Mechanical Design of the Magdalena Ridge Observatory Interferometer

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ABSTRACT

We report on the mechanical design currently performed at the Magdalena Ridge Observatory Interferometer (MROI) and how the construction, assembly, integration and verification are planned towards commissioning. Novel features were added to the mechanical design, and high level of automation and reliability are being devised, which allows the number of reflections to be kept down to a minimum possible. This includes unit telescope and associated enclosure and transporter, fast tip-tilt system, beam relay system, delay line system, beam compressor, automated alignment system, beam turning mirror, switchyard, fringe tracker and vacuum system.

Keywords: Optical interferometer, delay line, beam combining, fringe tracker, AIV plan.

1. INTRODUCTION

1.1 Background

The Magdalena Ridge Observatory Interferometer (MROI) project is an international consortium between New Mexico Institute of Mining and Technology (NMT) and the Astrophysics Group of the Cavendish Laboratory at the University of Cambridge in the UK [8]. The MROI project team is carrying out the technical development, with offices located in Socorro-NM. The observatory site is located on 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 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 UTs will send a collimated beam of starlight to a laboratory facility located close to the center of the array, the Beam Combining Facility (BCF) as shown in Figure 2. The UTs will be re-locatable amongst a discrete set of 28 foundation pads, giving baseline lengths (inter-telescope spacing) from approximately 7.8 meters to 380 meters. First light is scheduled to happen in 2011 and commissioning phase from then on. Other papers about MROI are presented in this conference.

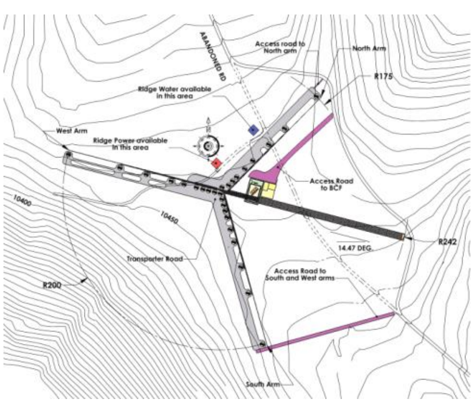

Figure 1 - Plan view of the MROI array.

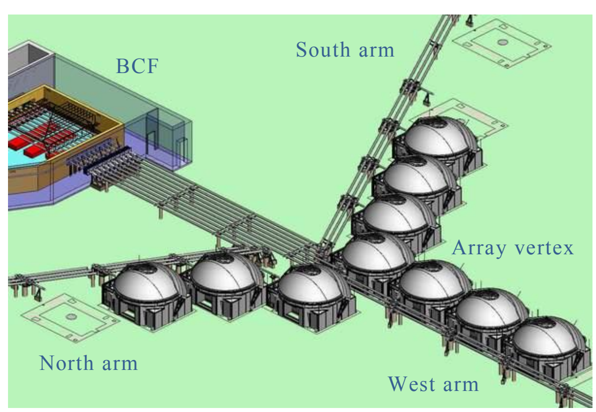

Figure 2 - 3D-CAD view of the vertex of the array with telescopes in closed pack configuration.

1.2 MROI Optical Layout and Mechanical Overview

Figure 3 is a traditional cartoon showing the optical layout of MROI (as shown at this and others SPIE conferences). The optical train consists of a total of 10 mirrors, going from the UT up to the switchyard optics located in the instrument area of the inner portion of the Beam Combining Area (Inner-BCA). During operation, starlight from each UT (three reflections - M1, M2 and M3) will be transported in up to ten evacuated Beam Relay System (BRS) pipes (two reflections - M4 and M5) to the BCF (Figure 2). Part of the BCF is the Delay Line Area (DLA) where up to ten evacuated single path traverse Delay Line (DL) pipes and cat's eye trolleys are placed (M6 and M7). These 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 being used. Upon exiting the DLA, light is directed to the Inner-BCA where will be optically compressed (M8 and M9) and directed to the Fringe Tracker (FT) via M10. The Inner-BCA is temperature controlled to ±0.1ºC by controlling the temperature in the adjacent building.

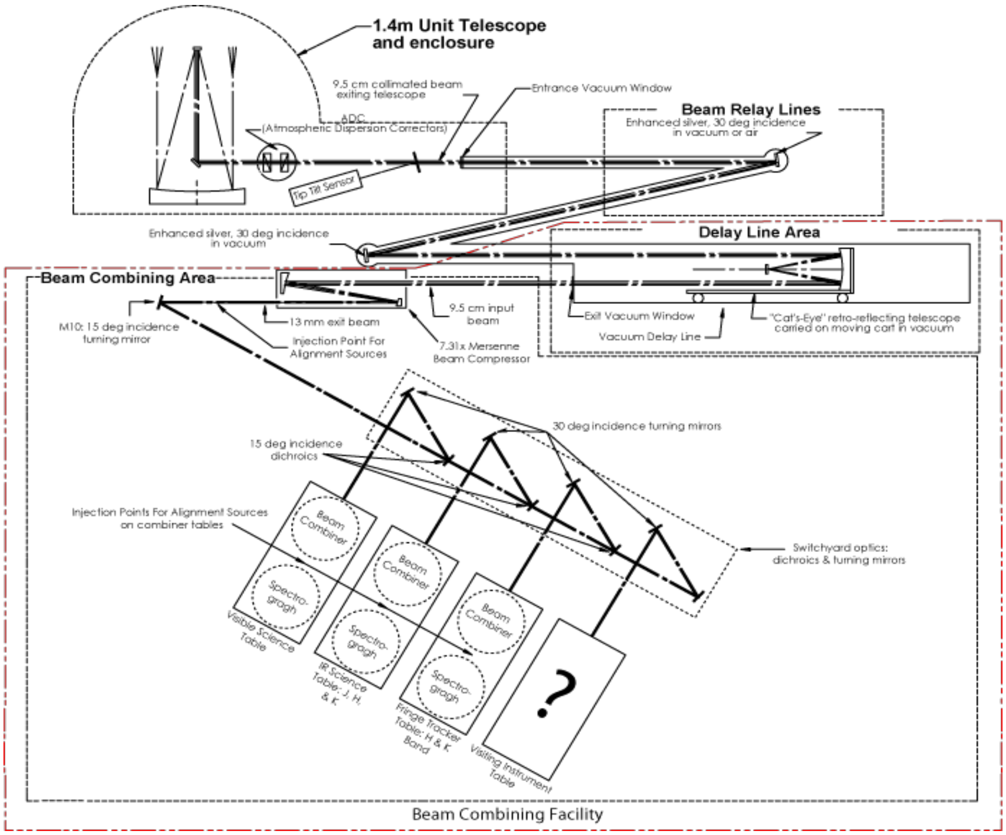

Figure 3 - The MROI optical layout.

2. MROI MECHANICAL SUBSYSTEMS

Figure 3 can also be explained as a functional block diagram of the MROI as illustrates all of its major mechanical subsystems, each of which performing a specific function. These subsystems have already passed critical design phase and some of them have matured to either construction or AIV phases. The mechanical design of MROI is then broken down into eight major subsystems. Following the order that they appear to the incoming beam of light these subsystems are the Unit Telescope Mount/Optics (UTM/O), Fast Tip-Tilt System (FTTS), Beam Relay System (BRS), Delay Line System (DLS), Beam Compressing Telescope (BCR), Automated Alignment System (AAS), M10 and Fringe Tracker (FT). The Unit Telescope Enclosure (UTE), Unit Telescope Transporter (UTT) and Vacuum System (VS) are also added as major subsystems. The following sections describe these MROI mechanical subsystems and report the status of each of them.

2.1 Unit Telescope Optics/Mount

The MROI unit telescope (UT) is a 1.4m Mersenne optics design assembled on an elevation over elevation gimbal configuration. It takes an input beam of light from the night sky and delivers a collimated beam of 95mm in diameter. The optical train is composed of an f/2.25 concave parabolic primary mirror (M1) with 1.4m in diameter, a convex parabolic secondary mirror (M2) with 115 mm in diameter and a flat elliptical tertiary mirror (M3) that is articulated to allow light to be directed to a fixed horizontal position out of the telescope (nominally at 1.6m above the BCF grade). The UT mount (UTM) is designed to provide high precision pointing and tracking during optimal observing environmental conditions (0.5arcsec rms on the sky after the application of a pointing model), and to hold small temporal variation of wavefront piston aberration due to vibration and changes in the pointing angle. For an optimal observing environment, the air temperature shall be between -15ºC and +20ºC and wind gust shall be no greater than 15m/s.

Figure 4 shows the first MROI-UTM under integration and testing inside the integration hall at Advanced Mechanical and Optical System (AMOS) test facility in Belgium (http://www.amos.be/). The optics is under contract with Optical Surface Technologies (OST) located in Albuquerque - NM (http://www.opticalsurfacetech.com). As one can notice, the telescope has a stiff and relatively compact mechanical structure with an overall dimension of 6.16x2.92x4.35m (LxWxH). The elevation over elevation axes are perpendicular to each other and precisely connected together by means of a gimbal box frame. The inner elevation axis supports an open frame tube which provides a suitable support for the optics. The primary mirror is passively supported on the bottom part of the tube through a removable mirror cell. The secondary mirror is installed on a dual stage hexapod system that provides both low and high frequency piston-tip-tilt compensation. The second stage hexapod is a high frequency compensation actuator that is primarily intended to correct for first order tip-tilt atmospheric turbulence. A preloaded spider vane arrangement secures the hexapod system in place. At the level of the inner elevation bearing a second spider vane arrangement supports an articulated tertiary mirror that steers light to a fixed horizontal position which passes through the outer elevation bearing. A Nasmyth optical table is rigidly attached to the fork to provide the interface support for the FTTS and components of the AAS and BRS. An AO and ADC may be added in the future. The total estimated weight of the UT is 15000kg.

Figure 4 - The MROI elevation over elevation 1.4m UTM under test at Vendor's facility (Courtesy of AMOS).

The UTM interfaces with any one of the 28 concrete stations available at the MROI array infrastructure. The interface is composed of three vertical supports, one central plug and one axial plug. The vertical supports are hardened mating pads on which the UTM stands and is anchored to. The central plug is a hardened pin with spherical head that is attached to the telescope base and used to define the nominal pivot point of the station. The axial plug is used to define the nominal orientation of the exit beam. A locating jig is used to achieve orientation and leveling with the required accuracy for all 28 stations. The UTM also interfaces with the enclosure during relocation mode by means of twelve pads machined in the fork for a firm and safe connection.

2.2 Unit Telescopes Enclosure

Each UTM/O will be housed within an enclosure (hereafter called UTE) that has been designed to operate under three different modes: Observation Mode: UT is completely disconnected from the UTE and operates for science or engineering on-sky observation under optimum observing environment or reduced performance observing environment; Shut-down Mode: UT is parked and protected by the UTE; and Relocation Mode: UTE and housed UT are being transported from one station to another within the array.

The following are major functions of the UTE: a./ To protect the UTM/O from the outside environment and to keep them refrigerated during daytime; b./ To provide a firmly and safety support for the UTM during relocation mode; c./ To be re-locatable together with the UTM/O amongst any of 28 stations with the accuracy required; d./ To be as compact as possible in order to allow the closed-pack configuration to be realized, but leaving enough internal space for general installation, servicing and maintenance; e./ To be as compact as possible in order to maintain the field of regard of an adjacent UT in the closed-pack configuration; f./ To maximize ventilation and thermal performance through louvers around the UTM/O; g./ To provide at least 50% reduction in the wind speed at the envelope of the UTE that is within 2m above grade, as compared to the external wind speed, for external wind speed ranging from 5m/s to 10m/s. No more than 10% wind acceleration is allowed at the location of the secondary mirror.
Figure 5 is a 3D-CAD view showing the final mechanical design of the UTE under contract with European Industrial Engineering (EIE) in Italy (http://www.eie.it/). It consists of a steel structure, moving mechanisms, walk ways, insulated wall panels and access doors. The steel structure is sized and shaped so as to meet the requirements in compactness and to accommodate the UTM envelope and UTE accessories and services (utilities and data connections). Overall dimension is about 7.20x6.90x2.60m (LxWxH). It interfaces with any of the 28 stations in the array infrastructure and with the BRS pipe during operation. During relocation mode, the UTE interfaces internally with the housed UTM and externally with the transporter. Two access doors on opposite sides of the UTE allow M1 to be removed from the UTM using removing jigs and temporary rails. Which door is used for removing/installing M1 depends on where the UT is installed in the "Y" array.

The moving mechanisms are the rotation dome (the brighter spherical callout in Figure 5), the observing shutter (the dark spherical callout in Figure 5) and twelve ventilation louvers placed below the dome. The rotation dome is made of fiberglass skins with a foam core. It sits on trolleys and can be rotated by a full 360º. The observing shutter consists of two steel frameworks connected by a CFRP shutter panel. Inflatable seals are placed between the steel structure and the rotating dome and also between the rotation dome and the shutter when the shutter is closed. Because of the orientation of the UTs in the "Y" array, one of the steel framework of the observing shutter is open to allow light from M3 to pass through the UTE using BRS evacuated tubing (Figure 8). The moving mechanisms can be moved manually but are entirely controlled by the observatory supervisory system during operation.

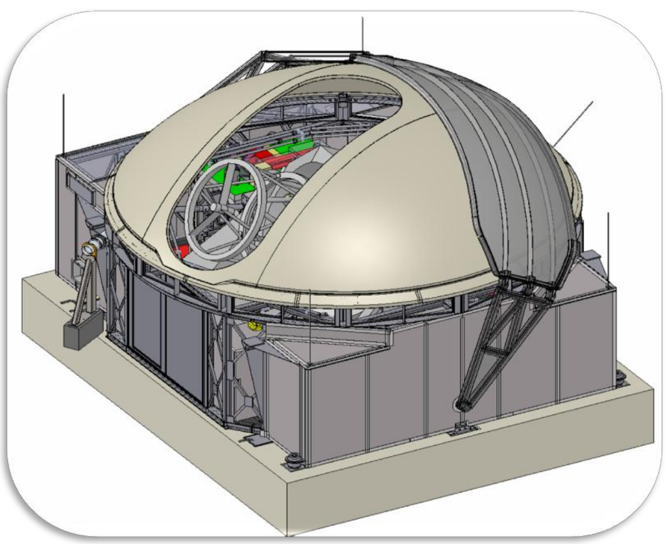

Figure 5 - A 3D-CAD view of the MROI UTE (Courtesy of EIE).

The cladding of the UTE structure is composed of sandwich panels with aluminum face skins over insulation foam. Similar cladding is also used in the two accesses doors and moving mechanisms. Simple gaskets bolted to the structure are used as general sealing strategy.

2.3 Unit Telescopes Transporter and Relocation Plan

During relocation mode, the UTE and housed UT are transported from one station to another using a Unit Telescope Transporter (UTT). EIE has performed the design of the UTT and the associated interface steel frame that is connected to the UTE (Figure 6). A container reach-stacker has been modified to meet a set of environment, infrastructure and procedural relocation requirements and will be used as a stand-alone UTT. The reach-stacker of choice has already been assessed by EIE as lifting/lowering scenarios, vibration level as a function of pavement and velocity/acceleration rates, and reaction forces to the UTM.

The UT is connected to the UTE through the use of a locating and guiding system. This system uses four interface pads placed on the bottom part of the UT fork to connect a guiding lifting and damping mechanism. Four additional pads are implemented above the center of gravity of the UT fork and are also foreseen for lifting and connecting stabilizing cross bars. Relocation mode is executed through a relocation plan, a chronological list of events used to prepare the UTE/UT for relocation, transport them from one station to another and set them up on the final station. The full relocation plan comprises the following steps: a./ daytime mode; b./ preparation of the UTE/UT for relocation; c./ transport UTE/UT to other station; d./ UTE/UT reconfiguration; and e./ daytime mode. In daytime mode, the UT is ready for operation.

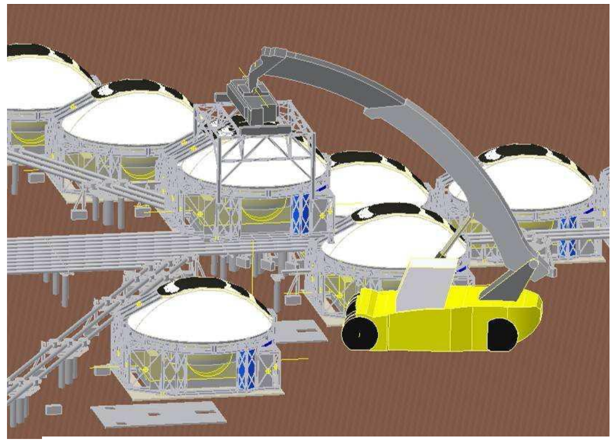

Figure 6 - A 3D-CAD view of the MROI UTT (Courtesy of EIE).

2.4 Fast Tip-Tilt System and Narrow-Field Acquisition System

The functions of the Fast Tip-Tilt System and Narrow-Field Acquisition System (FTTS/NAS) are twofold. One is to provide fast tip-tilt correction signals to the second stage hexapod actuators that allow fast tip-tilt motion of M2. The other is to operate under narrow acquisition mode which allows a telescope operator to find an object in the full field of view of the telescope. The design of the FTTS/NAS is being developed under contract by the University of Cambridge - UK. Construction, installation and testing on-site will also fall under responsibility of the University of Cambridge. MROI engineers will review designs and help with installation and final integration.

The FTTS/NAS is installed on the Nasmyth table. The anticipated opto-mechanical components are the ones that allow high precision positioning and alignment of a dichroic beamsplitter, an Off-Axis-Parabola (OAP) mirror, a CCD camera and a corner cube retro-reflector. One of the most stringent requirements for the mechanical design is the thermal tilt stability as the deviation of the beam of light is required to not exceed 0.015arcsec for temperature changes of 5ºC. One stringent requirement for the opto-mechanical design is the need to maintain the wavefront quality by not stressing (deforming) the dichroic and OAP mirror at any operational condition.

2.5 Beam Relay System

The major function of the Beam Relay System (BRS) is to transport light exiting M3 to the BCF in vacuum using two flat mirrors (referred as M4 and M5). When MROI is completed, a net of evacuated pipes will be available to feed all 28 stations and at any UT configuration in the "Y" array. A second function of the BRS is to allow tilt and shear errors between the UT and DLS axes to be minimized. The BRS is an in-house development.

On each of the three arms of the array, there is up to three BRS pipes, each of which is placed parallel to the others in a horizontal plane. In addition to these nine pipes, there is a 10th that continues from a UT located at the geometric center of the array. From there to the BCF, these ten 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, as discussed in section 2.6, rather than the spacing of the UTs.

This design calls for two different configurations of M4 and M5 depending on the array arm – if the West arm or North/South arms (Figure 1). In the West arm, M4 is positioned on the UT Nasmyth table and M5 is positioned close to that UT. In the North/South arms, M4 is positioned close to the UT and M5 is positioned in the vertex of the array. M4 and M5 mirrors are 8" in diameter to guarantee a clear aperture greater than 130mm. The mirrors are assembled in a commercial gimbal mount, modified for automation and performance. The modifications in the mount include motorization through DC servo motors, appropriate resolution with the use of high precision encoder and preloaded differential thread screw (one per axis), and tilt stability through material selection. The gimbal mount sits on an aluminum breadboard that is kinematically housed in an aluminum cross-over can (Figure 7). Round concrete piers are designed to hold three different configurations of cross-over cans and associated steel supports, depending on the number of cans needed along the array arm (1, 2 or 3). The cross-over cans are indexed in the support (pivot point for positioning and axial point for orientation). This design arrangement allows both reproducibility and thermal stability to be significantly improved, and also facilitates alignment in-site. Figure 7 is the three can configuration. As can be notice the pivot points are in different position for greater stability due to mismatch material between cans and support.

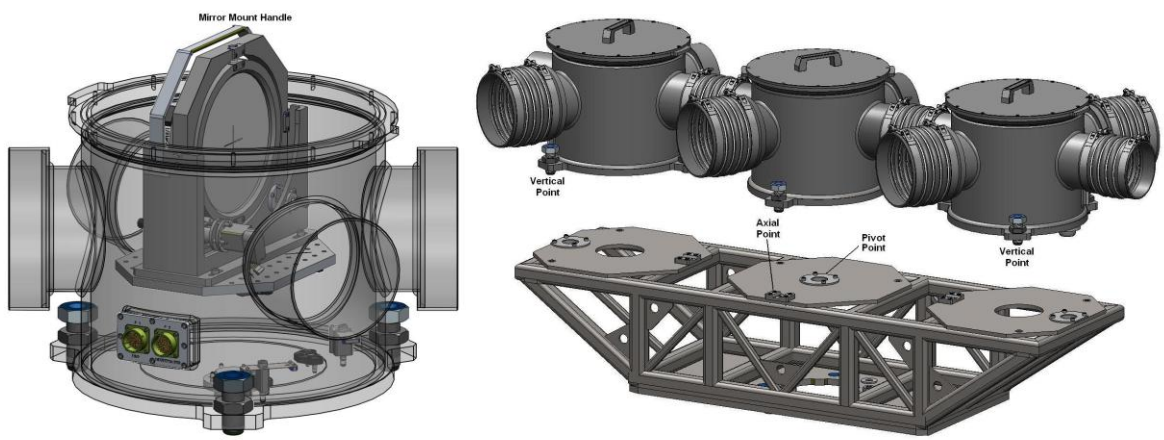

Figure 7 - Three cross-over cans configuration and associated support.

The mechanical design has adopted extruded aluminum pipes that are positioned at a height of 1.6m to the BCF grade. They are 8" external diameter outside the BCF and 6" in the inside. The pipes are connected to the cross-over cans by means of compressor bellows to not transmit vibrations, and supported by rigid steel frame on concrete pier (Figure 8). For convenience, four piping zones are considered in the design: a./ <u>injection zone</u> (which interfaces with a UT/UTE and first BRS mirror (M4)); b./ <u>transport zone</u> (between M4 and M5); c./ <u>interface zone</u> (between M5 and the BCF); and d./ <u>interior zone</u> (inside the BCF). Figure 8 shows the BRS portion in the vertex of the array.

BRS pipes penetrate the BCF wall, cross the entire Inner-BCA and are connected to the DLS pipes by means of compressor bellows. The pipes are also thermally insulated in the BCF interface. This scheme allows minimum vibration and thermal disturbances to be transmitted to the pipes inside the Inner-BCA. Figure 9 is a general view of the interior zone. From right to left one can notice the BRS pipes before entering the Inner-BCA (which place is called Outer-BCA) and optical tables for M10, automated alignment system, beam compressing telescopes, and delay line metrology system. At this stage, the BRS is also connected to the vacuum system.

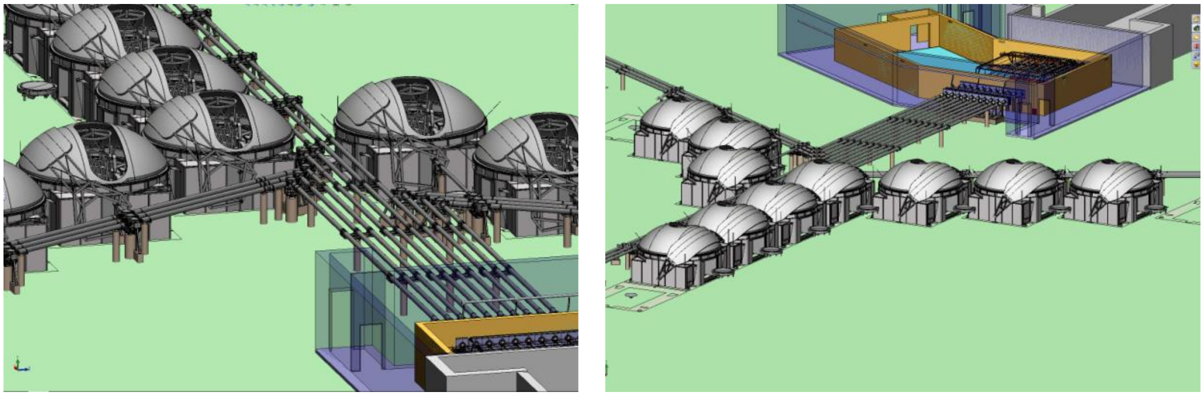

Figure 8 - Cartoon of the BRS portion in the vertex of the array.

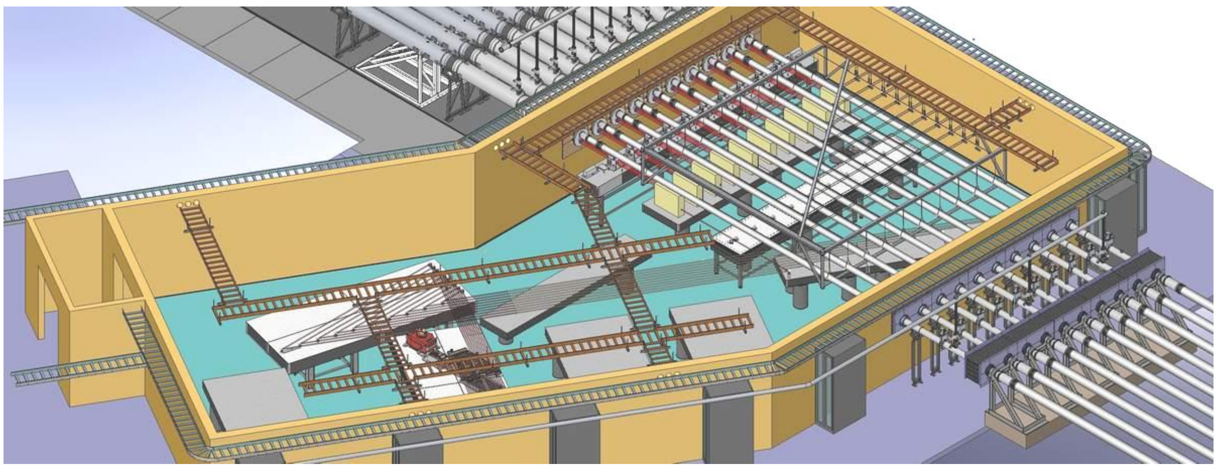

Figure 9 - Cartoon showing a general 3D-CAD view of the BRS interior zone.

2.6 Delay Line System

The major function of the Delay Line System (DLS) is to control the position of each cat's eye along its corresponding evacuated single path traverse DL pipe so as to match light paths from a star, via a pair of UTs, to within the coherence length of the light being measured. As already mentioned, the DLS is assembled inside the BCF, i.e. DLA, Inner-BCA and Outer-BCA. When MROI is completed: - the DLA will be equipped with up to ten 190m DL pipes/supports and Trolleys (cat's eyes assembled on wheeled carriages); - the Inner-BCA will be equipped with a laser metrology system with associated hardware and optics to feed up to ten DLs; and - the Outer-BCA will be equipped with electronics racks and computers.

The University of Cambridge is sub-contracted by NMT/MRO to undertake the design and development of a cost-effective DLS and also to deliver one Trolley with associated optics and control electronics. The NMT/MROI Project Team is responsible for the procurement & fabrication and assembly, integration and verification of all the components of that system. The first DL 100m long will be installed by summer 2010 when the first Trolley will be delivered and tested on-campus and on-site by the Cambridge Team.
In comparison with the DLS in use at other interferometer arrays, the (mechanical) 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 DL vacuum pipes; 2./ have the Trolleys running directly on the inner surface of the vacuum pipe, and not on pre-installed precision rails; 3./ have the end of each DL pipe anchored close to the Inner-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. A full description of this design is covered in [2] and the design of the Trolley is covered in [6].

Figure 10 shows 3D-CAD views of the fully populated DLA. That building is sized to accommodate up to ten DLs each of which 190m long and 409.6mm (2ft) apart. They are all supported and clamped at the ends using a steel cradle. Each cradle is supported by a flexural steel truss and connected to the concrete slab by means of anchor bolts. Adjustments in height and lateral tilt are available for alignment of the pipes. The slab is physically isolated from the rest of the building. An anchor support is placed on the thicker part of the slab and is dimensioned to take longitudinal forces in the pipe run due to an earthquake.

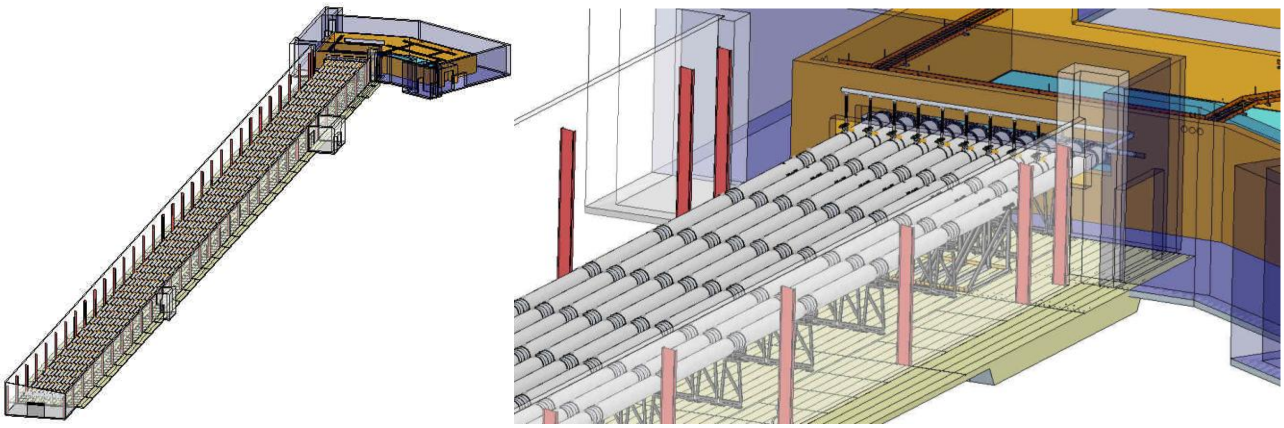

Figure 10 - Cartoons of the DLS portion in the DLA.

The length of most of the pipes is 3.6m (12ft long extruded seamless aluminum tubes – 16"OD x .5"WT) which allows the number of supports to be minimized and also guarantee straightness and sag to within acceptable values. Four lugs are welded at each end of the pipes for drawing them together or pushing them apart by using threaded rods. Pipe sections are held in alignment by the use of two pair of dowel pins, which are light press fitted into dowel holes accurately placed on each end of the pipes. The dowel holes are positioned so that the inner surfaces of the pipes to be joined together align accurately at the region where the Trolley wheels run. The holes are machined on a big mil and a "go-no-go" gauge is used to accept them. The criterion used is to have steps in the internal surface of the pipes no greater than 0.5mm, at that region where the Trolley wheels run. A fifth dowel hole is required to support a spacer 1.0mm thick so as to define the point of contact when the pipes are drawn together and a pivot point during alignment.

Once the pipes are drawn together and aligned, a vacuum rubber seal is positioned and tightened over the joint. To ensure good seal, the outer ends of the pipes need to be prepared (polished) to remove any die marks, particularly those that run along the pipe. When operational, the BRS and DLS pipes will be evacuated to a pressure of about 0.5 mbar to meet science requirements.

The University of Cambridge has designed and extensively tested a DLS prototype Trolley which runs inside the evacuated pipe run. Figure 11 is a cut-away view of the Trolley composed of a cat's eye assembly and a four-wheeled carriage. The wheels are compliant and assembled in a way to constraint four degrees of freedom (two translations and two rotations). The cat's eye houses the optical components, i.e. a parabolic primary mirror and a flat mirror. Both mirrors are assembled at the ends of a carbon fiber tube that is mounted to the carriage via flexure legs. This allows the optical system to move longitudinally with virtually no tilt and friction. Longitudinal motion of the cat's eye is produced via a voice coil actuator. Longitudinal motion of the carriage is produced via a DC servo motor that drives one of the back wheels. The other back wheel is used for the steering mechanism so as to constraint the degree of freedom in rotation (roll).

The third major component of the DLS is the metrology system installed on a 0.7x7.3m optical table across the DL pipes in the Inner-BCA. It is composed of a single Agilent laser head, a beam splitter and folding mirror module and one metrology block for each DL where two beam expanders, alignment mirrors and linear interferometer components are installed. As thermal stability is an important design parameter, all components are stainless steel construction, including the face skins of the optical table. Also, a shear camera is installed on the optical table and uses metrology light returning from the cat's eye to detect deviations in the pipes. These deviations are mostly caused by the pipes not being straight enough and can significantly degrade the optical quality of the science beam. Fortunately, a tip-tilt control of the cat's eye secondary mirror can be used to correct for these deviations [2 and 7]. A metrology system with all components for the first DL at MROI is installed and under test in the Inner-BCA (Figure 12).

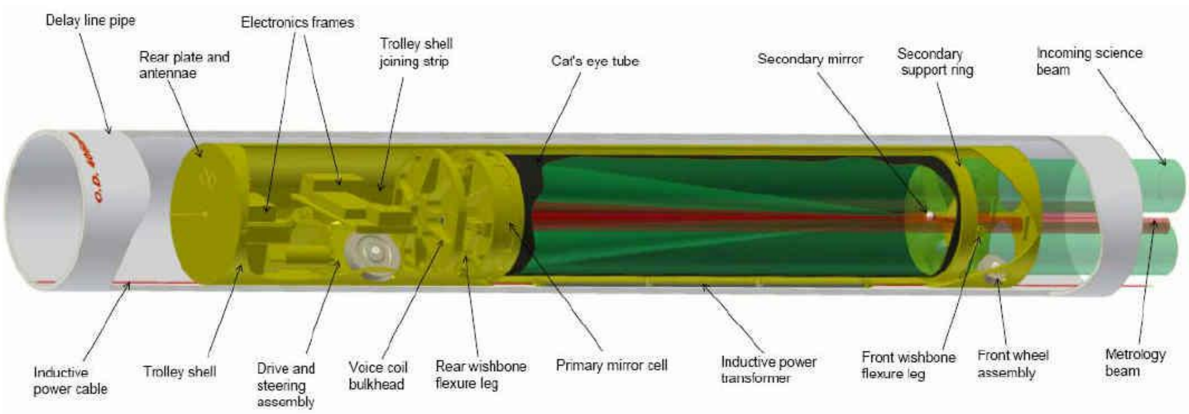

Figure 11 - Cartoons of the Trolley (Courtesy of the University of Cambridge).

Figure 12 - Metrology system in the Inner-BCA.

2.7 Beam Compressing Telescope

Upon exiting the DLA, light from each UT enters the Inner-BCA, pass above the DL metrology table and reach the Beam Compressing Telescope (BCR) where will be optically compressed from 95mm to 18mm and directed to the Fringe Tracker (FT). The BCR will be outsourced through a Request-For-Bid which considers design, fabrication, testing and delivery. Top-level requirements and SOW are completed for this RFP process to start. The overall space envelope required for the BCR is about 1.0m in length, 0.3m in width and 0.5m in height. Up to ten BCR sit on an optical table inside the Inner-BCA (Figure 9).

2.8 Automated Alignment System

A beam of light from each UT will travel distances ranging from 460m to 660m (depending upon its location in the array) before reaching a beam combiner and spectrograph. Considering that MROI is comprised of three major optical axes, i.e. UT, DLS and beam combiner (Figure 13), a suitable method for co-aligning these axes in a nightly basis is provided by the Automated Alignment System (AAS). Automated alignment is performed via M4/M5 and switchyard. The AAS is an in-house development.

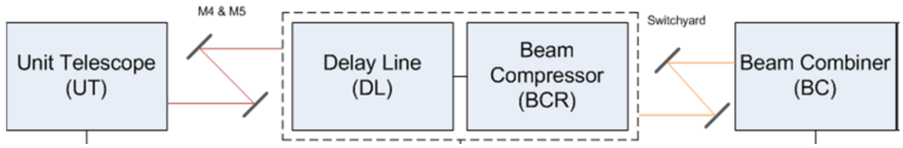

Figure 13 - Diagram showing the three optical axes of the MROI.

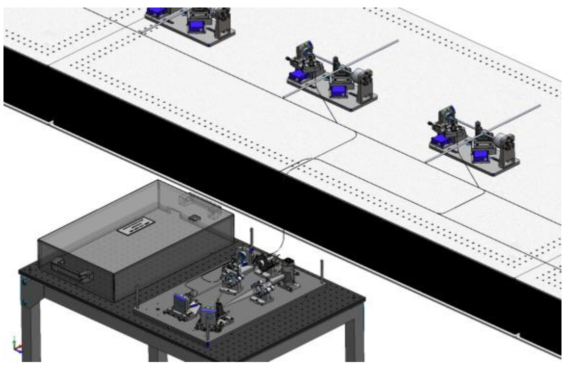

Figure 14 - Cartoon of the AAS primary fiducial in the Inner-BCA.

The mechanical design of the AAS is composed of four subassemblies named as: primary fiducial (MOB), UT tilt and shear measurement components (TASM), beam combiner TASM components, and secondary fiducial. Functionalities for each of these systems are described in [1]. These subassemblies are installed in different locations along the MROI optical train. The primary fiducial is installed inside the Inner-BCA and is used to create a reference axis in which the UT and FT axes must be co-aligned (Figure 14). It is composed of two major subassemblies: the Fiber Injection Sub-Assembly (FISA) and the Beam Injection Sub-Assembly (BISA). The FISA is responsible for generating a light source to BISA. Two light sources (white and laser diode) are combined to generate a single source that is transported using an optical fiber. These beams are combined using a beam splitter that transmits combined light to two OAP mirrors. The OAP mirrors send light toward the fiber optics. The white light is mounted in a thermally insulated box, which is glued to a heat sink to avoid heat to be dissipated to other components. The laser diode is mounted kinematically for better stability and accuracy. One-time adjustment is taken into account. FISA will be mounted and tested on a single aluminum plate 500x350x12mm (LxWxH) with no adjustments. An aluminum cover is used as shown in Figure 14. The resulting box is thermally insulated using fiberglass foam to support it. FISA is mostly aluminum construction. From FISA light is sent to BISA which is composed of an OAP, beamsplitter and corner cube. There will be up to ten equal BISA to create a reference axis between the UT and FT axes that must be co-aligned. The ten BISAs are installed on a 1x6m optical table in the Inner-BCA (Figure 9). All optical components are mounted on a single alignment template to ensure internal alignment with no adjustment. This assembly is also integrated by two Nanomotion slides with 50mm of travel. The first slide is used to remove a beamsplitter from the beam path. The second slide is used to correct the Optical Path Length (OPL).

The UT TASM is responsible for measuring the shear error between the UT axis and the DLS/BCR axis, requiring imaging of the telescope pupil. To do this, a ring of four equally spaced LEDs located around the primary mirror will be used to illuminate M2 and traverse to the Nasmyth table where is reflected by a beamsplitter to a focusing lens, which focuses the beam onto a detector. The assembly consists of a beamsplitter and a corner cube that is mounted on a single alignment plate to ensure internal alignment (Figure 15). The UT beamsplitter is assembled in a manual tip-tilt actuated mount which is supported by an L-shaped mounting support bolted to a translation stage. The beamsplitter is at an angle of incidence of 45º with respect to the beam travel axis. The corner cube is housed on a base mount. The beam reflected by the corner cube must be located right at its center as it must travel back the exact path of its original optical axis to the adjacent subassembly. This consists in a focusing optics and the shear detector. Both are mounted as a module on a single alignment plate and pre-aligned in the lab. The focusing optics is mounted on a translation stage for focusing adjustment.

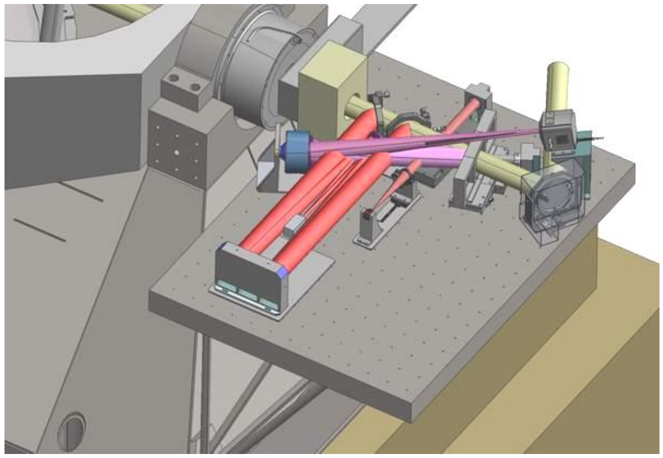

Figure 15 - Cartoon of the UT TASM.

Small quad-cells are used as secondary fiducials to detect shear in the beam at it travels upstream through the BRS up to the Nasmyth table. These quad-cells are located at the exit of the DLA in the Inner-BCA, inside the vacant vacuum cans at the vertex of the array and also in front of M4 and M5 of the BRS. Each cell is supported by a flipper mechanism so as to remove it from the optical path when not in use. This assembly is mounted together with the M4/M5 gimbal mount as a module (Figure 16).

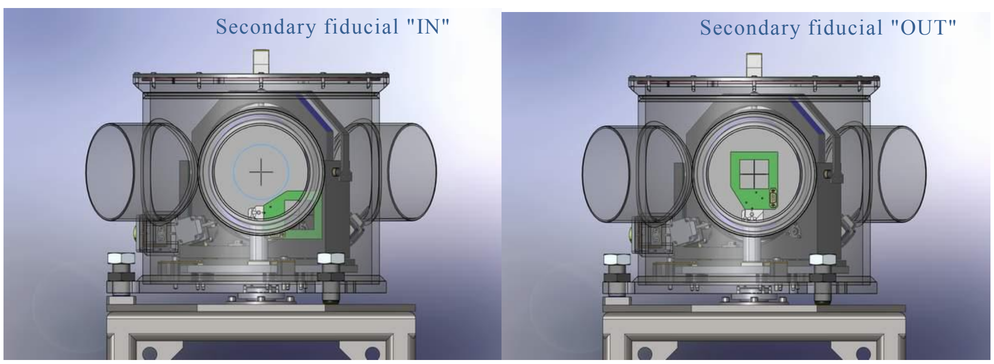

Figure 16 - Cartoon of the secondary fiducial inside a cross-over can.

2.9 M10

The M10 mirrors are responsible for converting the phase plane and beam pitch of ten beams of light exiting the BCR (609.6mm) to any switchyard (100mm) in the instrument area of the Inner-BCA. Each mirror can be adjusted in a nightly basis using a Newport Agilis mount and custom made support. All the ten supports sit on a 1x7m optical table as shown in Figure 9 (optical table on the right). An athermal mechanical design provides the required stability to the assembly. The M10 is an in-house development.

2.10 Fringe Tracker

Upon exiting M10, light is directed to the Fringe Tracker (FT) inside the Inner-BCA where it is positioned right after the visible science instrument and the IR science instrument (SIRCUS). The major role of the FT is to measure the group delay between all nearest neighbor UTs in the array and to send closed feedback signal to the corresponding DL trolleys for correction of atmospheric perturbations. The FT is an in-house development in which the mechanical design is broken down into four major subsystems named as switchyard, beam combiner (BC), periscope optics (PO) and spectrograph, as shown in Figure 17.

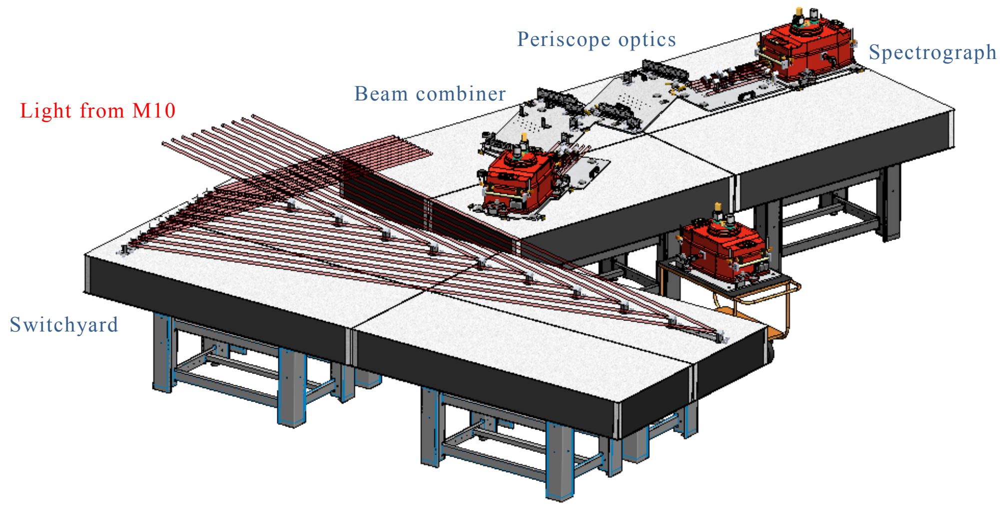

Figure 17 - Cartoon of the FT general assembly.

The switchyard is responsible for converting the phase plane and beam pitch from M10 to the BC and for co-aligning the DLS to the BC axes [3]. It sits on an optical table 2x5.1m that is aligned and leveled for a 1.1m beam height. Two Newport Agilis mount are used for each beam of light to position a pair of mirrors (Figure 17). An athermal mechanical design is possible by matching materials. This allows a tilt stability of 0.4µrad per mount for the expected 0.1ºC over-night temperature variation inside the Inner-BCA and a maximum of 6µm of shear error in the worst case scenario.

The BC is responsible for making the pair-wise nearest combinations [3]. Two paired outputs of combined light are used to feed up to four spectrographs through a PO arrangement (Figure 17 shows two spectrographs installed on the optical table). The whole assembly sits on an optical table 2.1x4.4m. A novel modular design philosophy was devised for the BC where only a very few one-time adjustments are necessary to remove shear and tilt from each beam. Long term creeping can be controlled by indexing each module on alignment templates made of same material as the optical table (mild steel). This means that after alignment is completed, the optical components of the BC (mirrors and beamsplitters) should hold position and orientation between them in an over-night basis. The modulator mirrors are positioned in a more robust mount which is also indexed to a template. Switchyard and BC are constructed and under lab test. Results are presented in another paper in this conference [4].

One PO assembly is placed at each output of the BC (Figure 18). They are both responsible to fold the linear output into arcs and to ensure that pair-wise nearest combinations arrive at the aperture stop in the spectrograph at the correct location and orientation [3]. One PO assembly takes up to nine beams and feed two spectrographs, one with five beams and the other with four. Currently, the PO assembly is designed to feed one spectrograph per BC output, which means six UTs in the array. Newport Agilis mounts are used to hold mirrors on V-type optical mounts. The mounts are indexed to steel templates and only azimuth adjustment is needed when the array is reconfigured.

The spectrograph is responsible for taking combined output beams exiting the PO, focusing them through aperture stops before re-collimation takes place, and making appropriate dispersion and focus onto the detector [3]. The mechanical design is basically sized and constructed to hold a cold optical system stably in place and to enclose a vacuum and cooling systems. During the preliminary design phase, a decision has been made on the use of a Cold Working Surface Plate (CWSP) to support all opto-mechanics and detector. This CWSP is connected to angle brackets at the base plate of the Dewar through a symmetric arrangement of four bipod flexures (Figure 19). An athermal modular design is adopted for the opto-mechanics. Following the order that each module appear to the incoming beams from the PO, they are: entrance windows, filter flipper mechanism, Eccentric Mersenne Gregorian 1, aperture stop, Eccentric Mersenne

Gregorian 2, Direct Vision Prism flipper mechanism, focus OAP and detector. The mechanical characteristics of the CWSP assembly are: a./ thermal stability (at room temperature of 25ºC and cryogenic temperature of 77K provided by LN2 - cool-down and warm-up cycles shall not affect the structural integrity of the opto-mechanics); b./ mechanical stability (the supports are stiff and lightweight - stiffness is required to guarantee that static and dynamic behaviors are appropriate - lightweight is important to not impact the mechanical interfaces of the support, to minimize the total cold parts and to improve handling capabilities); c./ point of symmetry (physical point that is kept unchanged during cool-down and warm-up cycles); d./ material (athermal design - all aluminum construction). Extensive thermal-stress analysis shows the feasibility of the mechanical design and the likelihood that it will allow the instrument to meet all top level requirements [3]. Appropriate indexing of each module and an alignment procedure with minimum adjustments are also characteristic of the design. These have led to a clear understanding of the thermal linear expansion between room and cryogenic temperatures for most parts. For convenience, the aperture stop module is installed at the point of symmetry of the CWSP and has no adjustment.

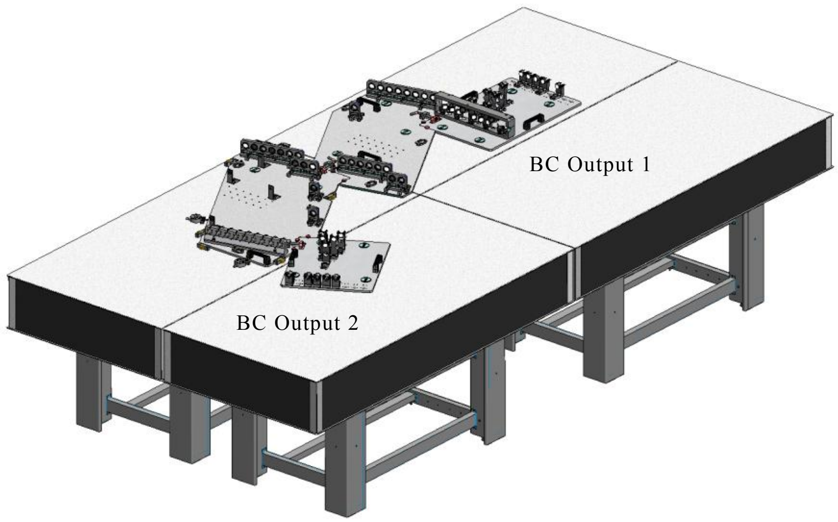

Figure 18 - Cartoon of the FT periscope optics.

The Dewar design is composed of a cryostat and a vacuum system. The cryostat by its turn consists of an enclosure shaped around the CWSP and LN2 tank, a cooling system and electro-mechanical interfaces. The LN2 tank is made of two cylindrical aluminum parts for compactness. The refrigeration capacity of the cryostat cooling system is determined by estimating the heat loading that needs to be absorbed during operation (by conduction and radiation). The total heat load is 12.98W in which 61% evaporation of LN2 is driven by radiation coupled with cryostat surface and 39% is via conduction from the insulation components (supports, washers and bushings) and filling tube. Considering one passive floating radiation shield (not thermally coupled to the cryostat), the FT spectrograph requires 6 liters of LN2 for 30 hours hold time.

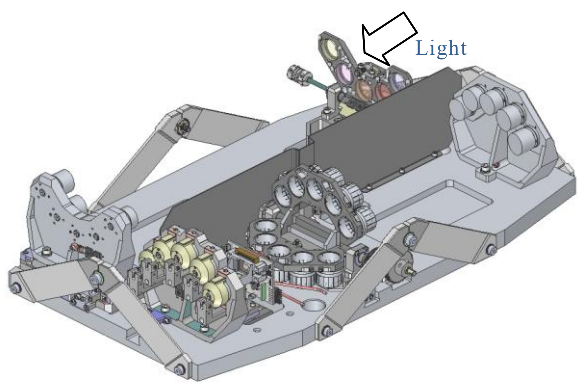

Figure 19 - Cartoon of the FT CWSP and opto-mechanics.

The spectrograph sits kinematically on a steel alignment interface plate. This is shown in Figure 20. The FT is in the final design phase but the switchyard and beam combiner are constructed and tested in the lab ([4] - presented in this conference). Construction and testing of the cryostat will start in 2010. The FT is planned to be used during commissioning of MROI.

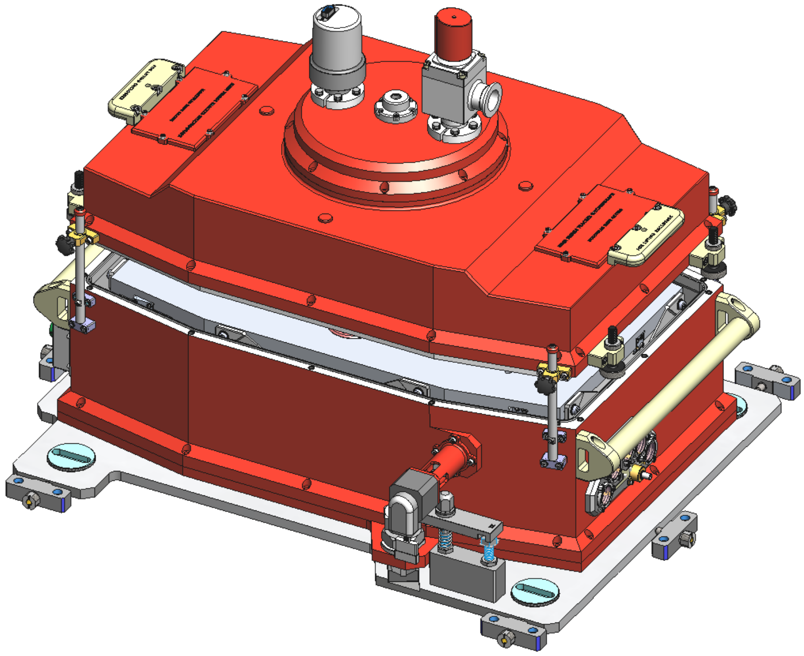

Figure 20 - Cartoon of the FT spectrograph.

2.11 Vacuum System

The Vacuum System (VS) is an in-house development used to evacuate the BRS and DLS. It is required to hold a vacuum level of 0.5mbar (3.75×10^{-1} Torr) over the night and has to evacuate a volume of approximately 320m^3. The VS consists of vacuum pumps, vacuum manifolds, backfill manifolds, and manifold drops. There will be two vacuum pumps to handle the full ten element interferometer. There are two manifolds consisting of aluminum tubing with ten vacuum ports for the DLS and three for the BRS. The manifold drops connect the manifolds to the DLS and the BRS and consist of flexible vacuum tubing, a gate valve, analog gauge, vacuum sensor, and an up-to-air valve for the backfill system. The backfill system will be used to bring the DLS or BRS volumes back up to atmospheric pressure and consists of a manifold (one for BRS and one for DLS) and air hoses. This will limit the threat of dust contamination when the volumes are opened to atmosphere. Most of the connections are quick-disconnect so that the whole assembly can be quickly and easily disassembled for maintenance or repair. The VS is in the final design phase and will be fully installed in 2011. Figure 21 is a cartoon of the VS at the BCF and Figure 22 is a cartoon of the VS at the DLA.

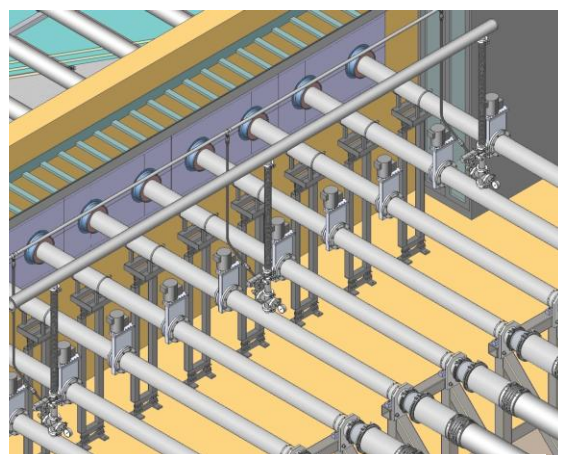

Figure 21 - Cartoon of the VS at the BCF.

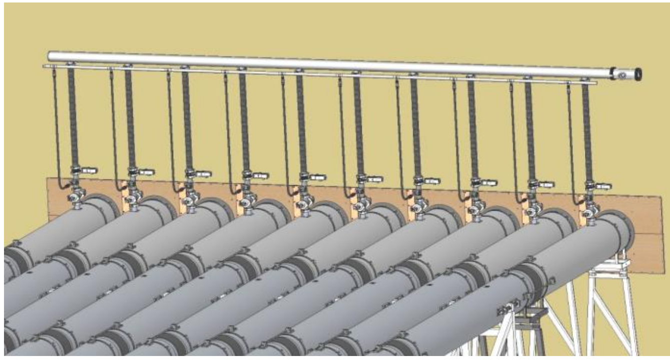

Figure 22 - Cartoon of the VS at the DLA.

3. ASSEMBLY, INTEGRATION AND VERIFICATION PLAN

Planning is a primary step in any observatory development process; in other words one should define an appropriate scope of work. Only then can final design, procurement and assembly, integration and verification (AIV) for optical, mechanical, electrical-electronics, software, and civil engineering proceed accordingly for each particular task. This is obviously not an exception for the MROI where the leader of each subsystem is responsible for defining top-level requirements together with the project scientist and system architects, producing the design, and proceeding with procurement, construction and AIV. An AIV planning/plan is then specifically defined for each subsystem and is tied to the commissioning plan and performance verification milestones as outlined for the MROI [see 5 for the MROI commissioning plan]. AMOS and EIE have defined their own AIV plan for the UTM and UTE/UTT, respectively. The FTTS/NAS and DLS AIV plans are defined in conjunction with the University of Cambridge. The AIV plan for all the other subsystems are defined by their own subproject leader. What follows is a summary on how an AIV plan is defined for each subsystem.

AIV is defined as the process in the life-cycle of a project beginning with the assembly of finished components and ending with the verification of system performance at the subsystem level, covering all characteristics of hardware and software. For the MROI-DLS for instance, all the lessons learnt with the Cambridge team in prototyping and testing of the DL Trolley in a 20m length test rig were taken into account. Overall an MROI-AIV planning involves three sequential parts. The main purpose for the assembly planning will be to list the activities which indicate how parts and sub-assemblies, or any combination thereof, should be put together to perform a specific function and capable of disassembly prior to integration. The main purpose for the integration planning will be to list the activities which indicates how major components of the subsystem should be put together to form a suitably larger unit prior to performance verification. Both assembly and integration should be planned with a focus on completing within a defined schedule and with an efficient use of resources. Finally, verification planning will allow for the full assessment of functional efficiency and performance to be undertaken with lowest risk and cost. The verification planning should provide confidence that the subsystem has met the performance requirements at MROI. Obviously, some major activities or sub-activities may well have dependencies that also need to be covered in the plan.

For planning an AIV scope of work, one first needs to identify what the high-level deliverables are and subsequently what are the associated AIV activities, this being carried out for each work package defined for each subsystem. The goal is to define and arrange a list of activities, preparation tasks and high-level deliverables in order to accomplish the AIV. This will result in a list of engineering activities needed to complete the subsystem on time, on budget and meeting all specification requirements. Preparation tasks are defined as independent engineering activities, not specifically part of the subsystem work package which nevertheless must be executed on an appropriate schedule. They are also break down into manageable smaller size tasks, each of which defined as a regular AIV activity. At MROI we have decided to break down the AIV activities into two categories. As members of these two categories will be a list of activities. For convenience it was decided to call them major activities and sub-activities. The sub-activities are the smaller pieces whose sizes are small enough to allow precise estimation of resources (cost, schedule, and physical resources), execution and monitoring.

After this document is completed, reviewed and revised, an AIV Project Plan is prepared. As part of this plan, each sub-activity defined in the AIV planning may be broken down into a sequence of lower-level tasks. Each of these tasks is then associated with a Description or a Work Definition Task Sheet (WDTS). These are numbered as a subset of the WBS, following the MROI numbering system, and list full details and dependencies of the actual task to be carried out. Each Description provides a brief explanation of the hardware/software being delivered, as well as the technical interfaces and related documentation. Each WDTS provides final level of technical details as information on the requirements for the task, the task input/output, the task duration, resources, required equipment & facilities, applicable documents, task procedure and any special notes. Sub-activities that contain tasks with a significant level of complexity and/or are safety critical must have their procedures documented to an appropriate level of detail to ensure risk mitigation. Estimates on schedule and task duration will also incorporate contingencies. The main subsections of the WDTS are described below:

a. Task name and WBS: This are the name of the task and the MROI part number;
b. Major input: This lists the hardware required for the task to be realized;
c. Task output: This lists what the outcome is for the task;
d. Requirements: This lists the specialists involved during the task, the major facilities required, the dependencies, the major documents where specific information can be obtained and any specialized equipment;
e. Task procedure: This is a detailed description of the task in terms of preparation, set-up, measurements and technical effort, together with information on safety; and
f. Notes: This is optional reserved to special notes and footnotes.

The AIV Planning and AIV Project Plan documents for each subsystem are expected to be used by the MROI-PM, the System Architects, the Cambridge Team, the subsystem leader and members of the team to demonstrate that the as-designed WPs, and consequently the whole MROI subsystems meet or exceed all the specification requirements. The commissioning of MROI then starts [5].

Figure 23 - Aerial view of the MROI site with a 3D-CAD drawing overlaid with the array infrastructure (Courtesy of M3 Engineering).

4. CONCLUSION

The major MROI subsystems are currently in different levels of maturity: final design with prototyping, construction or AIV phases. First light is scheduled for summer 2011. First fringes with two telescopes is scheduled for 2012. The design and construction of the complete array infrastructure will soon start, which will allow AIV plan for all subsystems to be undertaken.

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