then it is assumed that the trolley is sufficiently out of position that it must be slewed to the commanded position and Slew Mode is entered; if the error is smaller, then the trolley is in Track Mode. Operation of each of these modes is described next.

In Track Mode the VME system calculates the correction required to the cat’s eye position and transmits it over the low latency RF link to the trolley where it causes the cat’s eye to move in the required direction to minimise the error. The VME system also transmits, over the network link, the required trolley velocity to attempt to maintain the trolley carriage underneath the cat's eye with flexures unbent. Any residual difference between the cat's eye and the trolley position is sensed on board the trolley and corrected in the Differential Position Loop, described later.

In Slew Mode the trolley is required to re-position quickly without the metrology system losing lock (miscounting). The VME system commands the trolley microprocessor to switch to Slew Mode and sends a velocity demand which is dependent on the magnitude of position error. Signals on board the trolley switch the cat's eye drive circuitry so that the cat's eye is now controlled by the sensor which measures the differential position between itself and the trolley. In this way the cat's eye can be maintained upright while the trolley is slewed and this is the action of the cat's eye local loop, described later. The VME system employs an appropriate control algorithm to produce a velocity profile to accelerate the trolley and then decelerate it until it is sufficiently close to the commanded position for Track Mode to be engaged. The trolley velocity is limited to a maximum of 1 m/s in Slew Mode.

5.1.1 The Differential Position Loop

This loop is a modified form of the cat's eye local loop discussed later. Its purpose is two-fold:

(i) To modify the dynamics of the cat's eye correction in the Metrology Loop Track Mode.

(ii) To apply small corrections to the trolley velocity so that the carriage remains directly under the cat's eye

The differential position sensor is a high bandwidth displacement transducer with an analogue output signal which is proportional to the displacement between the cat's eye and the carriage. To modify the dynamics of the cat's eye the signal is used in a feedback loop such that the apparent natural frequency of the cat's eye is very low, approximately 0.5 Hz. This substantially improves the passive rejection to trolley disturbances at low frequency. A velocity term is also derived from the differential sensor signal and used to compensate for the damping effect of the voice coil magnetic field. This improves rejection to trolley disturbances at high frequency. Both of these feedback compensation terms are implemented in analogue processing on the cat's eye voice coil amplifier.

To correct the carriage position with respect to the cat's eye the signal from the differential position sensor is digitized by the trolley microprocessor, scaled and summed with the velocity demand received from the VME system. Thus small corrections to velocity are achieved which reduce any differential position error.

5.1.2 The Cat's Eye Local Loop

The cat's eye local loop is in force when the trolley is in Slew Mode. Its purpose is to hold the cat's eye firmly with respect to the carriage while the trolley is moved under direct command by the VME system (or Workstation). The differential sensor signal is used for feedback purposes in the same way as described for the Differential Position Loop but with much higher loop gain to provide the necessary holding force.

5.2 The Shear Loop (Secondary Tip/tilt)

The action of the cat's eye is to return a beam parallel to the input beam regardless of small tilts of the trolley with respect to the input beam. However, if the cat's eye primary is laterally displaced from the input beam the separation between the return beam and the input beam changes. This lateral deviation of the return beam is termed "shear". The purpose of the Shear Loop is to maintain the metrology beam (and hence the science beam) returned from the cat’s eye to within 1mm[1] of the nominal beam axis in the presence of lateral deviations of the delay line pipe of up to ±5mm. This is necessary for two reasons:

(i) so that the metrology system continues to work

(ii) so that the science beam remains unvignetted

The metrology beam provides a convenient method for measuring the shear. A small fraction of the return metrology light is redirected via a beam splitter onto the shear sensor. The shear computer then calculates the offset of the centre of the beam from the nominal return position and sends correction signals to the trolley microprocessor. This controls the tip/tilt secondary mirror mounted in the cat's-eye in such a way as to reduce any error between the beam centre and the nominal return position. The Shear Loop is a low frequency loop with a bandwidth of a few Hz and it is always closed.

5.3 The Roll Loop

There are only two degrees of freedom that are available to the trolley when it is constrained in the delay line pipe; piston (or motion along the pipe) and roll (about the axis of the pipe). The roll angle of the trolley must be closely controlled for two reasons:

(i) The axes of the secondary tip/tilt stage must remain in reasonable alignment to the beam shear sensor.

(ii) The trolley wheels must follow relatively narrow track zones to cross the pipe joints where the internal surfaces are aligned.

The roll servo loop is entirely contained on the trolley. An electronic tilt sensor measures the roll angle of the trolley. This is digitised and read by the onboard microprocessor which implements a simple algorithm that, taking into account the direction of travel of the trolley, adjusts the angle of the un-powered rear wheel to correct the roll as the trolley travels along the pipe.

5.4 Control loop action

The VME system decides on the basis of the current system mode (set by the workstation) and the position error whether the trolley should be in Slew Mode or in Track Mode and instructs the trolley accordingly. The action of the control loops depends on the mode of operation of the trolley and this is described in detail in the following sub-sections.

5.4.1 Track Mode

In Track Mode the VME system calculates the trolley velocity and also the correction required to the cat’s eye position. The trolley velocity is sent over the network link but the cat’s-eye correction is sent over the low latency link. The control actions carried out in Track Mode are as follows:

- The Workstation calculates trajectory information for a delay line and sends a set of ten pairs of velocity and position data every second to the VME system via the Ethernet. These data are the desired trajectory for times in the near future, sampled every tenth of a second.
- The VME system calculates the difference between the current cat’s eye position (provided by the metrology system) and the desired position

1 A more relaxed requirement applies in Slew Mode, where we are only interested in maintaining a metrology signal.

determined by interpolation of the trajectory information provided by the workstation. This “position error” is used to calculate a rate correction which is converted to an analogue voltage for transmission over the low latency communications link. The VME system also passes on interpolated velocity values to the trolley microprocessor over the network link to provide the velocity feed-forward function.

- To correct any deviation in the carriage velocity the voltage from the differential position sensor is digitised at 10 Hz sample rate by the trolley micro and combined with the velocity feed-forward term to modify the velocity command to the motor controller.
- To control the apparent spring rate of the cat’s eye flexures (and thereby increase its isolation from the carriage in the axial direction) a small amount of positive position feedback from the differential position sensor is applied to the voice coil amplifier.
- To compensate for ‘drag’ between the voice coil armature and magnet (caused by eddy current losses in the aluminium coil former) a small amount of velocity feedback derived from the differential position sensor is applied to the voice coil amplifier.
- For normal operations, the Shear Loop is constantly operating, ensuring correct beam separation.
- For normal operations, the trolley Roll Loop is constantly operating though with only small and very occasional corrections required.

5.4.2 Slew Mode

In Slew Mode the cat’s eye must be slaved or locked to the carriage to avoid large or uncontrolled motions. The carriage velocity is controlled by the VME system. The control actions carried out in Slew Mode are as follows:

- The VME system determines an appropriate velocity and acceleration or deceleration based on the magnitude of the position error, i.e. the difference between the demanded trolley position and the current trolley position. When the position error is sufficiently low the VME system will command a switch to Track Mode.
- The trolley microprocessor accepts a communication from the VME system to switch to Slew Mode and signals the trolley circuitry controlling the cat’s eye. The velocity received from the VME system is passed directly to the trolley drive controller.
- The cat’s-eye local loop is engaged and the cat’s eye command signal is effectively held at zero (corresponding to its centre of its travel between the mechanical limits). The cat’s eye is held firmly upright as the trolley is moved.
- For normal operations, the Shear Loop is constantly operating, ensuring correct beam separation.
- For normal operations, the trolley Roll Loop is constantly operating though with only small occasional corrections being applied.