Risk Reduction Experiments Review

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1. SCOPE

The Magdalena Ridge Observatory Interferometer (MROI) is a major component of the Magdalena Ridge Observatory, an international scientific collaboration between New Mexico Tech, the Astrophysics Group of Cavendish Laboratory at the University of Cambridge, New Mexico State University, New Mexico Highlands University, The University of Puerto Rico and Los Alamos National Laboratory. The interferometer will be sited in the Magdalena Mountains, part of the Magdalena Ranger District of the Cibola National Forest in central New Mexico.

One of the major contributions that the Cavendish Astrophysics Group (hereafter referred to as AP) will be making to the delivery of the MROI is the design and development of a cost-effective delay line to meet the performance requirements for the array. The scope of this work package will include the delay line carriage and associated optics, an appropriate delay line "track", a vacuum vessel, mechanical supports, control electronics and prototype software, and the metrology system required to operate the delay-line system at the MROI.

As part of the work package AP will be undertaking a series of risk mitigation experiments aimed at rapidly assessing the relative and absolute risks associated with any of the solutions being proposed and identifying whether any alternative strategies need to be investigated in parallel.

The principal aims of this paper are to allow the Review team to address the following three questions:

1. Are the top-level delay line requirements adequately defined and do they support the system level requirements?
2. Are the risks associated with the proposed concept reasonable?
3. Is the risk associated with the proposed concept being managed correctly?

To this aim, we present in this report a summary of the top level system requirements for the MROI delay lines and an explanation of their origin, a description and brief rationale for the proposed solution, and descriptions of the risk-reduction experiments being planned. A programmatic summary of the whole of the delay-line work package is provided for information in Appendix A.

2. BACKGROUND

The MROI is an optical/IR synthesis array. When fully deployed it will consist of ten 1.4m-class afocal telescopes arranged in a Y configuration. The telescopes themselves will be transportable and allow for reconfiguration of the array from a compact state – with arm lengths of as short as 82 feet (25m) to a high-resolution configuration with arm lengths as long as 656 feet (200m). The latter case will allow for a maximum baseline length of just under 1150 feet (350m).

At present the baseline design for the array assumes transport of the signals from each telescope taking place via the propagation of collimated beams of light, with a diameter of approximately 95mm, within evacuated pipes. Upon arrival at the beam combining facility, these beams will be introduced into the delay line system where appropriate compensation for the OPD between beams from each telescope will take place.

In the context of its delay lines, the primary functional specifications that distinguish the MROI from other interferometer arrays are as follows:

- A focus on model-independent imaging as opposed to astrometric or precision phase or visibility measurement.
- A wavelength of operation that covers both the visible and near infrared, between 600 nm and 2400 nm.
- A need to accommodate baseline lengths as long as 350 m (1150 feet).
- A concern for polarization fidelity in the image, i.e. to make images which are of a pure unpolarized state (i.e. Stokes I).
- A requirement to reach a limiting group-delay tracking limiting magnitude of H=14 to allow observations of extragalactic targets.

The last of these requirements most strongly drives the specifications of the delay line, because it sets stringent limits on both the allowable light loss and the allowable fringe visibility loss of the system. A system-wide error budget for the throughput and visibility loss has been developed, which is summarized briefly here.

The interferometer light throughput error budget is presented below:

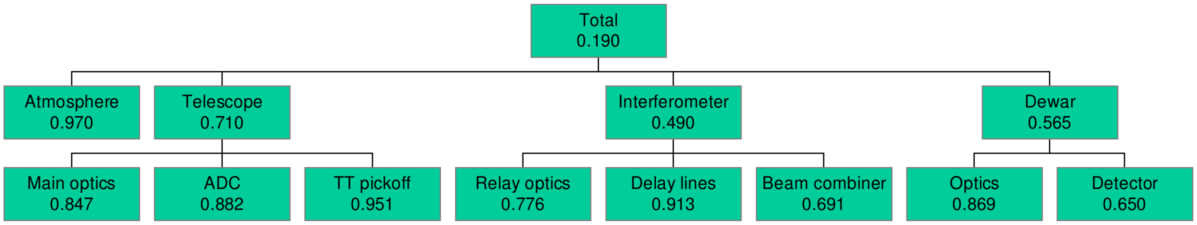


Table 1: A summary of the MROI throughput error budget.

Note that in this error budget, the throughput losses due to the delay line exit window are included under the "beam combiner" budget heading – this has been taken into account when calculating the delay-line top-level specifications.

An abbreviated version of the overall system visibility loss error budget is given below:

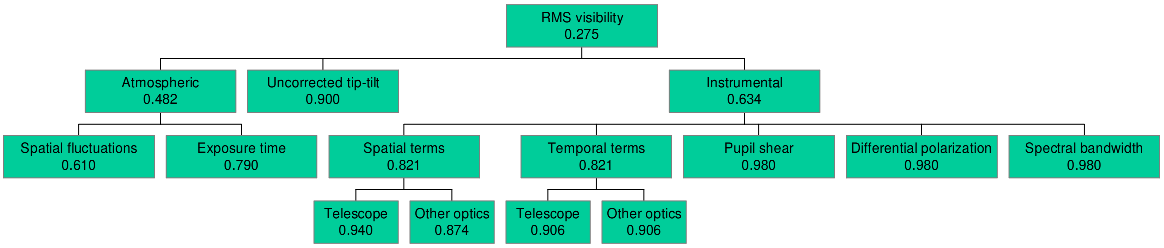


Table 2: A summary of the MROI visibility loss budget.

In this budget the contributions from the delay lines are included under the headings for "other optics" under both the temporal and spatial branches. It should be noted that a visibility reduction of 0.906 corresponds to an rms wavefront error of λ/20.

The critical wavelength at which both the throughput and wavefront quality requirements need to be met is in the H-band (central wavelength 1650 nm), the wavelength for which the group delay fringe-tracker is being been optimized. At shorter wavelengths, it is likely that aperture diameters smaller than the 1.4m unit telescope size will be used to reduce the atmospheric wavefront errors, and thus the instrumental wavefront error specifications will apply over smaller clear apertures.

The subdivision of the budget headings relevant to the delay lines at 1650nm wavelength is as follows:

1. **Spatial wavefront terms – non-telescope optics: 94.5nm rms**

   1.1. Delay line: 60nm rms
      1.1.1. Cat's eye optics: 57nm rms
      1.1.2. Exit window optics: 16nm rms
   1.2. Total other optics (relay optics, beam compressors, beam combiners): 73nm rms

2. **Temporal jitter terms – non-telescope optics: 82.5nm rms**

   2.1. Delay line jitter: 41nm rms
   2.2. Total other optics jitter (relay optics, beam compressors, beam combiners): 72nm rms

3. **Differential pupil shear: 2% visibility loss, i.e. shear of 2% of pupil size**

   3.1. Static alignment errors: 1% shear rms
   3.2. Unit telescope pupil wobble: 1% shear rms
   3.3. Delay line pupil shear: 1% shear rms
   3.4. Other: 1% shear rms
4. **Spectral bandwidth effects: 2% visibility loss**

   4.1. Fringe curvature due to differential dispersion: 1% visibility loss
   4.2. Group delay errors: 1% visibility loss
      4.2.1. Static group delay errors: 0.7% loss
      4.2.2. Dynamic group delay tracking errors: 0.7% loss

3. TOP LEVEL REQUIREMENTS

The following summary of the top-level delay line requirements apply to the *overall design* of the delay line: where all the components required to meet a particular specification are not to be delivered as part of the Cambridge work package, e.g. the production software, the delivered design must include a demonstration of the feasibility of meeting the specification. The detailed interface requirements associated with the delay line sub-system are not presented here.

1. **Range of delay**: The delay line shall have a total stroke of 380m (1250 feet) of optical path change, i.e. 190m (625ft) of travel for a single-pass design. *Rationale:* this will allow the equalization of the optical path delay (OPD) between any set of telescopes situated on a 'Y' array with arm lengths of 200m, for astronomical targets at all elevations above 30 degrees from the horizon.

2. **Delay precision**: The delay line shall be able to introduce any commanded OPD change allowed within its stroke with an intra-night repeatability of better than 10μm rms and a night-to-night repeatability of better than 100μm rms. When commanded to do so, the delay line shall be able to go to a mechanical datum and sense the position of this datum to a precision of better than 10μm rms. *Rationale:* on long baselines, atmospheric seeing is expected to introduce a random OPD error of order 10μm rms, assuming an outer scale similar in character to that measured at other sites. Night-to-night mechanical drifts of the interferometer baseline and internal delays are expected to be of order 100μm.

3. **Slew speed:** The delay line shall be able to slew between any two points within its available stroke corresponding to a change in OPD of up to 30m (i.e. a physical motion of 15m or approximately 50ft for a single-pass design) in less than 30 seconds, including the time taken to accelerate and decelerate to/from sidereal tracking speeds. The delay line shall be able to slew from any position in the available stroke to any other position in less than 5 minutes. *Rationale:* a slew of 30m corresponds to the worst-case OPD change required to switch between two stars separated by 5 degrees on the sky on a 350m baseline. The goal for the interferometer is to be able to switch between two such stars and be taking data with a total overhead of less than 60 seconds. Thus the switching overhead would be less than 50% for repeated switches between stars when the typical on-source dwell times are 60 seconds or more.

4. **Sidereal tracking and jitter:** The delay line shall, when commanded to do so, introduce a smoothly changing OPD trajectory with speeds of up to 30mm/s (corresponding to physical speeds of the trolley of up to 15mm/s) and accelerations of up to $2.5\mu m/s^2$. The OPD shall follow the commanded trajectory with a jitter of less than 15nm rms as measured over any 10ms interval, a jitter of less than 41nm rms over any 35ms interval, and a jitter of less than 55nm rms over any 50ms interval. It is acceptable to exceed these jitter limits for a total of 0.5 seconds during any 60 second tracking interval. *Rationale:* the numbers given for velocity and acceleration correspond to the maximum sidereal rates for a 400m (1300 foot) baseline. The jitter values given correspond to a $\lambda/40$ rms OPD jitter over a $2t_0$ integration at wavelengths of 600nm, 1650nm and 2200nm respectively, where t_0 at 500nm wavelength is 4ms. These figures are derived from the system OPD

jitter error budget. The jitter limits may be exceeded temporarily when the trolley traverses the joints in its tracks.

5. **Clear aperture:** The delay line shall have a clear aperture for the starlight beam of 125mm diameter on both input and output. *Rationale:* the collimated beam diameter at the telescope is ~95mm and an extra 30% must be allowed for diffraction and misalignment.

6. **Static wavefront quality:** The delay line shall introduce no more than 60nm rms wavefront aberrations to the starlight beam across the clear aperture, including focus errors and the aberrations introduced by the exit window. *Rationale:* this requirement derives from the overall interferometer wavefront quality error budget.

7. **Dispersion:** The differential optical dispersion between beams propagating through any two delay lines shall be such that there is less than 0.175 radians of differential optical phase change across any bandpass with a fractional bandwidth of 5%, anywhere within the R,I, J, H and K astronomical photometric bands. In calculating this phase change, it is acceptable to subtract the component of phase change with wavenumber which is linear across the relevant photometric band, i.e. the overall group delay for that band. *Rationale:* this requirement derives from the fringe curvature part of the spectral dispersion component of the interferometer visibility loss error budget.

8. **Polarization:** The di-atennuation of any beam propagating through the delay line shall be less than 1% for light of wavelengths between 600nm and 2400nm. *Rationale:* this requirement derives from the overall interferometer system goal to maintain as high polarisation fidelity as is reasonably possible.

9. **Pupil shear:** The delay line shall introduce no more than 1mm rms variations in the position of the center of the starlight exit beam compared to a reference position, provided the input starlight beam has been aligned with the mean direction of delay line travel. This shear criterion can be exceeded when the delay line is slewing as long as the delay line trolley metrology signal is not lost. *Rationale*: this requirement derives from the overall interferometer visibility loss error budget: a 1mm shear results in a 1% fringe visibility loss.

10. **Optical throughput:** The delay line shall introduce no more than 15% throughput loss (unpolarized) between its input and output for light at wavelengths between 600 and 2400nm. *Rationale:* This is derived from the system throughput error budget (and here includes the contribution from the exit window of the delay line).

11. **Dynamic tracking of atmospheric fluctuations:** The delay line shall support the closed-loop tracking of atmospheric OPD fluctuations when used in combination with an external group delay fringe tracker. In particular, the delay line shall accept an external offset demand signal at sampling rates of at least 15Hz and have a step response time (command input to 90% response) of less than 30ms for step sizes of up to 10 microns. It is a goal but not a requirement that the delay line should respond to offset demands with sampling rates of up to 200Hz with a step response time of less than 2ms for step sizes of up to 0.5 microns. *Rationale:* In order to have an rms residual visibility loss of less than

0.7% for a 5% bandpass at 1650nm wavelength, the residual OPD error from the group-delay tracking system needs to be less than 1.4 microns rms. This error can be achieved with a first-order servo with a 3dB bandwidth of 1.5 Hz when t_0 at 500nm is 4ms. A servo loop with this bandwidth is straightforward to implement when the bandwidth of the "actuator" (i.e. the delay line) is a factor of 5-10 greater than this. The fringe tracker can also be operated in a phase-tracking mode at a maximum sample rate of 200Hz, so it is a goal to be able to make use of such a mode on bright stars. However, such a mode is not critical to the top level science goals of the array.

12. **Power dissipation:** A set of 10 delay lines, including their control electronics and metrology system shall dissipate no more than 10 × 200W (= 2 kW) in total. Efforts shall be taken to minimize the power dissipated by the delay line system and any of its associated electronics located in the interferometer Beam Combining Area. *Rationale:* The total electrical power budget on the Magdalena Ridge is limited. Heat dissipation in the BCA will degrade the optical seeing there.

13. **Volume envelope:** A system of 10 delay lines and their associated support structures (but not foundations, or metrology system) shall be capable of fitting within a rectangular region of dimensions 656 feet long × 7 feet high × 24 feet wide. The delay lines shall be designed to allow access for maintenance and alignment.

14. **Environment:** The delay lines shall meet all performance requirements inside a building maintained at temperatures between 32F and 60F with diurnal variations of no more than 2F peak-to-peak, and spatial variations of 10F peak-to-peak. The delay lines shall be capable of surviving temperatures from –20F to 90F without damage. The delay lines shall meet all performance requirements when attached to a floor with up to 1μm rms vibration at frequencies between 0.1Hz and 500Hz.

15. **Cost:** The design of the delay line shall have goal costs for the fabrication and installation of the production delay line system as follows:

    a. Complete trolley hardware for 6 delay lines, including 6 assembled trolleys with optics, mounts and on board electronics, external control hardware and metrology: less than $370K.
    b. Pipe, rail (if any) and support hardware (adjusters) for 6 × 100m (328 foot) delay lines: less than $700K
    c. Total installation cost for 6 × 328 foot delay lines (including labor and rigs): less than $180K

4. DELAY LINE CONCEPT

Our proposed concept for the MROI delay line system is to use single long-stroke vacuum delay lines for each telescope beam. These would utilize a cat's-eye optical assembly that would be flexure-mounted, and voice-coil actuated, on a motorized carriage. Hereafter, we shall use the term "carriage" to denote the motorized assembly excluding the cat's-eye, and the entire assembly including the cat's-eye as a "trolley". In comparison with the delay line systems in use at other interferometric arrays, the proposed design would:

- Introduce the entire 1250 feet (380m) of optical path delay in each telescope beam by using a single-pass traverse of the delay-line vacuum pipes.
- Have the delay line trolleys running directly on the inner surface of the vacuum pipe, and not on pre-installed rails.
- Uses low-bandwidth tilting of the cat's-eye secondary mirror to compensate for pupil shear variations introduced by imperfections in the pipe straightness.

One potential alternative would be to use a two-stage system consisting of a shorter continuously variable delay line together with longer switched static delays, as exemplified by the CHARA and NPOI interferometers (the only interferometers with comparable maximum baselines to MROI). The advantages of the proposed single-stage system are as follows:

1. The proposed system would use fewer reflections and hence be more likely to meet the high throughput and low wavefront error goals.

2. The proposed system – which we envisage using a parabola/flat cat's eye – would have all its reflections at near-normal incidence, hence meeting the polarization fidelity goals.

3. The proposed system would not require an absolute-path metrology system to monitor the switched delay – existing switched-delay systems do not use such a metrology system, but it is likely that they suffer performance disadvantages as a result.

4. The proposed system would give continuous coverage in optical path compensation through the night, thereby placing no extra restrictions on the observing sequence. The CHARA interferometer requires several hours to switch and subsequently realign the mirrors of its switched delay system: this is 10-20 times longer than a single-stage system would take to slew over its full range. There is currently no operational data from NPOI, as the switched-delay system is not yet in regular use. The single-stage system is therefore likely to have a much higher observing efficiency

5. If the continuous stage of the two-stage delay were not in vacuum (as at CHARA) it would introduce additional differential optical dispersion and wavefront errors due to the passage of the starlight through the air, which would make it less likely that we could meet the aggressive visibility loss goals for the MROI. If it were in vacuum (as at NPOI), there would be twice as many vacuum systems to build and maintain.

6. The proposed system, by using only a single system to introduce the full range of OPD desired, might reasonably be expected to be easier to install, test, operate and trouble-

shoot than a system using a combination of variable and static delays. In particular, the process of calibration of the interferometer baseline and internal path delays using observations of a range of stars with known positions is likely to be considerably simpler when only one delay needs to be calibrated per telescope.

Given the high priority in the top-level design of the MROI for securing observations of extragalactic sources and to efficient and automated operations, the additional throughput losses and operational inefficiencies that have been experienced at two-stage (i.e. static plus variable delay) delay line implementations are strong drivers for our choice. Furthermore, it seems unlikely that any of the technical risks associated with the development of the proposed delay line system concept will be very strong functions of the stroke of the optical path that has to be delivered.

Figures 1 and 2 overleaf show in more detail some of the features associated with our proposed concept. The key features of the delay line design can be summarized as follows:

Delay line trolley

- A cat's eye optical system using a 12-inch diameter f/4 parabola with a one inch diameter flat secondary mirror. Both elements will be mounted co-axially with the bore of the delay line vacuum pipe within a cylindrical assembly.
- The use of an actuated mirror mount for the secondary mirror so as to allow for low-bandwidth tip, tilt and focus correction of the secondary.
- The use of a four-wheeled steerable carriage, driven along the inner surface of the delay line vacuum pipe, and carrying the cat's eye.
- The use of a laser metrology path running through the same optics as the stellar beam, but entering and leaving the delay line trolley in the central horizontal plane as opposed to the central vertical plane (used for the stellar beams). d
- The use of compliant wheels for the delay line carriage to accommodate small ripples in the inner surface of the vacuum pipe.
- Flexure mounting of the cat's eye so as to provide rejection of disturbances to the optical path introduced by the delay line trolley and to allow for voice coil control of the position of the cat's eye.
- The presence of an on-board tilt sensor to permit the control of rotation of the trolley to better than 2.5 degrees as it moves within the vacuum pipe.
- The use of radio frequency communication for control and communication with the trolley.
- The use of inductive power transmission to the trolley using a wire lying within the interior of the vacuum pipe.
- A total mass of order 80kg.

Support and vacuum mechanism

- The use of thick walled (½ inch) aluminum pipe, assembled from ~16 foot sections, to act as the vacuum enclosure for the delay line system.
- The use of supports for every pipe section length so as to limit bending of the vacuum pipes due to self-weight and/or the mass of the delay-line trolley to less than a few tenths of a mm.

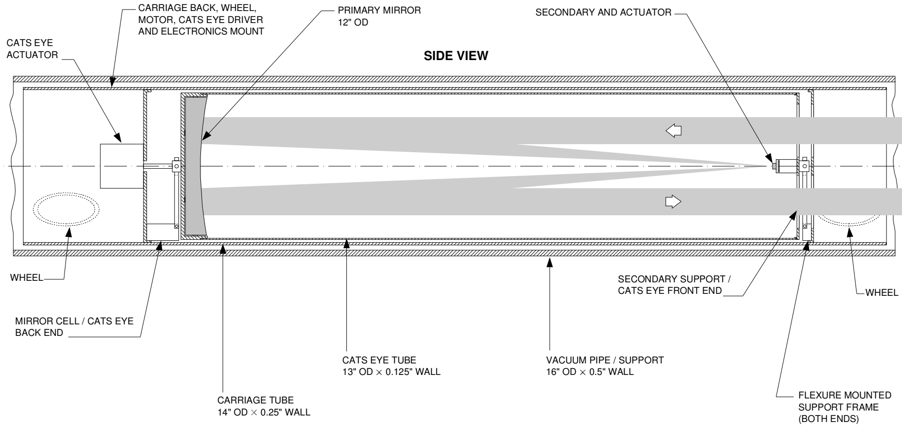


Figure 1: A schematic diagram of a side-on view of an MROI delay line trolley located within its 16 inch diameter vacuum pipe. The co-incident optical and mechanical axes of the carriage are shown as the horizontal dashed line. The path of the stellar light beam is denoted by the grey shaded area.

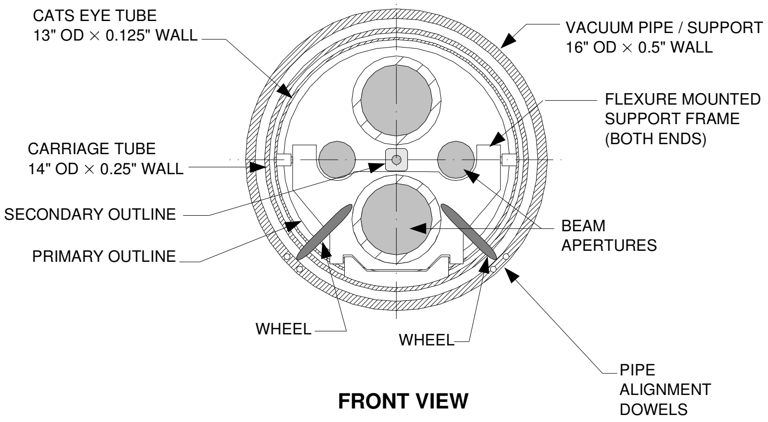


Figure 2: A schematic face-on view of an MROI delay line trolley located within its 16 inch diameter vacuum pipe. The input and output beams are shown as the upper and lower shaded circles, while the shaded circles to the left and right of center represent the input and output metrology beams. Note that the pile alignment dowels are located close to the positions where the wheels touch the vacuum pipe interior, and that the wheels themselves point towards the optical and mechanical axis of the trolley.

- Evacuation of the delay line pipes to a pressure of roughly 10^{-3} to 10^{-4} bar to meet the requirements on differential optical dispersion for non-astrometric applications.
- The use of elastomeric seals with steel surrounds as vacuum joints between pipe sections.
- The use of the interior surface of the aluminum pipe as the surface on which the delay line trolleys will run.
- The use of active, low bandwidth, control of the secondary mirror tip and tilt to correct for vertical and horizontal undulations in the inner pipe walls.

- The use of dowel pins to mate the separate sections of delay line pipe and align them at the locations of the carriage wheels.
- Anchoring of the end of the delay line pipes closest to the beam combination building to a deep concrete pier, and thereafter using steel flexure mounts to support the delay-line pipes above short concrete footings along their length to accommodate any thermal expansion of the vacuum pipes.
- The use of a broad-band anti-reflection coated infrared-transmissive window to act as the interface for the exiting optical beams.

Control system

- The use of an on-board CPU mounted on the delay line carriage to provide local control communicating with an external CPU providing overall control and feedback from the external metrology and shear sensors.
- The use of two nested control loops handling the drive motor and voice coil controls to provide OPD control.
- Low-bandwidth control of the carriage steering using feedback from an onboard tilt sensor.
- Low-bandwidth control of the secondary tilt using feedback from an off-board pupil shear sensor.

Estimated hardware costs

The following cost estimates indicate that we expect the hardware cost goals identified in the top-level requirements can be reached using this concept. Installation cost estimates for this design have been made elsewhere as part of the MRO budget, and come to approximately $160K.

Trolleys and on-board hardware

Item	Number	Unit cost (k$)	Total cost	Source
Cat's eye primary	1	9.60	9.60	Actual one-off cost (UK)
Cat's eye secondary	1	0.05	0.05	Quotation
Cat's eye frame and mirror mounts	1	2.00	2.00	DMAW estimate
Voice coil	1	1.44	1.44	Actual one-off cost (UK)
Flexures	8	0.36	2.88	DMAW estimate
Carriage frame and wheels	1	2.00	2.00	DMAW estimate
Wheel drive motor & controller	2	1.11	2.22	Quotation (UK)
Secondary tilt & focus adjusters	3	0.50	1.50	Thorlabs catalog
Steering adjusters	4	0.50	2.00	Thorlabs catalog
Onboard microcontroller	1	1.26	1.26	Actual one-off cost (UK)
Misc control electronics	1	2.00	2.00	DFB estimate
Power supply	1	0.50	0.50	DMAW estimate
RF link	1	0.16	0.16	Actual one-off cost (UK)
Contract assembly	1	10.00	10.00	DFB estimate
Subtotal (one trolley)			**37.61**	
Subtotal (6 trolleys)			**225.66**	

Trolley external control electronics and metrology

Item	Number	Unit cost (k$)	Total cost (k$)	Source
ZMI 7702 laser head, PSU & cable	1	10.95	10.95	Zygo quotation 2004/09/17
ZMI 7002 linear interferometer	6	2.41	14.44	Zygo quotation 2004/09/17
ZMI 2002 dual-axis VME board	3	7.54	22.62	Zygo quotation 2004/09/17
Zygo connectors	6	0.30	1.80	Zygo quotation 2004/09/17
Zygo beamsplitters	6	0.70	4.20	Zygo quotation 2004/09/17
VME cage	1	5.00	5.00	AJF estimate
VME control processor	2	3.50	7.00	AJF estimate
Small metrology optics with mounts	48	0.30	14.40	DFB estimate
Large metrology optics with mounts	12	1.00	12.00	DFB estimate
Alignment actuators	36	0.50	18.00	Thorlabs catalog
Shear sensor optics & camera	6	2.00	12.00	DFB estimate
Shear sensor control PC	2	2.00	4.00	DFB estimate
Misc additional hardware	1	5.00	5.00	DFB estimate
Subtotal			**120.46**	

Pipes and supports for 6 × 100m (328 foot) delay lines, based on 12 foot pipe sections

Item	Number	Unit cost (k$)	Total cost	Source
16 inch OD x 0.5 inch thick pipes	168	0.96	161.70	Actual 1-off cost
Vacuum seals	168	0.30	49.74	Actual 1-off cost
Machining pipe ends	168	0.18	30.24	DMAW estimate
Flexure supports	168	0.50	84.00	DFB estimate
Alignment assembly and clamps	168	0.50	84.00	DFB estimate
Ends and windows	12	3.00	36.00	DFB estimate
Subtotal			**435.68**	

By way of comparison, below we have provided a cost estimate for an alternative concept, using precision rails mounted within vacuum pipes, and flange joints instead of steel shrouded elastomeric sleeves. This estimate was provided by Jonathan Kern and is for the pipe plus rails alone, and so does not include any costs for supporting the vacuum pipes.

Item	Number	Unit cost (k$)	Total cost (k$)
304L 16" OD x 0.188" sch 10S pipe	168	0.79	133.18
MDC ISO NW400 flange assembly	168	1.25	209.66
D125 Dolphin Guide rails	168	1.78	299.74
Ameriflex bellows (every 4th section)	168	0.20	33.60
Manpower (20 man hours/joint, $40/man hour	168	0.80	134.40
Subtotal			**810.58**

5. RISK REDUCTION EXPERIMENTS

An initial assessment of the risks associated with the development of the proposed MROI delay line system has led to the identification of eight areas where it seems prudent to undertake a sequence of short-term analyses and/or experiments to better assess the repercussions of our proposed concept prior to finalizing on a design. Broadly speaking, these mainly relate to three aspects of the proposed design:

1. The use of jointed pipe sections as the vacuum vessel within which the delay line carriages will run.
2. The use of jointed pipe sections as the track along which the delay line carriages will run.
3. The use of a long (656 foot) vacuum pipe, with the associated difficulties of delivering power and communications to the delay line trolley from a distance, and of monitoring the position of the delay line trolley in-situ.

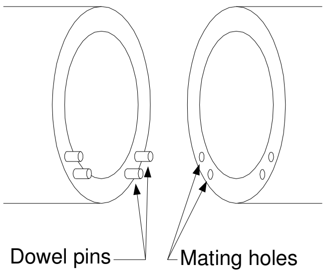
In the subsections below, we outline the specific analyses and experiments we intend to perform over the next 5 months to address these uncertainties. In each case we briefly describe the potential risks and present the proposed test and/or analyses and some commentary. Each set of tasks is identified by its provisional WBS code.

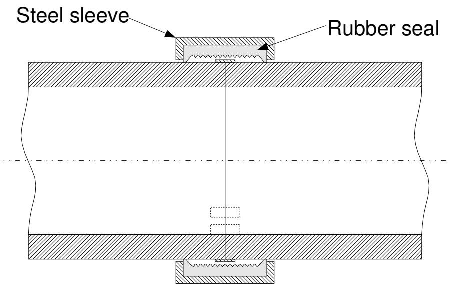
[002-01] Risk assessment of pipe coupling scheme

Principal risks:
That the coupling mechanism used to join of sections of delay line pipe may not maintain a suitable level of vacuum integrity.

That the coupling mechanism used to join sections of delay line pipe may lead to gaps and bumps at the pipe interfaces that cause the delay-line carriage trajectory to be impacted sufficiently so as to effect the delay-compensation performance of the carriage, principally through the loss of the metrology signal.

Background: The current baseline plan is to mate sections of delay line pipe using dowel pins located close to the wheel tracks, and to seal the joints using commercial elastomer/steel vacuum sleeves. We assume the presence of a rig incorporating 2 jointed sections of vacuum delay line pipe mounted and joined as proposed for the MROI.





PIPE SECTION

Figure 3: A schematic cartoon showing the proposed mechanisms for aligning and vacuum sealing the MROI delay line pipes. The figure does not show the mechanism providing the axial force to pull the joint together during assembly (see figure 4).

Proposed analyses/experiments:

1. Evaluate the minimum permissible step and gap sizes that are likely to lead to loss of the metrology signal.
2. Set up a mechanical rig supporting two 10 foot sections of the 16" aluminum pipe proposed for use at the MROI together with two separate end sections.
3. Assemble the two end pieces and joint and seal these (including the center join) as proposed.
4. Pump down to ~1 millibar and monitor the rate of loss of vacuum as a function of time for several days. Repeat the test a number of times at different temperatures to mimic temperature cycling.

5. Measure any step and/or gap in the internal surfaces at the joint interfaces for the above test rig using dial and feeler gauges. Repeat the measurements for the different, but representative, joints obtained by connecting the end sections in various combinations and orientations.

6. Measure the effects of differing gaps between the jointed pipes on the OPD disturbance spectrum measured on the delay line carriage. This experiment is described under heading [002-07].

Fallback options & comments:

Initial vacuum tests of the proposed vacuum seals using 10-inch diameter aluminum pipe show a leak rate of approximately 0.1 millibar/day, i.e. within the limits necessary at MROI. The seals to be used for the 16″ diameter pipes will, however, employ less porous rubber and will operate with a lower joint area to pipe volume ratio are thus expected to perform significantly better.

The tests of pipe alignment proposed here will measure the actual features of the pipe and not the delay line trolley's response to them. Those data will be secured separately in later tests, when a dummy carriage will be driven over a typical joint and the resulting pupil shift and OPD disturbance spectrum will be measured. We expect the use of slightly compliant wheels will relax the tolerances on the maximum permissible step and gap considerably compared to a hard-wheel system.

The initial tests assume the use of pipe sections with square cut ends but no additional machining. If necessary, it should be possible to machine the ends of the pipe sections so as to guarantee a suitably flush interface, albeit at some additional expense.

Resources required:

Mechanical engineer: 3.6 weeks
Mechanical technician: 1.6 weeks
Draughtsman: 1.0 weeks

[002-02] Risk assessment of proposed pipe support design

Principal risks:
That it may be difficult to design and fabricate a suitable pipe support system in a cost effective manner.

That building a suitable system within a sensible space envelope may be difficult.

That the proposed supporting mechanism may lead to the possibility of undamped oscillations of the delay line pipes.

Background: The current baseline plan is to use ~1m high steel flexures mounted to concrete piers to support the delay line pipes. The proposed experiments involve the analysis and design of such supports and experimental investigations of their performance.

Proposed analyses/experiments:

1. Design and fabricate a prototype flexure mount.
2. Perform preliminary analysis of the design to assess its longitudinal and lateral resonances and propagate these estimates through an initial model for the delay line carriage disturbance rejection transfer function.
3. Check the test flexures and pipe mounts for parallelism, ease of alignment and space envelope constraints.
4. Excite and then measure two connected pipe sections mounted on the flexure legs. To assess:
    a. The resonances of the combined system.
    b. The damping of the combined system.
5. Use the above data to assess the validity of the initial modeling of the system and extrapolate to a longer sequence of jointed pipe.

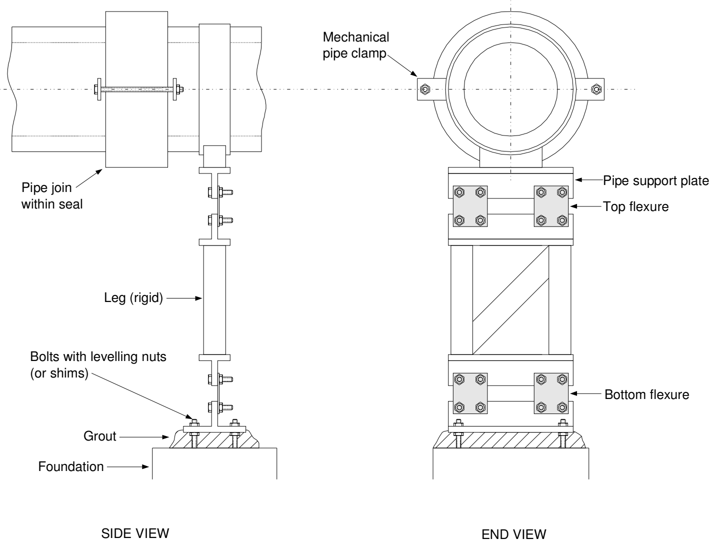


Figure 4: A schematic view of the type of mounting scheme we are proposing for the MROI delay line pipes. Not all adjusting features are shown. One end of the

vacuum pipes will be anchored, while the remaining sections will be mounted on flexure legs to accommodate thermal expansion.

Fallback options & comments:

The design of the flexure legs proposed for the MROI delay line pipes will draw heavily on the flexure legs used to support the 82 foot (25m) long optical tables supporting the rails for the COAST delay lines. An initial analysis has suggested that rolling or sliding supports for the delay line pipes might possibly lead to uncontrollable small amplitude "stick-slip" events shaking the delay line pipes longitudinally, and is the primary reason for our preference for flexures. Should our proposed flexure scheme prove unsatisfactory, we will re-open our investigations of these alternatives.

Resources required:

Mechanical engineer: 2.8 weeks
Electrical engineer: 0.2 weeks
Controls engineer: 1.6 weeks
Mechanical technician: 2.2 weeks
Electrical technician: 0.2 weeks
Software engineer: 0.2 weeks

[002-03] Risk assessment of carriage trajectory

Principal risks:
That the carriage trajectory defined by the inner surface of jointed aluminum pipe may not be uniform enough to allow the top-level system requirements to be met. In particular that the rate and amplitude of the pupil shifts introduced by a non-ideal carriage trajectory will be larger than can be accommodated by the proposed delay line trolley.

Background: The current baseline plan is to use a tip-tilt actuated secondary mirror on the cat's eye to compensate for deviations of the delay line carriage trajectory from the nominal desired trajectory. We assume the presence of a rig incorporating a section of vacuum pipe as well as a "dummy" delay line carriage with representative wheels. The location of these should be broadly representative of the proposed prototype trolley. This dummy carriage will carry an optical corner cube centered on the mechanical axis of the pipe.

Proposed analyses/experiments:

1. Enumerate the allowed rates and amplitude of pupil shear for sidereal and slewing motions.
2. Measure the linearity of two 10 foot sections of the 16" aluminum vacuum pipe we proposed to use in several orientations against a flat lathe bed using a dial gauge. This will measure any external bowing of the pipe sections. Note that the self weight deflection expected for a section supported by its ends is only 0.06mm.
3. Install the dummy delay line carriage in a leveled pipe section and drive it at a quasi-constant rate along the interior of the pipe. Reflect a laser beam propagated parallel to, but slightly offset from, the mechanical axis of the pipe, and monitor the position of

the return beam using a fixed CCD camera. The position of the return beam will then be a proxy for any deviations in the trajectory followed by the dummy carriage.

4. In parallel, monitor the inclination of the dummy delay line carriage to ensure that any changes in spot position are not due to rotation of the delay line carriage within the vacuum pipe section.

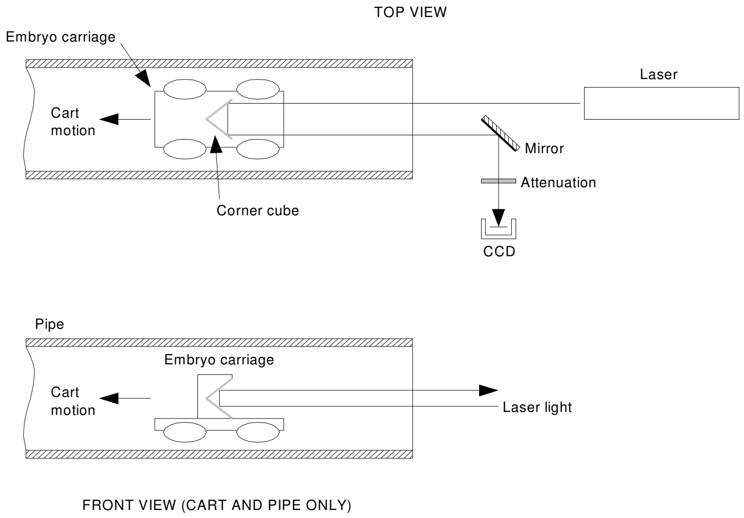


Figure 5: A schematic diagram of the test proposed to measure the effects of low spatial frequency variations in the delay line carriage trajectory due to imperfections in the delay line vacuum pipe.

Fallback options & comments:

ZEMAX analyses we have performed imply that deviations of at least ±6mm can be corrected for without impacting the error budget for the output wavefront quality of the cat's eye. Initial measurements on an existing 12 foot section of 12" diameter aluminum pipe show deviations of ±2.5mm. On this basis, we do not expect low-frequency warping of the 16" diameter pipe we intend to use to take us outside the dynamic range associated with the proposed secondary actuators.

Resources required:

Mechanical Technician: 0.6 weeks
Optical Engineer: 1.2 weeks
Software Engineer: 0.4 weeks

[002-04] Risk assessment of control and communication to the delay line trolley

Principal risks:
That it may prove difficult to implement suitable high bandwidth links to communicate with and control the delay line trolley over a distance of 656 feet in an evacuated pipe.

Background: The current baseline plan is to use an 864 MHz transmitter/receiver link for the low-latency communication required for OPD control and a separate Ethernet wireless link for higher-latency control signals.

Proposed analyses/experiments:

1. Identify a suitable 864 MHz transmitter/receiver link that meets our latency requirements and compare these with the latency requirements for the existing COAST delay line control.
2. Replace the existing wire link between the metrology system and one of the COAST delay line carriages with such a 864 MHz link and perform the following diagnostics experiments to assess whether the demanded delay line carriage position is affected at any frequencies greater than 1Hz:
    a. Race two carriages against each other at the same rate and check for any differential OPD.
    b. Measure the metrology error signals from each trolley and check that the new communication link introduces no significant increase in this.
    c. Look at the fringes from an internal artificial star and examine the temporal fringe spectra for an existing and modified COAST delay line carriage.
3. Compute the attenuation expected for propagation at 864 MHz within a 16" aluminum vacuum pipe for short (20 foot) and long (656 foot) propagation paths.
4. Measure the attenuation of the 16" aluminum vacuum pipe at 864 MHz and ensure that the RF standing-wave ratio seen over a 20 foot section is within acceptable limits.
5. Extrapolate the measured attenuation to a 200m propagation path and assess its impact on successful communication with the delay line carriage.

6. Obtain a pair of suitable Ethernet wireless (2.4GHz) bridges and set them up at COAST, in place of an existing higher-latency communication link. Demonstrate suitable performance of the link.
7. Analyze the RF performance of the link within a long (656 foot) section of 16" aluminum vacuum pipe.
8. Design suitable terminators and launching aerials for tests of the wireless link within a conducting pipe.
9. Install the wireless link in a 20 foot section of jointed vacuum pipe, and check its satisfactory performance. Assess whether it impacts detrimentally with a parallel 864 MHz link. Extrapolate its measured behavior to 656 feet.

Fallback options & comments:

If necessary we will be able to use different frequencies within the 864 MHz band to eliminate the potential for interactions between parallel delay lines. We do not expect significant (>nW) RF leakage between the vacuum pipes or to the outside world.

Resources required:

Electrical engineer: 1.8 weeks
Controls engineer: 0.6 weeks
Electrical technician: 1.0 weeks
Software engineer: 1.2 weeks

[002-05] Risk assessment of power transmission to the delay line trolley

Principal risks:
That it may prove difficult to deliver power to the delay line trolley over its expected 656 foot travel for two reasons:
(1)The power delivered may not be stable, leading to unreliable operation
(2) That losses in the power transmission mechanism may lead to failure to meet an overall power budget.

Background: The current baseline plan is to use an inductive pickup scheme (as used, for example, to power trams in warehouses) to power the delay line carriages.

Proposed analyses/experiments:

1. Design and install an inductive power delivery system within the COAST bunker and use it to power one of the COAST delay line trolleys. Compare the performance of the inductively powered trolley to that of a conventionally powered one over 25m of stroke.
2. Build a system to deliver 24 Watts (24V at 1A) to a dummy delay line carriage running within an aluminium pipe (see Fig. 6). Measure the stability and regulation of the power delivered.
3. Project the measured performance to a 656 foot pipe length and assess how other effects, e.g. losses, can be managed then.

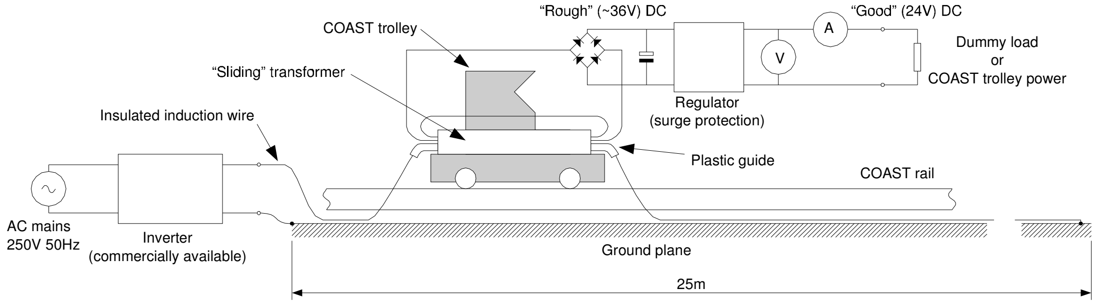


Figure 6: A schematic diagram of the proposed power transmission test to drive a delay line trolley at COAST.

Fallback options & comments:

Initial lab tests have already demonstrated 10W transmission over a few meters. If necessary, fallback options including batteries, sliding contacts, and RF power transmission will be investigated.

Resources required:

Electrical engineer: 6.2 weeks

[002-06] Risk assessment of delay line trolley steering

Principal risks:

That it may be difficult to design a suitable steering mechanism for the delay line trolley to counteract the tendency of the trolley to rotate about its optical axis – hereafter we shall refer to this as "clocking".

That control of the delay line trolley steering may interact unfavorably with control of the longitudinal motion of the trolley.

Background: We assume the presence of a rig incorporating a section of vacuum pipe as well as a "dummy" delay line carriage with a mass and wheel configuration (location and type) representative of the proposed prototype trolley. This dummy trolley will carry an inclinometer and a data acquisition system to allow the inclination of the trolley to be monitored as it travels along the pipe.

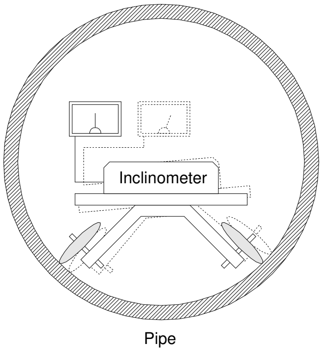


Figure 7: A schematic diagram of a dummy delay line trolley mounted within the prototype MROI vacuum delay line section.

Proposed analyses/experiments:

1. Perform a numerical analysis to identify the maximum clocking angle allowed for the delay line trolley in terms of affecting its optical performance and its metrology.
2. Run the dummy delay line trolley along a vacuum pipe section and monitor the typical clocking associated with motion at sidereal and slewing rates.
3. Repeat the above experiment with the carriage wheels deliberately misaligned to identify how the amplitude of clocking varies with wheel misalignment.
4. Based on the disturbance amplitudes inferred from the previous experiments, perform an analysis and outline design for a suitable concept for steering the delay line carriage.
5. Perform a controls analysis for the outline design to assess what, if any, crosstalk may exist between the control of clocking angle and longitudinal control of the delay line carriage.

Fallback options & comments:

Wheels with different levels of compliance will be tested. If the steering concept is shown to be too high-risk, a guide-rail alternative will be explored.

Resources required:

Mechanical engineer: 3.0 weeks
Controls engineer: 2.6 weeks
Mechanical technician: 0.4 weeks

[002-07] Risk assessment of expected OPD disturbance spectrum

Principal risks:
That the OPD disturbance spectrum expected for the proposed delay line concept will be considerably larger than that expected (and managed) by a trolley running on precision rails, for example the COAST delay lines.

Background: We assume the presence of a rig incorporating two 10 foot jointed sections of vacuum pipe as well as a "dummy" delay line carriage with a mass and wheel configuration (location and type) representative of the proposed prototype trolley. This dummy carriage need not carry any of the optical elements associated with the prototype trolley. By way of background information, the COAST delay line roof mirrors have an rms jitter of ~15nm when run at sidereal rates corresponding to 100m baselines.

Proposed analyses/experiments:

1. Procure a 3-axis accelerometer with milli-g resolution and a data acquisition system capable of reading and storing the accelerometer data at rates $\geq$ 500Hz for periods $\geq$ 10 seconds.
2. Mount the accelerometer and data acquisition system on the carriage of one of the COAST delay line trolleys and measure the spectrum of the raw OPD disturbance as the carriage tracks at the sidereal rates associated with 50m, 100m, and 200m baselines. These data should allow the power spectrum in all three axes to be reliably estimated between 1 and 250Hz.
3. Record the associated jitter of the COAST delay line OPD as measured by the metrology system when running at the above rates.
4. Repeat the experiment with the accelerometer mounted on the MROI dummy carriage as it traverses its vacuum pipe. Repeat the experiment at carriage speeds associated with 50m, 100m and 200m baselines.
5. Compare the OPD power spectra for the COAST and MROI carriages and check to see whether or not the spectrum for the proposed MROI carriage is significantly higher than that of the COAST carriage.
6. Use the measurements of the OPD power spectra from the COAST trolley to assess what typical disturbance rejection is associated with it, and hence how significant any excess power seen in the MROI data may be.

7. Propagate the measurements of the raw OPD power spectra from the dummy MROI trolley through the predicted rejection response based on a numerical model of the delay line carriage and assess what typical disturbance spectra might remain.
8. Repeat the measurements for the prototype MROI delay line carriage with a deliberately introduced gap between the pipes. Estimate the maximum permissible gap size that could be tolerated in practice without losing the metrology signal.

Fallback options & comments:

Wheels with different levels of compliance will be tested. In addition, the parameters characterizing the rejection model of the MROI carriage will be optimized to see how best to damp any potentially difficult regions of the disturbance spectrum.

Resources required:

Mechanical engineer: 0.2 weeks
Electrical engineer: 1.8 weeks
Controls engineer: 2.6 weeks
Mechanical technician: 0.6 weeks
Electrical technician: 0.6 weeks
Software engineer: 1.6 weeks

[002-08] Risk assessment for long stroke laser metrology

Principal risks:
That there may not exist a cost-effective solution that meets the requirements on the frequency stability and maximum permissible diffraction losses of the metrology laser.

That it may be difficult for the metrology beam to be suitably expanded prior to propagation and for the opto-mechanical stability requirements of the beam expansion system to be met in a cost-effective manner.

Background: The baseline design for the metrology system assumes the use of a commercial Zygo interferometer.

Proposed analyses/experiments:

1. Perform the diffraction calculations necessary to assess power and fringe visibility losses in different diameter metrology beams after propagation through the delay line system.
2. Perform calculations to assess the tilt and shear stability required to guarantee successful operation of the metrology system. Compare these with expected performance of potential stages and mounts.
3. Compute the frequency stability criteria needed on timescales from 1-100ms for the metrology laser. Test the frequency stability of one Zygo laser head against another by beating their beams on a high-speed photodiode (f>10MHz) and monitoring the output with a spectrum analyzer and/or digital frequency meter. Compare the measured frequency stability with the requirements.

Fallback options and comments:

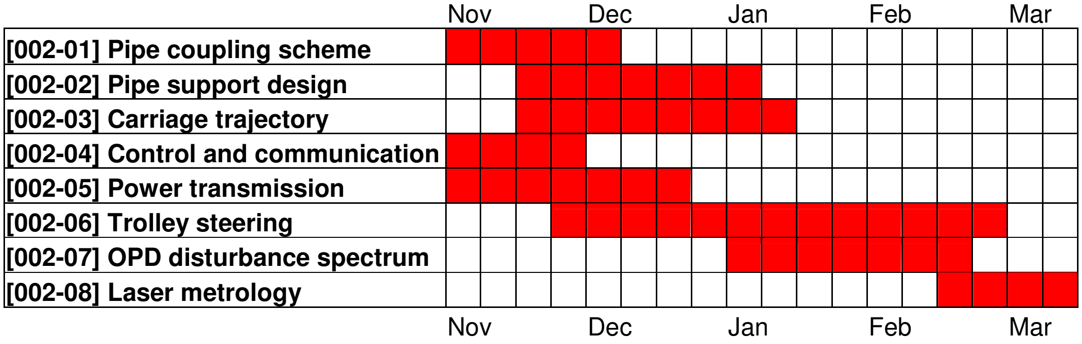
If necessary, we will be able to test a number of different laser heads and mounting schemes. Discussions with Zygo have suggested that their existing products will satisfy our frequency stability requirements, but we have also sourced a number of alternative metrology systems and lasers.

Resources required:

Electrical engineer: 1.8 weeks
Optical engineer: 2.0 weeks

<u>Total resources required</u>:

Mechanical engineer: 9.6 weeks
Electrical engineer: 11.8 weeks
Controls engineer: 7.4 weeks
Mechanical technician: 5.4 weeks
Electrical technician: 1.6 weeks
Draughtsman: 1.0 weeks
Optical engineer: 3.2 weeks
Software engineer: 3.4 weeks



	Nov				Dec				Jan				Feb				Mar	
[002-01] Pipe coupling scheme	🟥	🟥	🟥	🟥	🟥													
[002-02] Pipe support design			🟥	🟥	🟥	🟥	🟥	🟥	🟥									
[002-03] Carriage trajectory			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥								
[002-04] Control and communication	🟥	🟥	🟥	🟥														
[002-05] Power transmission	🟥	🟥	🟥	🟥	🟥	🟥	🟥											
[002-06] Trolley steering				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		
[002-07] OPD disturbance spectrum									🟥	🟥	🟥	🟥	🟥	🟥	🟥			
[002-08] Laser metrology															🟥	🟥	🟥	🟥
	Nov				Dec				Jan				Feb				Mar	

Figure 8: A preliminary Gantt chart for the effort associated with the risk reduction experiments. The main interdependency of the tasks is the effort for the production of the dummy carriage, and this has been bookmarked with the first part of [002-06].

APPENDIX A: PROGRAMMATIC SUMMARY

The following is a summary of the initial statement of work (SOW) for the delay line work package. The document reflects the baseline program at the time of drafting the SOW (September 2004) and so parts of it may be inconsistent with the current (i.e. most recent) definition of the risk reduction experiments.

1. Scope of work

The primary goal of the delay line work package is the design and development of a cost-effective solution for a 200 meter single stage continuous delay line that meets the performance requirements for the Magdalena Ridge Observatory Interferometer (MROI).

The delay line work package includes the design and development of a complete delay line system suitable for the MROI. The delay line system includes the delay line carriage and associated optics, an appropriate delay line "track", a vacuum vessel, mechanical supports, control electronics and prototype software, and the metrology system required to operate the delay-line system at the MROI.

The design and development approach will utilize risk mitigation experiments enabling the early assessment of new or risky technologies that are being proposed. Following and in parallel with the risk mitigation experiments will be the development of appropriate prototype subsystems that can be used to comprehensively validate the proposed solution. Lastly a production design will be developed with suitable documentation enabling the transfer of the delay line technology and production processes to New Mexico Tech (NMT).

The scope of this work package includes the assembly and testing of the first complete production carriage with its associated control electronics in the UK, its shipment and testing in New Mexico, and oversight of the manufacture, but not testing, of the second complete production carriage at NMT.

The subsequent procurement, fabrication and installation of the full delay line system, including the vacuum pipes, the metrology system and the remaining carriages, will be undertaken by the MROI project, with assistance from Cambridge. These activities will not fall within the scope of the work package described here.

2. Work Breakdown Structure

WBS000 Management/system engineering

This component of the work package includes the definition of the requirements for the delay-line system, the system engineering including the flow-down of the top-level requirements to a detailed error budget for the subsystems, and the overall management of the project.

The following interfaces will need to be defined and agreed on as the work package proceeds:

1. The mechanical interface of delay line pipes with their mountings in the Delay Line Area (DLA) of the Beam Combining Facility (BCF).

2. The optical and mechanical interfaces of the delay line pipes with the input and output optical beams.
3. The software interface with the array control system, described at a level that allows the MROI controls team to design the operational control software.
4. The software interface with the fringe-tracking beam combiner outputs, again described at a level that allows the MROI controls team to design the control software for the production delay line system.
5. The software interface with the metrology system outputs, again described at a level that allows the MROI controls team to design the control software for the production delay line system.
6. The vacuum interface with the overall vacuum system of the MROI.

[000-01] Prepare top-level Systems Requirements Documents

[000-02] Overall oversight of the effort associated with this work package.

WBS001 Conceptual design and risk mitigation experiments

[001-01] Identify initial concepts (includes metrology system)

[001-02] Identify and detail risk mitigation experiments

[001-03] Review with MROI

WBS002 Risk reduction experiments

Risk-mitigation experiments will be undertaken early in the delay line work package effort so as to confirm the suitability of the approaches being considered in a timely manner. This list is not meant to be exclusive, and so additional experiments may also be undertaken if, after completion of WBS001-02, they are agreed by Cambridge and NMT to be necessary.

[002-01] Tests of coupling procedures for sections of delay-line pipe to assess vacuum integrity and level of alignment of internal running surfaces.

[002-02] Tests of the design of the delay line pipe supports to assess their cost, adjustment range and resolution, space envelope and stability in the presence of temperature changes.

[002-03] Measurements of the typical carriage trajectory defined by the inner pipe surface of a section of jointed pipe so as to specify the amplitudes and rates of control needed to maintain the pupil shear within the necessary limits and hence guide the design of the secondary mirror stage.

[002-04] Initial design, procurement and tests on control and communication. Risk reduction experiments will be undertaken to ensure that a link with suitable bandwidth and a low enough error-rate can be provided over a 200m length of delay-line pipe.

[002-05] Initial design, procurement and tests on power transmission. Risk reduction experiments will be undertaken to ensure that suitable power can be delivered along a 200m length of delay-line pipe in a way that remains within our overall power budget.
[002-06] Initial design, procurement and tests of mechanisms to control clocking of the delay-line carriage. Risk reduction experiments will be undertaken to ensure that a suitable mechanism can be delivered to mimimize any clocking of the delay line carriage to a suitably low level as it traverses up to 200m of delay-line pipe.

[002-07] Measurements of the spectrum of OPD disturbances in a moving carriage with a non-isolated retroreflector.

[002-08] Risk reduction experiments and analyses will be undertaken to ensure that the requirements on the frequency stability, power output and diffraction losses of the metrology laser can be met. Similar experiments/analyses will also be performed to assess the stability and cost of suitably expanding the metrology beam prior to propagation.

[002-09] Review of results of experiments and analysis

WBS003 In-air tests of prototype carriage

[003-01] Initial design and procurement of parts for prototype cats-eye.

[003-02] Initial design and procurement of parts for prototype carriage.[003-03] Initial design and procurement of parts for secondary mirror and mount for shear control.

[003-04] Initial design and procurement of parts for focus control.

[003-05] Initial design and procurement and tests of components of prototype metrology system.

[003-06] Assemble prototype carriage, control electronics and metrology system.

[003-07] Assemble test rigs, including 20m test pipe section.

[003-08] Tests on clocking, shear control and wavefront quality.

[003-09] Tests on OPD stability.

[003-10] Tests on power transfer.

[003-11] Tests on communication and control.

[003-12] Tests on metrology.

[003-13] Prepare and submit report to MROI team.

WBS004 Vacuum compatibility tests

[004-01] Prepare vacuum rig and test.

[004-02] Repeat opto-mechanical tests performed in WBS003-08 to WBS003-12 above to confirm that specifications are met when operating in vacuum conditions.

[004-03] Review of performance of prototype carriage, electronics and metrology system together with any proposed changes desired for the production systems.

WBS005 Production rework

[005-01] Prepare build-to drawings.

[005-02] Document software for testing.

[005-03] Prepare parts and supplier lists.

[005-04] Prepare assembly instructions.

[005-05] Document test procedures.

[005-06] Review final design, interfaces and acceptance test procedures with NMT.

WBS006 Fabricate, test and ship first production carriage

[006-01] Procure, assemble and test first production carriage and set of control electronics in UK.

[006-02] Dismantle, pack and ship to NMT.

[006-03] Review of performance of first production carriage.

WBS007 Technology transfer

[007-01] Travel to NMT to advise on procurement of parts for production carriages and advise on construction of delay-line test rigs at NMT.

[007-02] Receive, re-assemble and test first production carriage.

[007-03] Oversee production of second carriage and control electronics.

Reviews, meetings and status reports

We expect that formal reviews of progress will take place as outlined above in the WBS, in particular:

WBS001 Review of concept selections and proposed risk reduction experiments.

WBS002	Review of risk reduction results, concept final selection and interfaces for delay-lines, delay line pipe supports and metrology system.
WBS003/4	Review of performance of prototype carriage and proposed production changes.
WBS005	Review of production drawings and other delivered documentation.
WBS006	Review of performance testing of first production carriage.

In addition, day-to-day progress will be summarized in the normal weekly teleconference between NMT and Cambridge and written monthly status reports will be submitted to the MROI Project Manager as work progresses.

3. Deliverables

The deliverables associated with this work package will be:

- System Requirements Documents
- Build-to drawings of the delay-line carriages.
- Build-to drawings of the delay-line control electronics.
- Build-to drawings of the delay-line pipe joints and supports.
- Build-to drawings of the delay-line metrology system.
- Build-to drawings of all necessary test assemblies.
- Part lists and supplier lists for all the above.
- Acceptance test procedures for all the above components.
- Assembly procedures for all of the above sub-systems.
- Subsystem and system test procedures to be used at NMT for the above systems.
- Prototype control software & documentation – this will be written to the level required to test and confirm the performance of the production carriages. The documentation will be adequate to guide the development of the control software for the production delay line system.
- The first production delay-line carriage and control electronics.

The following components will not be part of the deliverables for this work package:

- The prototype cart, control electronics & metrology system – this will be kept in Cambridge for long-term support.

- The design, coding and integration of the control software for the production delay line system.

The hardware for the production metrology system.