Magdalena Ridge Observatory Interferometer: advancing to first light and new science

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ABSTRACT

The Magdalena Ridge Observatory Interferometer is a 10 x 1.4 meter aperture long baseline optical and near-infrared interferometer being built at 3,200 meters altitude on Magdalena Ridge, west of Socorro, NM. The interferometer layout is an equilateral "Y" configuration to complement our key science mission, which is centered on imaging faint and complex astrophysical targets. This paper serves as an overview and update on the status of the observatory and our progress towards first light and first fringes in 2012.

Keywords: Optical interferometer, telescope facilities, high-resolution imaging, fringe tracking, beam combiners, delay lines, alignment systems

1. MAGDALENA RIDGE OBSERVATORY INTERFEROMETER INTRODUCTION

The Magdalena Ridge Observatory is a Federally funded facility being built and managed by New Mexico Institute of Mining and Technology (NMT) which also serves as host for the observatory offices on the NMT campus in Socorro, NM. The observatory consists of two major facilities: a fast-tracking 2.4 m telescope and an optical/infrared interferometer. The interferometer is being designed and built in collaboration with our partners at the University of Cambridge. In this last development phase the interferometer is moving towards a first fringes date in 2012. Phase A of the interferometer build will include 6 telescopes and infrared fringe-tracking and scientific imaging capabilities. Phase B will add 4 more telescopes and associated beam trains, visible operations, and will have an additional location in the beam combining laboratory for guest instruments (See Figure 1). The greater observatory facilities include over 8 miles of maintained road, on-site water, power, ethernet, housing facilities and a location on the Ridge for a third scientific facility yet to be determined.

2. PERFORMANCE AND SCIENCE VERIFICATION MILESTONES

The Key Science Mission for the Magdalena Ridge Observatory Interferometer (MROI) is centered on three main areas: 1) studies of the environs of Active Galactic Nuclei (AGN) at the hearts of nearby external galaxies, 2) stellar formation and the earliest phases of planet formation, and 3) the processes of mass-loss, mass-transfer and accretion in single and multiple stellar systems. A more comprehensive discussion of the Key Science Mission basic objectives appears in previous SPIE proceedings [1] and new simulations of some of the science we expect to perform in coming years

Figure 1. An artist's conception of the Magdalena Ridge Observatory Interferometer in its most extended configuration. The equilateral Y configuration with 28 pads is clearly visible to the right of the interferometric buildings. The long extension to the left is the delay line building, which is on the eastern side of the facility. To the west below the mountain on the plains of St. Augustine is the Extended Very Large Array (EVLA) operated by NOAO.

are presented in these proceedings [2]. Derived from this Key Science Mission are the system requirements that drive the design and build for MROI. This design is centered on maintaining a world-class capability for producing rapid, high-resolution images of faint and complex astrophysical systems. Fundamentally this goal requires a systems approach to the design, analysis and build of the facility. Flow down from our Key Science Mission leads us to conclude MROI must have, at a minimum: 1) many relocatable telescopes, 2) optical and infrared operations on several hundred meter baselines, 3) as few reflections as can be used in order to maintain high throughput and minimal wavefront aberrations, 4) single-pass long-stroke delay lines operating under vacuum, and 5) state-of-the-art beam combiners and detectors.

In order to insure that we produce a fully integrated and well-functioning distributed interferometer system, we have developed a set of Performance Verification Milestones (PVMs) which describe the interrelationships and necessary technical operability levels of each subsystem during the assembly and testing phases of MROI. These PVMs have been discussed in previous SPIE proceedings [3] and we will begin executing them as part of the technical commissioning activities beginning in 2011.Verification of PVMs occurs during a process of assembly, integration and verification – a process we call AIV. AIV plans are specific to each sub-system of MROI and are tied back to both the PVMs and the commissioning plan for the facility. A discussion of a specific AIV plan is included in Santoro et al. [4] in these proceedings. As certain PVMs are reached and verified, science capabilities necessarily become available for MROI. Verification of each capability is considered a part of each Science Verification Milestone (SVM), and these begin with routine acquisition of stabilized interferometric fringes.

3. PROGRESS ON INDIVIDUAL SUBSYSTEMS

The design of nearly all off the MROI subsystems is complete and many systems are in advanced stages of build and assembly. Several of these subsystems are being presented at this conference and so will only be discussed in broad terms herein. One of the guiding principles in the design of MROI is to utilize the best in existing interferometric technology, and only redesign a subsystem when this technology fails to meet our system-wide requirements. For subsystems in which we have implemented major redesigns, community involvement from outside experts in the field through consultation and service on external review panels has been invaluable toward our development and progress.

We are grateful for and welcome continued community input in this regard. Below, we discuss the progress in each major subsystem of MROI, along with expected design implementation and schedule.

3.1 Beam combining and delay line facility

The MROI beam combining facility includes all the interconnected buildings on the Ridge housing the control facilities, optical, electrical and mechanical laboratories, delay lines, vacuum system and beam combiners and detectors. The requirements for these facilities were derived to maintain a stable environment in terms of temperature, vibrations and humidity for the scientific instrumentation, along with ease of access and operations for the scientists and engineers. As a specific example, the temperature environment for the delay lines, which include 190 m of continuously joined pipe, must not vary more than +/- 1^{o} C diurnally. The beam combining optics require a much tighter specification of +/- 0.1^{o} C. The temperature stability has nearly been met in the inner beam combining area (BCA) and was easily met in the delay line area; we are in the process of tuning the heating/cooling system to attain our requirements in the inner BCA. We have addressed the requirements on vibrational stability by arriving at a design which includes "technical slabs" (i.e. physically separated from the exterior shell of the building and the rest of the vacuum and air handling equipment in the facility) and buildings which are passively thermally maintained whenever possible. The beam combining room-within-a-room concept (basically a thermally isolated inner facility) has been designed and fully thermally modeled to meet our requirements, but is capable of withstanding only 100 Watts of internal thermal dissipation to meet the thermal specifications above. Accordingly, it has been outfitted with a simple airlock entry system, positive pressure, and multiple heat ducting conduits over each optical table to take away all heat produced by the different electronics in the room. The facility architects were M3 Engineering and Technology Corporation in Tucson, AZ. The facility was completed and we took occupancy of the facility in 2008 (Figure 2). The facility is presently being populated with equipment including computers, optical tables, electronics and metrology systems, with delay line installation scheduled for later this year.

Figure 2. The beam combining and delay line facilities for MROI. Note the 200m long portion of the building extending off to the left, which houses 10 delay lines, extends toward the east of the building. Beams enter the building from the center of the equilateral-Y array arms on the right side of the photograph.

3.2 Delay lines

The MROI delay lines were one subsystem that required an entirely new approach chiefly because no inexpensive, single pass, vacuum delay line system existed for our use. MROI's innovative delay line trolleys are being designed by our collaborators at the University of Cambridge [5]. A major feature of the design is the use of the vacuum pipe itself as the "rail" for the trolley to travel on. This places the burden of maintaining the beam alignment and direction on the trolley itself rather than traditionally utilized precision-aligned rails for this function. Thus, the cart includes compliant wheels and an active secondary mirror in the cat's eye assembly. Other innovative features include wireless communication, inductive power pick-ups and a carbon fiber assembly to maintain focal distance (for further details see Haniff et al. [5], Young et al. [6], and Fisher et al. [7]). The first delay line trolley will be delivered and installed at MROI in the coming months (Figure 3). One element in maintaining a low-cost on the delay line systems is the utilization of standard metal pipe. Because the fully populated delay-line system will contain nearly 2 km of pipe, it is important that this pipe be easy to acquire, and indeed off-the-shelf extruded aluminum pipe typically meets all our specifications on shape, straightness and wall thickness, and only requires moderate finishing on the ends in order to interface pipe segments. A pipe in the finishing process is shown in the second panel of Figure 3.

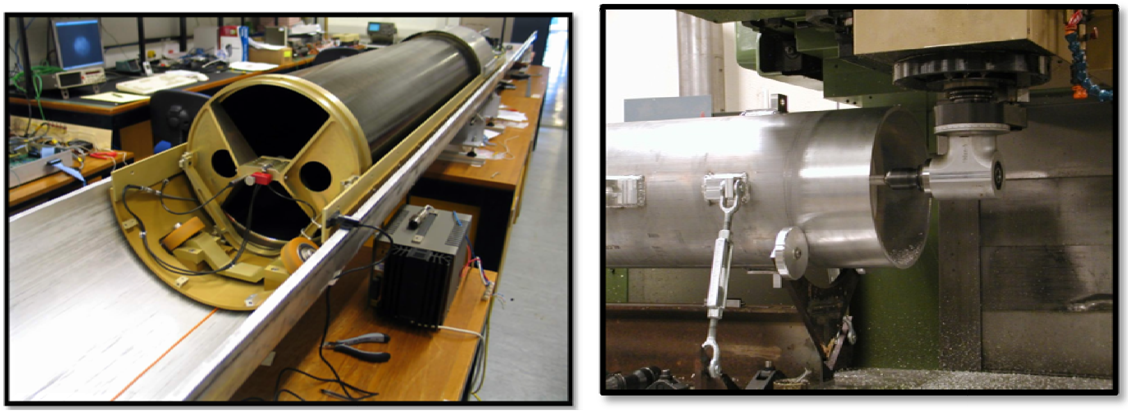


Figure 3. A delay line trolley is shown on the left. The science beams enter at the top and exit at the bottom, while the metrology beams travel perpendicular to these. In the bottom of the half-pipe (for lab testing) can be seen the wire used for inductive pick-up. On the right is shown a delay line pipe being machined on the end for mating with an adjacent pipe upon installation in the facility later this year.

3.3 Telescope mounts, optics and enclosures

The telescope design, while non-standard for traditional astronomical uses, is an old design (altitude-altitude mount) used at facilities like the 1.8m ARC Telescope [8] and in laser range-finding experiments. The principal reasons for using this design are the low number of reflections (3 versus typically 7 for altitude-azimuth telescopes in interferometric applications) before directing the light into the beam train of the interferometer, and the ability to maintain polarization fidelity. This is important when trying to image resolved and potentially polarized sources [9]. The telescopes are capable of operating down to within 30 degrees of the horizon even within a close-packed configuration. They produce beams approximately 95 mm in diameter with 62 nm rms wavefronts and 92% throughput from one aluminum-coated and two silver-coated mirrors. Our telescope mounts are being designed and built by AMOS in Liege, Belgium [10] and the first telescope is in factory acceptance testing at the time of the writing of this paper. While telescope one could be delivered in 2010, we will wait to conduct site acceptance testing until the inner portion of the array foundations and the enclosures are ready in 2011. Telescopes two and three have been placed on order and are expected to arrive in 2011 and 2012 respectively. First fringes are expected in 2012.

The optics for the telescopes are made from Zerodur in order to minimize surface changes with temperature variations. The primary is 1.425 m in diameter and a 9:1 edge aspect ratio, with a secondary of 115 mm and an elliptical tertiary of 260 by 110 mm. The telescope mount cell has 54 mount points on an 18-point whiffle tree to support the mirror and maintain the wavefront. Earlier this year the first primary optic reached one-wave rms on the surface. Six complete sets of optics for Phase A are being figured and will be coated by OST in Albuquerque, NM.

The MROI unit telescope enclosures have three main functions: 1) to protect the telescopes during observations, 2) to support and protect the telescopes during relocation, 3) and to not vignette neighboring scopes while in the close packed configuration (~7.8m on center). The telescope enclosures have completed design and final review and are currently out for qualification of builders at the writing of this paper. The design was completed for us by EIE of Venice, Italy and readers should see their papers at this conference for more details [11] & [12]. We expect the build of each enclosure to take less than a year once the contract is let. See Figure 5 for two views of the enclosures.

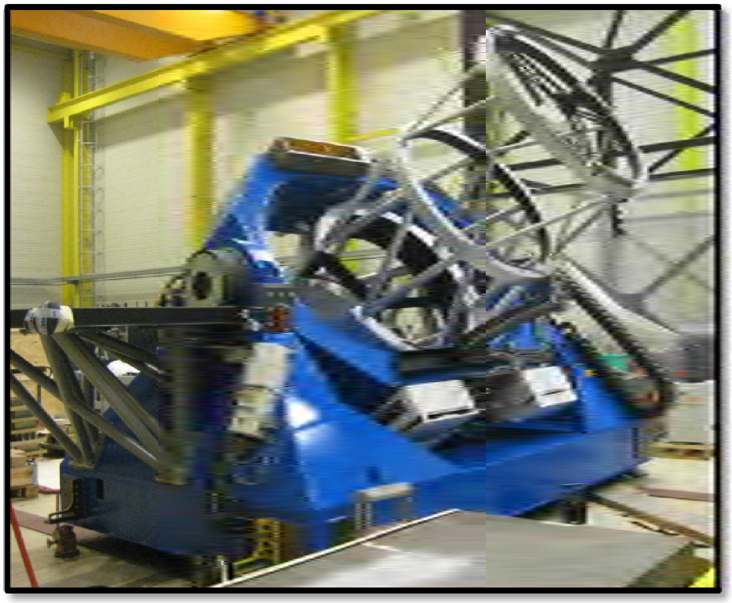
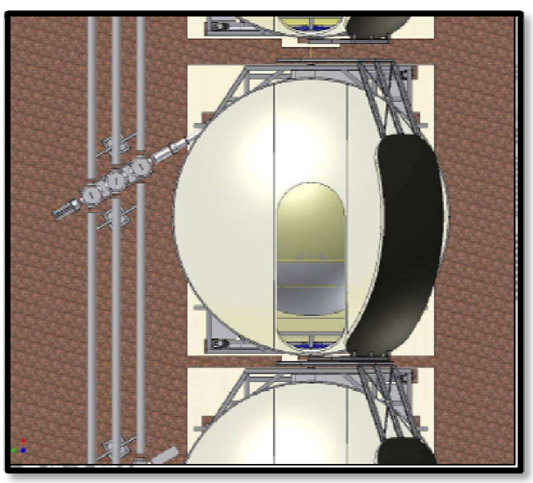


Figure 4. An altitude-altitude telescope mount for the MROI 1.4m movable unit telescopes. Notice the Nasmyth table on the left side of the mount where the atmospheric dispersion correctors, fast tip-tilt system and automated alignment system components will be stationed to correct and align the light beam before sending it into the beam transport system. This telescope will be delivered to the MROI site in 2011.

Finally, the array infrastructure and foundations are being designed by M3 (Tucson, AZ) and will be installed by NMT. The foundations include jacks, fixings and alignment plates for use during relocation of the telescopes, lightning suppression connectors, and support the enclosure and telescope on mechanically isolated pads. The telescopes and enclosures will be relocated between various pads during array configuration with a modified reach stacker, commonly used at shipping docks for moving shipping containers. For more information on the foundations and relocation system for MROI, see Payne et al. [13].



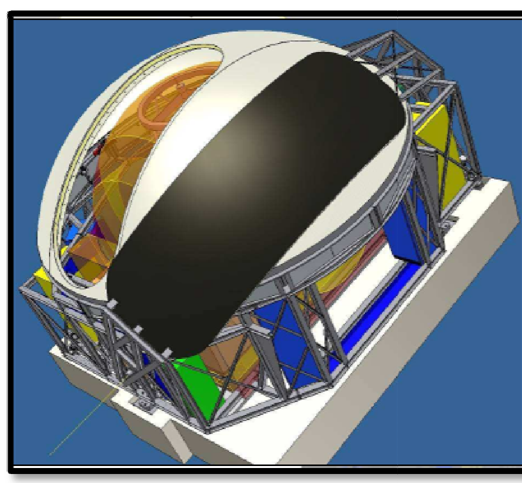


Figure 5. On the left is an overhead view of the enclosure designed by EIE in the close-packed configuration of 7.8m on centers. On the right is a side-view of the enclosure mounted on a foundation with part of the internal structure exposed. Note the innovative design of the enclosure slit which was inspired by Italian refuse cans.

3.4 Fringe tracking beam combiner and camera

The fringe tracker and the associated beam combiner operate under the concept of nearest neighbors, pairwise, pupil-plane combination. We have derived an innovative design which allows us to multiplex 5 mixed beams into one dewar (see Figure 6, right panel), therefore utilizing only one detector, so that the Phase B version of the observatory will only require 4 dewars to collect all the light from all beam combinations of the 10-telescope array. All dewars and internal mechanisms are being designed and built in-house at NMT. The fringe tracking wavebands are H or K_s, depending upon what science waveband is being used. Our current design anticipates upgrading to a lower-noise detector (than our current PICNIC detector) when one becomes available. The beam combiner is a modular design which supports from 2 to 10 telescopes in any configuration on the Ridge. The beam combiner mounts and optics were completed earlier this year and we achieved first fringes in the lab using laser diodes on all 5 initial inputs a few weeks ago. White light fringes will be achieved later this fall with deployment of the system on the Ridge scheduled for early 2012. See Jurgenson et al. [14] for more information on the MROI fringe tracker, McCracken et al. [15] for information on our modulation scheme, and Nyland et al. [16] for information on the performance of the beam combiner coatings.

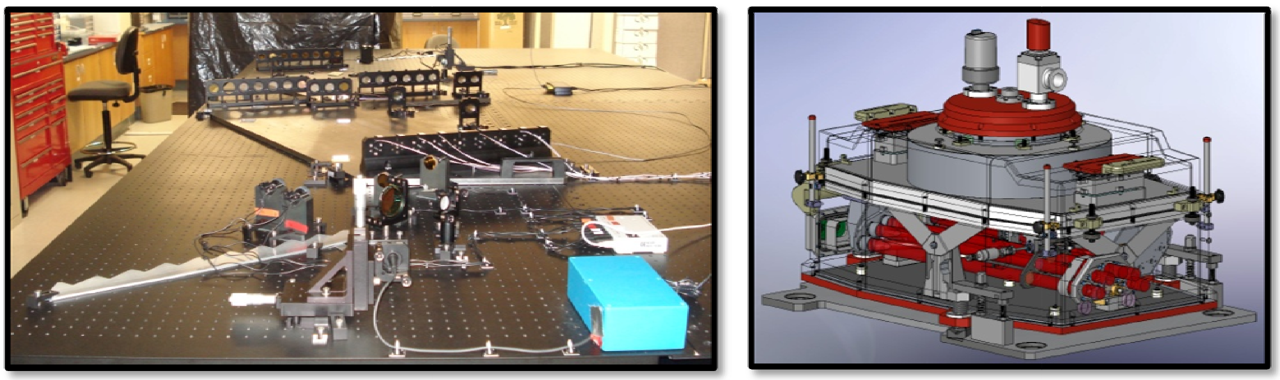


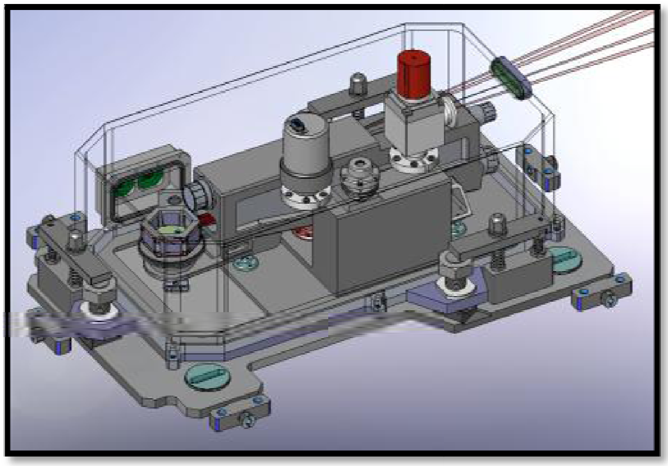
Figure 6. The left panel shows the fringe tracking beam combiner being tested in the lab in June of this year. The observant reader will note this beam combiner will support all ten telescopes. The right panel shows a partial cut-away of the fringe tracking dewar. On the front face 5 combined beams can be seen entering the dewar.

3.5 Infrared science instrument - SIRCUS

We have developed a conceptual design for the MROI infrared science instrument, SIRCUS, "Spectroscopic Infra-Red Combiner for Ultra-faint Sources". SIRCUS will allow for the combination of up to 6 light beams, by using an automated switchyard in front of its cryogenic dewar so as to feed any 4 of the 6 input beams into its combining optics. It is presently being designed to work at resolving powers of 30 and 300 at J, H or K band, with higher-resolution still under consideration. It will accept a stabilized fringe from the infrared fringe tracking system, which operates at either H or K_s depending upon what science wavelength observations are being made. Our design goal for SIRCUS is to achieve a fringe signal-to-noise adequate for imaging in a broad photometric band, using spectral resolution of R~30, four magnitudes fainter than has been realized at any interferometer facility to date. See figure 7 for a cartoon of the SIRCUS conceptual design and a table of its design SNR realized under "good" seeing (0.7" optical) conditions. For some examples of science imaging that can be done with MROI using SIRCUS, see Creech-Eakman et al. [2] in these proceedings.

3.5 Automated alignment system

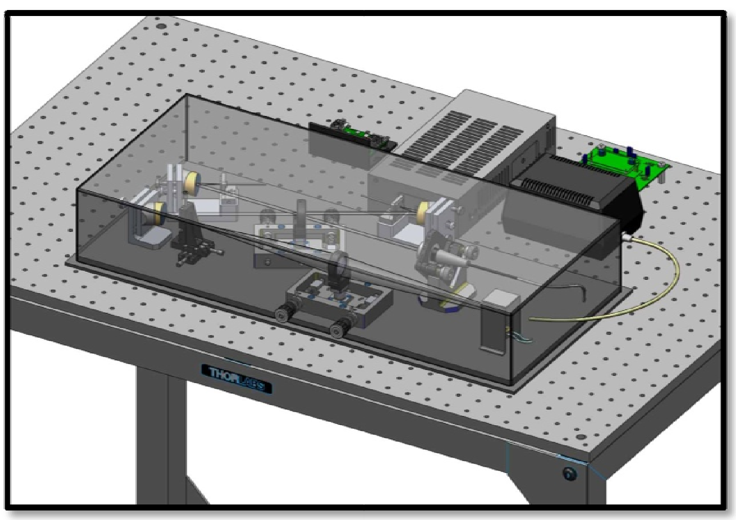
In order to maintain high throughput both in a photon and a scientific-productivity sense, early in the development of MROI we determined that an end-to-end automated alignment system would be required and should be designed from the inception of the project. This alignment system operates by envisioning the interferometer as three optical axes



Magnitude/Band	J	H	K
13	0.45	0.54	0.53
11	17.6	20.8	18.4
9	195	207	159

Figure 7. The left panel shows the SIRCUS dewar receiving 4 non-redundantly spaced beams for dispersion and image plane combination. The right table shows the SNR obtained per spectral channel after 100 seconds of incoherent integration when configured with spectral resolution of 30 under good seeing conditions. At 13th magnitude the individual data from the individual spectral channels will need to be combined to achieve an adequate SNR.

which must be aligned in tilt and shear with respect to each other; they are: 1) telescopes, 2) delay lines and beam compressors, and 3) beam combiners and detectors. The heart of the system includes white light and LED components in in-house designed housings, called Magical Optical Boxes, which inject light into the system for end-to-end alignment of these non-powered optics (see Figure 8). It uses nearly all off-the-shelf components, with the exception of the quad-cell shear detectors for the large beams from the telescopes. These quad-cells are being designed and assembled in-house using solar photovoltaic cells (Figure 8). The automated alignment system will allow rapid alignment of the interferometer at the start of the night, and ease in debugging subsystems during the night when in routine operations. All software for the alignment system is being written and managed in-house (see below for more details on software). For complete details see Shtromberg et al. [17] in these proceedings. The system has passed conceptual and preliminary design reviews, with final design review later this fall.



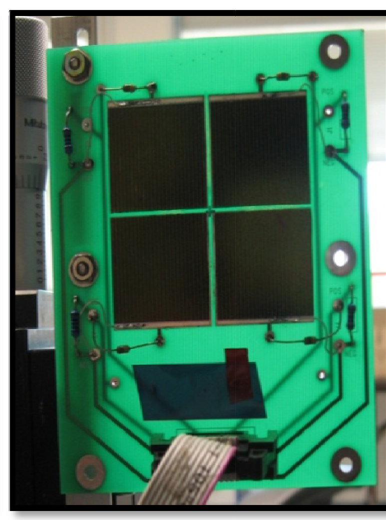


Figure 8. On the left is the conceptual layout of the Magical Optical Boxes used to inject light for the Automated Alignment System. On the right is of one of our prototype quad-cells shear detectors used to align the 95mm beams at the telescopes and in the beam transport arms of the interferometer.

3.6 Control software

MROI's approach to control software has gone through a re-evaluation and new approach since our previous SPIE update in 2008. The MROI system includes software from 36 independent sub-systems, and thus we seek to address this challenge not by controlling each package's implementation, as requirements vary widely, but by using standardized interface software generated from simple high-level descriptions of these individual systems. Further, we rely only on Linux, GNA and POSIX using gigabit Ethernet with TCP/IP protocols as the backbone for these systems, abandoning more complex software as is used in CORBA-based approaches. This provides us with the necessary flexibility to integrate and manage these independent and diverse systems using only a centralized Supervisory System which provides for a database manager, data collectors, fault handling and operator interfaces. At present, our Supervisory System has been completely designed and partially implemented. Code generation is being used extensively, and database design and interface software have all been implemented. Rudimentary versions of other components are being developed and will be brought online to meet with the PVM and SVM schedules. For a more detailed description of our new approach see Farris et al. [18].

3.7 Fast tip-tilt system

The fast tip-tilt system for the MROI telescopes provides a low-order correction of the incoming stellar signal. Because the MROI telescopes are only a few characteristic cell sizes (Fried parameters) across in the infrared, we do not anticipate needing higher-order correction during the Phase A implementation of the observatory. The specifications on this system are that it work in the visible with a 50 Hz closed loop 3dB bandwidth. Once the atmospheric tip-tilt perturbations have been sensed at the Nasmyth optical table, actuation of the telescope secondary mirror will be used to correct for the atmosphere. We anticipate using a photon counting EMCCD for sensing the light, several of which are available off-the-shelf. We have recently awarded the design and build contract for the fast tip-tilt system to the University of Cambridge team as part of their deliverables for the observatory and the system Conceptual Design Review is scheduled within a few months.

3.8 Remaining subsystems

Other major subsystems included in MROI which are not formally part of the above-mentioned systems include the beam relay system, the beam compressors, and the vacuum system. Except for the primaries of the telescopes, all mirrors along the optical train are coated with protected silver and all transmissive optics have custom coatings. The beam relay system accepts the beams exiting the telescopes into the vacuum transport pipes, relaying the light into the beam combining facility to add delay and mix for detection. The system is designed to have all small incidence angle reflections to minimize polarization effects. Relay and mirror cans along the length of the interferometer house portions of the automated alignment system which is used to align these beams after exiting the telescopes (Figure 9). A central telescope and three along each arm (in the Phase B configuration) lead to a handful of different mirror can designs along the beam arms.

The beam compressors for the MROI are a Mersenne design available using off-the-shelf optics. They will reduce the 95 mm telescope beams exiting the delay lines to approximately 18 mm before the beams are sent to the beam combiners and detectors for combination and sensing. The system will be fully assembled on a monolithic bread-board in order to maintain focus and alignment at all times. Immediately after the beam compressors are the injection ports for the automated alignment system. The next optics in the beam train system are the turning mirrors (mirror 10 in the system), which direct the light into the switchyards where beam direction and pitch are changed and various wavebands are separated out using dichroics.

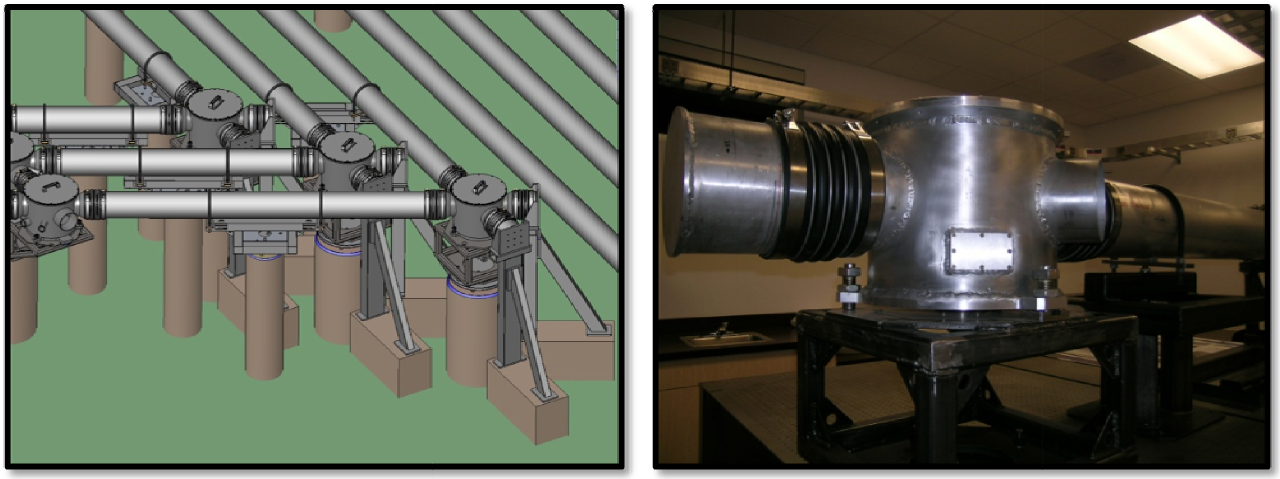


Figure 9. On the left is a view of the vertex of the array with turning mirrors to bring light from the telescopes into the beam combining facility. On the right is one of these cans in the lab under test setup.

The final major subsystem is the MROI vacuum system, which is housed in an isolated room on the far end of the building away from both the delay lines and beam combiner room. It is designed to be able to pump out the entire vacuum volume of MROI in about 8 hours. Individual automated safety valves exist at various interface locations along the vacuum system, but there are no internal windows in the system between the entrance window at the telescope and the exit window after the delay lines. Manual valves are located at the interface between the interior and exterior of the building so that either inside or outside pipes may be pumped down individually as needed for maintenance. The vacuum system is specified to hold at 1 millibar for 12 hours, though we anticipate much better performance than this based on tests of the delay lines at Cambridge. Nevertheless, it will be possible to pump down the vacuum system daily and still resume night-time operations, were the need to arise. For more details on the optomechanics of the MROI beam relay and vacuum systems, see Santoro et al. [4] these proceedings.

A total of 19 reflections exists between the telescope primary and the detector for any given beam as it travels through the interferometer. This fact alone contributes substantially to our ability to maintain high throughput and wavefront specifications for the system. We currently budget a final throughput of 13% at H band with a total high-order wavefront error of 99 nm. Using detectors capable of producing 3 electrons read-noise, with this budget, we will be able to group delay fringe track on a 14th magnitude unresolved source with MROI, fully 4 magnitudes deeper than can currently be achieved at other interferometric facilities.

4 SCIENTIFIC COMMISSIONING

Scientific commissioning of MROI will begin when sustained fringes have been achieved and verified. This commissioning is based on specific sets of technical competencies and is designed to both highlight the technical capabilities of the array and produce new science with the facility. Current Federal funding for MROI does not include operational funding, and so we are pursuing various scenarios for funding operations of the observatory including State and Federal funding, peer-reviewed funding, university funding, philanthropic funding and partnership scenarios. Our over-riding philosophy for scientific commissioning is to allow technical competencies to be fully realized so that any data taken can be considered reliable and can be published quickly once acquired.

MROI's scientific commissioning notionally has three periods: 1) technical competencies/commissioning, 2) imaging demonstrations, and 3) open time. The technical competencies/commissioning period concentrates on demonstrating non-imaging science capabilities of the array such as sensitivity and stability of the system (as measured by visibilities, throughput, efficiency, etc.) over various periods of time. This period is highly dependent on the timeline for deployment of the array, but is expected to start in 2012. Imaging demonstrations begin in earnest once light from 4 or more telescopes is available to be combined on the SIRCUS instrument. Much of the science done during this period will be focused on our Key Science Mission and will be directed in concert with lists developed through Science Working Groups. This period is expected to last about one year, after which time we hope to move to open access/shared risk observations for our collaboratory partners and the broader scientific community (the distribution of which time is dependent upon the detailed funding sources for this phase).

Preparations for scientific commissioning are underway and include: 1) the formation of catalogs of targets aligned with our Key Science Mission, 2) the development of a calibrator star database along with interface software (called LoCal Star) to access this database [19], and 3) the initial formation of Science Working Groups (SWGs) to address key questions and begin taking ancillary data needed to insure the success of the scientific commissioning activities. With the help of these SWGs, detailed Scientific Verification Milestones will be developed which will commence in 2012. It is expected that all data from MROI will be written using the OIFITS format [20] so that any of the many publically available packages may be used on calibrated data for visualization and modeling efforts. We intend to maintain an archival database for all data obtained with MROI, and will enforce a proprietary time period so that data will become publically available after a reasonable period of time. Time Allocation Committees (TACs) will be formed to adjudicate proposals and there will be no embargoed target lists for the observatory during the open time period.

5 SCHEDULE TOWARDS FIRST FRINGES

With first funding obtained for the observatory facilities in FY2000, we are still on an aggressive timeline to obtain first fringes by 2012. The observatory completed and received a record of decision from the US Forest Service on our Environmental Impact Survey in 2003 and completed the majority of the site infrastructure work by 2006. Array infrastructure on the inner 13 stations of the array arms is expected to be substantially complete by fall 2011. With the beam combining building now complete, and Site Acceptance Testing (SAT) of the first telescope expected in 2011 (and for telescopes 2 in 2012), we are anxious to obtain first fringes by our 2012 target date. We anticipate completing SAT for telescope three sometime in early 2013 and taking measurements with all three later that year. In general, we expect to receive telescopes about every 6-9 months thereafter, and could therefore begin our open time phase with initial imaging capabilities as early as 2014. Initiation of Phase B and the acquisition of hardware associated with the final 4 telescopes, enclosures, beam-trains and delay lines is highly dependent upon funding and partners, and we invite all interested parties to contact our Principal Investigator, Dr. Van Romero, for further information and inquiries.

6 ACKNOWLEDGEMENTS

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