Magdalena Ridge Observatory

Requirements Specification for the MROI Delay Line System

INT-406-TSP-0002 rev.0.6

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1. INTRODUCTION

1.1. BACKGROUND

The Magdalena Ridge Observatory (MRO) project is an international consortium between New Mexico Institute of Mining and Technology (NMT), the Astrophysics Group of the Cavendish Laboratory at the University of Cambridge, New Mexico State University, New Mexico Highlands University, University of Puerto Rico and Los Alamos National Laboratory. The project office is located in Socorro, New Mexico. NMT is acting as the fiscal agent for the majority of the capital funds for the construction, and the project is overseen by the Office of Naval Research (ONR). The observatory is sited in the Magdalena Mountains, about 48 km (30 miles) west of Socorro, at an elevation of 3230 meters (10600 ft) above sea level. The observatory is primarily intended for astronomical research and will be composed of two facilities, a single 2.4-meter telescope and a long-baseline imaging optical and near-infrared interferometer, the Magdalena Ridge Observatory Interferometer (MROI), the latest being the main focus of this document. The interferometer will comprise an array of up to ten 1.4-meters Mersenne afocal unit telescopes (UT) arranged in an equilateral "Y" configuration (Figure 1). Each of these telescopes will send a collimated beam of starlight to a beam-combining facility located close to the center of the array. The telescopes will be re-locatable amongst a discrete set of 28 foundation pads, giving baseline lengths (inter-telescope spacing) from approximately 7.5 meters to 380 meters. The layout of the array on the Magdalena Ridge is constrained by the local topography of the site. Fortunately, the site contains a large plateau situated at a saddle point on the mountain. Further information about the observatory can be found on the web at http://www.mro.nmt.edu/.

When MROI is operational, starlight from each UT will be transported in up to ten evacuated Beam Relay (BR) pipes to a central Beam Combining Facility (BCF) as shown in Figure 2. Part of the BCF is the Delay Line Area (DLA) where up to ten evacuated Delay Lines (DL) are placed. These DLs will be used to match light paths from a star, via a pair of UTs, to within the coherence length of the light being measured in any spectral channel of the detector system. Upon exiting the DLA, light is directed to the Beam Combining Area (BCA) where will be combined to generate interferometric fringes used to reconstruct astronomical images.

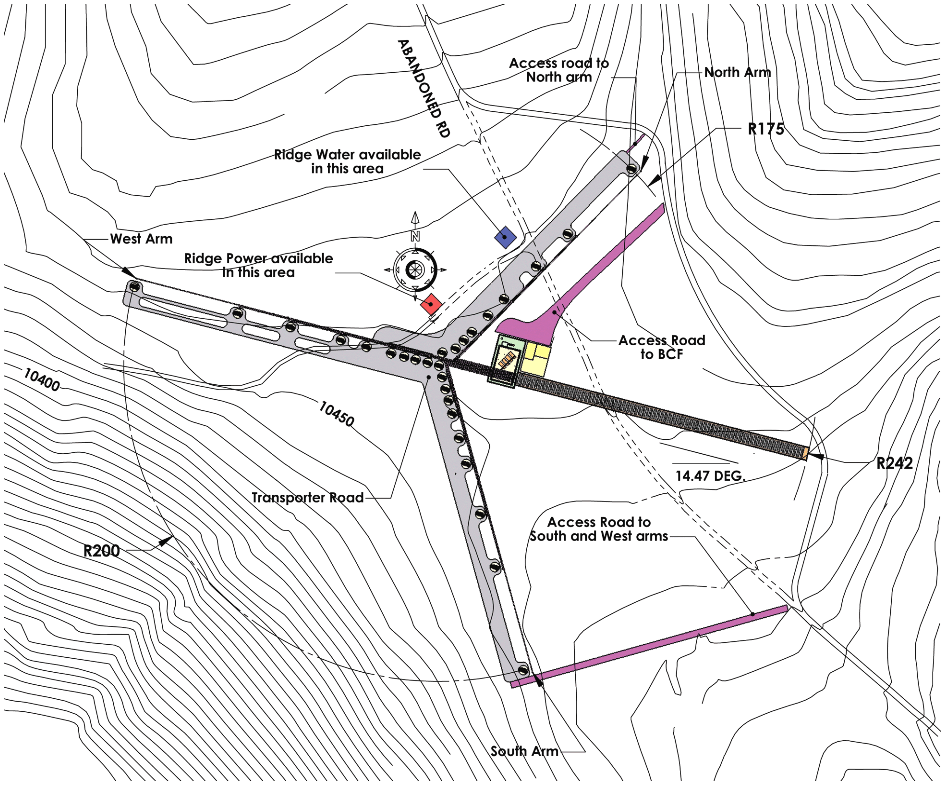

Figure 1 - Plan view of the Magdalena Ridge showing the MROI array. The North arm is towards the top of the diagram and East to the right.

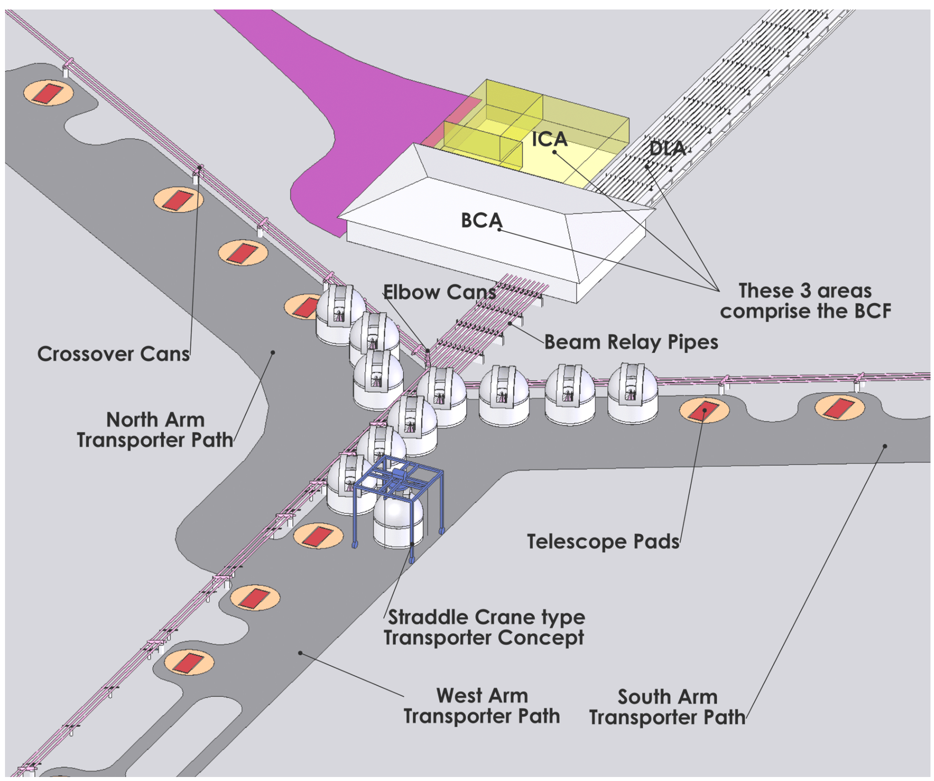

Figure 2 - CAD schematic showing the BCF near the right vertex of the array (hand side in the illustration). Telescopes are shown in a “close packed” configuration. BR pipes feed light to the DLA, in the BCF.

1.2. SCOPE

The scopes of this requirements specification document are to briefly outline the design of the MROI DL sub-project and to present its top-level requirements, following what have been previously reviewed by the University of Cambridge on November 2004 (Risk Reduction Experiments Review - INT-406-VEN-0000). The main purpose for this effort is to bring all work packages (WP) to the same level as the DL-Trolley designed by Cambridge, so that design and procurement for optical, mechanical, electrical, software, and civil engineering can proceed accordingly at MROI. The DL sub-project indexed as 4.06, comprises five WPs:

- **4.06.01.** Delay Line System, which includes the integrated and tested DL system, the DL documentation (built-in drawing package), the installation and commissioning plan, and the maintenance manual;
- **4.06.02.** Delay Line Trolley, which includes the DL trolleys and associated optics and electronics;
- **4.06.03.** Delay Line Pipes and Supports, which includes prototyping (DL Test-Rig), the DL pipes as a precision rail for the DL trolleys, the DL pipe as a vacuum vessel (couplings, seals, bellows, access hatches, and optical/electrical feeds), the DL pipe structural support/alignment system, the DL pipe gantry crane, and the DL vacuum interfaces;
- **4.06.04.** Delay Line Metrology System, which includes the metrology hardware and optical system for the full set of DLs; and
- **4.06.05.** Delay Line Software, which will be outlined in a separated document, referred to as INT-406-TSP-0003-rev01.

Most contents included in these WPs are being developed under contract by the University of Cambridge, specially the Trolley, Pipes and Supports, and the Metrology System. Requirements are divided into two different sections: functional requirements and performance requirements. This effort intends to provide a basis for the conceptual and preliminary design development phases at MROI. To avoid distraction, derived flow down requirements will be defined and included in upcoming documents.

The MROI DL System is expected to meet or exceed all requirements specification outlined in this document, so they are set as the minimum acceptable. All interfaces between the DL and other WPs and MROI facilities may have this document as a reference to generate Interface Control Documents (ICD), as needed. Cambridge's proposed list of ICDs is presented in this document (*Delay Line ICD Allocations and N^2 Diagram Subset* - (v4 - Feb. 2007)).

2. RELATED DOCUMENTS

The following documents are hereby incorporated by reference:

- *A System Design for the MRO Interferometer* - (Doc. no. INT-402-MIS-0000 rev1.31 - Oct. 2002);
- *Risk Reduction Experiments Review* - (Doc. no. INT-406-VEN-0000 - Nov. 2004);
- *Results of the Risk Reduction Experiments* - (Doc. no. INT-406-VEN-0005 - July 2005);
- *The Optical Error Budget for the MRO Interferometer* - (Doc. No. INT-402-ENG-nnnn-rev0.2 - Mar. 2007);
- *Delay Line ICD Allocations and* N^2 *Diagram Subset* - (v4 - Feb. 2007).
- *Software Requirements Specification for Delay Line Control System* - (Doc. no. INT-406-TSP-0003-rev01 - Apr. 2007);
- *Draft MROI Beam Relay Requirements - for comment and discussion* - (Doc. no. INT-405-TSP-0004-rev0.2 - Sept. 2006);
- *Draft MROI Vacuum System Requirements* - (Doc. no. INT-405-TSP-0011-rev0.3 - April 2007);
- *Requirements for the Vacuum Delay Lines for the MROI Interferometer* - (Doc. no. INT-406-TSP-0001-rev0.01 - Apr. 2005); and
- *Project Quality Management Plan* - (Doc. no. INT-401-PMG-0011-rev0.7 - Mar. 2007).

3. ABBREVIATIONS AND ACRONYMS

- BCA Beam Combining Area
- BCF Beam Combining Facility
- BR Beam Relay
- DL Delay Line
- DLA Delay Line Area
- ICD Interface Control Document
- MRO Magdalena Ridge Observatory
- MROI Magdalena Ridge Observatory Interferometer
- NMT New Mexico Institute of Mining and Technology
- ONR Office of Naval Research
- OPD Optical Path Difference
- UT Unit Telescope
- WP Work Package

4. SYSTEM DESCRIPTION

The baseline design of MROI is presented in INT-402-MIS-0000 - *A System Design for the MRO Interferometer*. Conceptual drawings for the array are shown above in Figures 1 and 2. Night sky light is transported from each UT via evacuated beam relay pipes. The output beam is collimated and nominally 95 mm in diameter (3.75 inches). On each of the three arms of the array, there is up to three beam relay pipes, each of which is placed parallel to the others in a horizontal plane. In addition to these 9 pipes, there is a 10th that continues from a UT located at the center of the array. From there to the BCF, these 10 pipes are laid out side by side with no additional optics. The minimum spacing of the beams is limited by the size and spacing of the DLs rather than the spacing of the array telescopes. Upon arrival at the BCF, these beams of light are introduced into the DLA where appropriate compensation for the optical path difference (OPD) between beams from each UT will take place.

The DLA is one of the major parts of the MROI infrastructure. As described in INT-402-MIS-0000, the proposed concept is to use single long-stroke vacuum DLs for each telescope beam of light so as to save on reflections. Inside each DL there is a cat's-eye optical assembly that is flexure-mounted and voice-coil actuated on a motorized carriage. Hereafter, we 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 system in use at other interferometer arrays, the design proposed by Cambridge would:

1. Introduce the entire 380 m (1250 feet) of optical path delay for each telescope beam of light by using a single-pass traverse of the delay-line vacuum pipes;
2. Have the delay line trolleys running directly on the inner surface of the vacuum pipe, and not on pre-installed rails;
3. Have the end of each DL pipe anchored close to the BCA to a stable concrete pier, and thereafter using steel flexure mounts on each pipe support in order to accommodate thermal expansion of the pipes; and
4. Uses low-bandwidth tilting of the cat's-eye secondary mirror to compensate for pupil shear variations introduced by imperfections in the pipe straightness.

The primary reasons for keeping the DL under vacuum are:

- Longitudinal dispersion: Since there is the need to match the optical paths in all arms of the interferometer across the entire bandpass, air in the beam transport system limits the bandpass and hence the sensitivity of the instrument.
- Atmospheric turbulence: Turbulence in the beam transport pipe will cause instrumental seeing. The seeing will be proportional to the pressure so the lower the vacuum the better.

- Refraction: Even without atmospheric turbulence, air in the beam transport can cause problems. A small temperature gradient across the beam will refract it causing beam deviation. Keeping the system in alignment will require maintaining a constant temperature gradient across the pipes.

- Scattered light: By completely transporting the light from each telescope to the BCF through a dark environment (evacuated pipeline), makes it possible to do performance and alignment tests during the day.

5. TOP LEVEL REQUIREMENTS

The following sections describe only the top-level requirements for the *overall design* of the MROI DL System. These requirements are divided into two different sections: functional requirements, which present what the operational DL System must do; and performance requirements, which present how well and under what conditions the system must perform its function. Flow down requirements, strictly necessary for achieving all functional and performance requirements during the lifetime of the observatory, will be described on upcoming documents, whenever applicable and consistent with these top-level requirements. For each requirement, the document used as reference is indicated.

5.1. FUNCTIONAL REQUIREMENTS

Absolute delay: The DL System must be able to introduce a given absolute delay with a precision significantly better than the random perturbations introduced by the atmosphere. **Ref.** INT-402-MIS-0000.

Response from path correction signals: During sidereal tracking mode, the DL carriage must respond to path-correction signals from the fringe acquisition and tracking signals in real time. Latencies of less than a millisecond for small amplitude signals are desirable if phase tracking is to be implemented. **Ref.** INT-402-MIS-0000.

Paths from a star: During sidereal tracking mode and in order to get high-contrast fringes, the paths from a star need to be matched, via a pair of telescopes, to within the coherence length of the light being measured in any spectral channel of the detector system. **Ref.** INT-402-MIS-0000.

Clear aperture: The DL shall have a clear aperture of 125 mm in diameter. This is consistent with an input starlight beam of 95±1 mm in diameter plus diffraction and dispersion after traveling through the beam relay system. **Ref.** INT-406-VEN-0000.

Beam height: The DL shall be designed so as to be compatible with the beam relay system output beam height of 1.6 m (3 feet and 3 inches) above local grade. This means 1.6 meters from the beam center to the top of the DLA concrete slab. **Ref.** INT-405-TSP-0004.

Volume envelope: The DLs shall be expandable for up to 10 telescopes. To meet this requirement, a system of up to 10 DLs and their associated support structures, not including foundations and metrology system, shall be capable of fitting within a rectangular region of dimensions: 200 m long x 2.15 m high x 7.3 m wide (approximately 656 feet long x 7 feet high x 24 feet wide). The DLA shall be designed to allow access for installation, maintenance and alignment. **Ref.** INT-406-VEN-0000.

Vacuum system: The vacuum system for MROI is defined as the work package 4.05.02 and so is not a deliverable for the DL sub-project. The DL pipes shall be sealed so as to provide a dust and moisture free environment for the beams of light to propagate through it. The DL pipes must be evacuated to a pressure of about 3 mbar to meet the requirements on differential optical dispersion for non-astrometric applications. The vacuum level requirement for MROI is 0.5 mbar, set initially before beginning of night time operations. Seeing into evacuated pipes is negligible below 10 mbar, as thermal perturbations dissipate rapidly. Thermal conductivity from DL trolley to pipe body is approximately constant from 0.03 mbar to 1 bar. **Ref.** INT-406-VEN-0005 and INT-405-TSP-0011-rev03.

Power dissipation: A set of 10 DLs, including metrology system and control electronics shall dissipate no more than 10 x 200 W (2 kWatts) in total. Efforts shall be taken to minimize the power dissipated by the DL system and any of its associated electronics located in the BCA. **Ref.** INT-406-VEN-0000.

Lifetime: As for all MROI sub-projects, the DL system shall be designed for an estimated lifetime of 20 years. Its design shall be compatible with a preventive maintenance regime, undertaken no more frequently that once per 2 years.

Environmental conditions: The DLs shall be operational and meet all performance requirements inside a building maintained at temperatures between -10ºC (14F) and 25ºC (77F) with diurnal variations of no more than 1.1ºC (2F) peak-to-peak, and spatial variations of 5.5ºC (10F) peak-to-peak. The DLs shall be capable of surviving temperatures from -20ºC (-4F) to 32ºC (90F) without damage. The DL shall be capable to survive relative humidity up to 90% without running the risk of condensation. The DLs shall meet all performance requirements when attached to a floor with up to 1 μm rms vibration at frequencies between 0.1 Hz and 500 Hz. **Ref.** INT-406-VEN-0000.

Safety and Environmental: All equipment shall be designed and manufactured with safety and ease of operation and handling.

Reliability and Maintainability: Because the DL will be in continuous use, a complete, extensive and detailed Operational & Maintenance Manual will be generated as part of the project. It will contain all available information about the component parts and detailed instructions required for operation, maintenance and repair of the DL WPs. Because of the remote observatory location and especially the nighttime operational environment and limited manpower for support, a high premium is placed on DL reliability and fault-tolerance as a whole.

Automation: MROI design philosophy assumes a highly automated sequencing and operation approach (tracking of specific trajectories, calibration during the night, etc). Considerable design effort shall be spent on a control architecture that allows for remote diagnostic testing of all DL hardware.

5.2. PERFORMANCE REQUIREMENTS

Wavelength of operation: The DL shall be able to support the transport of radiation for all wavelengths from 0.6 µm to 2.4 µm. **Ref.** INT-402-MIS-0000.

Range of delay: The DL shall have a minimum total stroke of 380 m (1250 feet) of optical path change, i.e. 190 m (625 ft) of travel for a single-pass design. **Ref.** INT-406-VEN-0000.

Optical throughput: The DL shall introduce no more than 15% throughput loss (unpolarized) between its input and output beam of light, considering its wavelength of operation. **Ref.** INT-406-VEN-0000.

Delay precision: The DL shall be able to introduce any commanded OPD change allowed within its stroke with an intra-night repeatability of better than 10 µm rms and a night-to-night repeatability of better than 100 µm rms. These requirements shall be kept for all atmospheric seeing and mechanical drift allowed to the system. When commanded to do so, the DL shall be able to go to a mechanical fiducial sensor and detect the position of this datum to a precision of better than 10 µm rms. **Ref.** INT-406-VEN-0000.

Slew speed: The DL shall be able to slew between any two points within its available stroke, corresponding to a change in OPD of up to 30 m (i.e. a physical motion of 15 m or approximately 50 feet for a single-pass design), in less than 30 seconds, including the time taken to accelerate and decelerate to/from sidereal tracking speeds. This 0.5 m/s of slew-rate corresponds to the slewing time of the UTs (star switching overhead). The DL shall be able to slew from any position in the available stroke to any other position in less than 5 minutes. **Ref.** INT-406-VEN-0000.

Sidereal tracking and jitter: Also called the wavefront piston stability. The DL shall, when commanded to do so, introduce a smoothly changing OPD trajectory with speeds of up to 30 mm/s (corresponding to physical speeds of the trolley of up to 15 mm/s) and accelerations of up to 2.5 $\mu m/s^2$. Jitter shall be less than $\lambda/40$ in $2t_o$. Therefore, the OPD shall follow the commanded trajectory with a jitter of less than 15 nm rms as measured over any 10 ms integration period, a jitter of less than 41 nm rms over any 35 ms integration period, and a jitter of less than 55 nm rms over any 50 ms integration period. It is acceptable to exceed these jitter limits for a total of 0.5 seconds during any 60 second tracking interval. **Ref.** INT-406-VEN-0000.

Static wavefront quality: The DL shall introduce no more than 60 nm rms wavefront aberrations to the starlight beam across the clear aperture, including focus errors and the aberrations introduced by the exit window. In this sense, it must meet the wavefront quality requirements necessary to support the MROI global static wavefront quality budget. **Ref.** INT-406-VEN-0000.

Dispersion: The differential optical dispersion between beams propagating through any two DLs 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 J, H and K astronomical photometric bands, and 0.5% anywhere within the R and I bands. In calculating this phase change, it is acceptable to subtract the component of phase change with wave number which is linear across the relevant photometric band, i.e. the overall group delay for that band. **Ref.** INT-406-VEN-0000.

Polarization: The diattenuation of any beam propagating through the DL to the BCA shall be less than 1% for the considered wavelength of operation, so as to not reduce the system visibility significantly. **Ref.** INT-406-VEN-0000.

Pupil shear: The DL shall introduce no more than 1 mm rms variation 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 DL travel. This shear criterion can be exceeded when the DL is slewing as long as the DL trolley metrology signal is not lost. This requirement derives from the overall interferometer visibility loss error budget: a 1 mm shear results in a 1% fringe visibility loss. **Ref.** INT-406-VEN-0000.

Dynamic tracking of atmospheric fluctuations: The DL shall support the closed-loop tracking of atmospheric OPD fluctuations when used in combination with an external group of delay fringe tracker. In particular, the DL shall accept an external offset demand signal of at least 15 Hz sampling rate and have a step response time of less than 30 ms for step sizes of up to 10 μm. Also, it is a goal that the DL accepts external offset demand of at least 200 Hz sampling rate and has a step response time of less than 2 ms for step sizes of up to 0.5 μm. **Ref.** INT-406-VEN-0000.

6. INTERFACES

The following interface control documents to the DL System are required (*Delay Line ICD Allocations and N^2 Diagram Subset* - (v4 - Feb. 2007)):

1. **ICD: DL to ICS (INT-406-ENG-0002)**, which defines the communication and control interface between the Interferometer Control System (ICS) and the DL;
2. **ICD: DL to Beam Relay System (INT-406-VEN-0008)**, which defines the mechanical interface between the DL pipe and the beam relay pipe;
3. **ICD: DL to BCF infrastructure (building) (INT-406-VEN-0009)**, which defines the mechanical and space envelope interfaces between the DL and the BCF (DLA and BCA areas);
4. **ICD: DL to Metrology System (INT-406-VEN-0010)**, which defines the opto-mechanical and electronic interfaces between the DL and the metrology system;
5. **ICD: DL to Vacuum System (INT-406-VEN-0011)**, which defines the mechanical interfaces on the DL pipe required to connect to the vacuum system;
6. **ICD: Metrology System to BCF (INT-406-VEN-0012)**, which relates the metrology bench, services and electronics racks to the BCF (BCA) area; and
7. **ICD: DL to Beam Relay System (INT-406-VEN-0013)**, which defines space envelope for beam relay pipes above the metrology table.

7. MILESTONES SCHEDULE

A detailed milestones schedule was prepared considering all five WPs of the DL sub-project (Refer to INT-406-PMG-0001-rev01-20070411). This document comprises all MROI DL milestones, initial analysis of required tasks to accomplish each milestone, actions, relationships between tasks, priorities, task duration and milestone dates. The following milestones are identified from this document, also considering milestones from the University of Cambridge (described as Cam-DL to differ from MROI-DL). Dates which represent events are highlighted in red.

Table 1 - MROI DL System Milestones Schedule.

Milestones	Dates (mm/dd/yy)	
	BEGIN	END
Cam-DL prototype tests	03/12/06	07/20/07
MROI-DL Requirements Specification Review (RSR)	05/02/07	**05/02/07**
MROI-DL Conceptual Design Review (CoDR)	05/01/07	**07/11/07**
Cam-DL Trolley - Final Design Review (FDR)	**07/24/07**	**07/25/07**
Cam-DL Trolley drawing package delivered - a	-	**08/24/07**
Cam-DL Trolley drawing package delivered - b	-	**10/12/07**
MROI-DL Preliminary Design Review (PDR)	07/17/07	**10/17/07**
MROI-DL Prototyping (first light at the MROI Lab)	10/22/07	**12/31/07**
MROI-DL Final Design Review (FDR)	10/22/07	**01/23/08**
MROI-DL Production (Stage-I)	01/28/08	08/20/08
MROI-DL Factory Acceptance Tests (FAT - Stage-I)	06/25/08	09/30/08
Cam-DL Production Trolley #1 - (FAT)	**03/21/08**	-
Cam-DL Trolley - Campus Acceptance Test (CAT)	**04/21/08**	TBD
MROI-DL Campus Acceptance Tests (CAT)	**04/21/08**	07/30/08
MROI-DL Site Acceptance Tests (SAT)	**10/01/08**	04/30/09
MROI-DL On-Sky Acceptance Tests (OAT) - DL first light	05/01/09	**09/15/09**
MROI First Fringes	09/30/09	**10/03/09**
MROI-DL Production (Stage-II)	05/01/09	01/15/10
MROI-DL Factory Acceptance Tests (FAT - Stage-II)	02/01/10	03/10/10
MROI-DL Sub-project fully operational at MROI	03/12/10	09/30/10

The DL sub-project team will be responsible for the design, development, procurement, manufacturing, testing, debugging and commissioning of the project components. This includes all optical, electronics, and mechanical parts and mechanisms and for obtaining the hardware and developing the software needed for the control of these mechanisms. They are also responsible for delivering complete documentation for the project, including detailed drawings and technical manuals (maintenance and operational manuals). This includes all effort done by the Cambridge team.

As described in Table 1, there will be up to fourteen major events planned during the development phase of the DL sub-project. They are presented in details in INT-406-PMG-0001-rev0.1-20070411 and listed below as reference.

Conceptual Design Review (CoDR): To be carried out after the Requirements Specification Review. The timing for this review will be as short as possible since most DL WPs are well conceptualized by Cambridge.

Preliminary Design Review (PDR): To be carried out after the Conceptual Design Review. This review will determine how the project should go forward to the level of prototyping and final design phases. The timing for this review should also be kept as short as possible.

DL Prototyping (first light at the MROI Lab): To be carried out after the completion of Conceptual Design Review. A Cambridge like DL Test Rig, which includes a 10-15 m evacuated pipe and a full operational metrology system, will be built during this phase. Cambridge shall provide sufficient details to allow NMT to build is own test facility. Cambridge and NMT teams shall jointly complete alignment of the test rig.

Final Design Review (FDR): To be carried out after completion of Preliminary Design Review. A successful review will determine if and how the project should go forward to the level of DL Production (Stage-I) ("green light for starting fabrication"). Any additional prototype required during this design phase shall be built as planned in the PDR.

Production (Stage-I): To be carried out after the conclusion of Final Design Review. Production (Stage-I) means three DLs installed on the DLA of the Magdalena Ridge, each one with 50 m long. Two of these DLs are intended to be used during "first fringes". The other will be used for performance tests of production trolleys 3 through 6. The Metrology System will be mounted with corresponding optics to feed all three DLs.

Factory Acceptance Tests (FAT - Stage-I): To be carried out at MROI Lab after completion of Production (Stage-I). Detailed set of measurements and tests will be proposed during Final Design Review, based on Cambridge's previous knowledge in this area.

Campus Acceptance Tests (CAT): To take place after the conclusion of Factory Acceptance Tests - Stage-I. The majority of the remaining work will be related to integration, refinements, testing and debugging. Cambridge will unpack, assemble and align Production Trolley #1, as well as carry out all tests to assess it in function and performance. This meeting must precede the Site Acceptance Tests and will verify that the DL sub-project meets its performance specifications.

Site Acceptance Tests (SAT): To be carried out after the conclusion of Campus Acceptance Tests. This will mark the first set of tests done with a single trolley on the site. A full set of functional and performance tests will be performed as agreed during the Campus Acceptance Tests meeting. NMT team will carry out all tests.

On-Sky Acceptance Tests (OAT): To be carried out after the conclusion of the Site Acceptance Tests. This will mark the first light for the DL System. Again, functional and performance tests will be performed. Full set of tests will be agreed during the Site Acceptance Tests meeting. Cambridge and NMT teams will jointly carry out all tests.

MROI First-Fringes: To be carried out after the conclusion of On-Sky Acceptance Tests. This will mark first fringes for MROI and the use of two production trolleys.

Production (Stage-II): To be carried out after MROI first-fringes. Production (Stage-II) means the upgrade of the three DLs previously installed on the Magdalena Ridge, and the additional three fully operational DLs, each one with 200 m long. The Metrology System will be upgraded with corresponding optics to feed all six DLs.

Factory Acceptance Tests (FAT - Stage-II): To be carried out sometime after the Campus Acceptance Tests. Detailed set of measurements and tests will take place as done for Factory Acceptance Tests - Stage-I.

8. RESOURCES ESTIMATE

A breakdown of material and travel costs for this effort is presented as a cost baseline and it is referred to as INT-406-PMG-0002-rev0.1. It is limited to the delivery of only six DLs to MROI. This file is to be updated during the different phases of this sup-project. Updates will be referred to revisions.

9. SUMMARY OF REQUIREMENTS AND CHECK LIST

The following table summarizes the performance requirements for the DL sub-project. First column is the performance requirement name. Second column is a description for the performance requirement. Third column is the proposed acceptance test criteria to assess each performance requirement. This table shall be used as a check list for product acceptance.

As suggested in *Project Quality Management Plan* - (Doc. no. INT-401-PMG-0011-rev0.7 - Mar. 2007), the columns heading below 'Acceptance Criteria' are given by: 'design', which refers to calculations by methods or procedures; 'analysis', which refers to computational verification; 'inspection', which refers to visual inspection of items or documents, or test certificates; and 'test', which refers to direct measuring. A ✓ sign is used to indicate the criteria to be used.

Table 2 - Summary of requirements and check list.

Performance Requirement	Description	Acceptance Criteria			
		Design	Analysis	Inspection	Test
Wavelength of operation	0.6 µm to 2.4 µm	✓	✓		
Range of delay	190 m of travel for a single pass design (a minimum total stroke of 380 m (1250 feet) of optical path change)	✓		✓	✓
Optical throughput	Less than 15% throughput loss between input and output beam of light	✓	✓		
Delay precision	Intra-night repeatability of better than 10 µm rms and a night-to-night repeatability of better than 100 µm rms	✓			✓
Slew speed	Change an OPD of up to 30 m (15 m for a single-pass design) in less than 30 seconds. Slew from any position in the available stroke to any other position in less than 5 minutes	✓			✓
Sidereal tracking and jitter	Smoothly change of OPD trajectory with speeds of up to 30 mm/s (physical speeds of the trolley of up to 15 mm/s) and accelerations of up to 2.5 µm/s^2. Jitter shall be less than $\lambda/40$ in $2t_o$. OPD	✓	✓		

	shall follow the commanded trajectory with a jitter of less than 15 nm rms as measured over any 10 ms integration period, a jitter of less than 41 nm rms over any 35 ms integration period, and a jitter of less than 55 nm rms over any 50 ms integration period				
Static wavefront quality	Wavefront aberrations to the starlight beam across the clear aperture shall be less than 60 nm rms, including focus errors and the aberrations introduced by the exit window		✓		
Dispersion	The differential optical dispersion between beams propagating through any two DLs 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 J, H and K astronomical photometric bands, and 0.5% anywhere within the R and I bands	✓	✓		
Polarization	Diattenuation of any beam propagating through the DL to the BCA shall be less than 1% for the considered wavelength of operation, so as to not reduce the system visibility significantly	✓	✓		
Pupil shear	DL shall introduce no more than 1 mm rms variations in the position of the center of the starlight exit beam compared to a reference position	✓			✓
Dynamic tracking of atmospheric fluctuations	External offset demand signal of at least 15 Hz of sampling rate and a step response time of less than 30 ms for step sizes of up to 10 μm. Also, as a goal for a faster rate mode, external offset demand signal of at least 200 Hz of sampling rate and a step response time of less than 2 ms for step sizes of up to 0.5 μm	✓			✓

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