Magdalena Ridge Observatory Interferometer: Progress Towards First Light

M. J. Creech-Eakman[a], V. Romero[a], D. Westpfahl[a], C. Cormier[a], C. Haniff[b], D. Buscher[b], E. Bakker[a], L. Berger[a], E. Block[a], T. Coleman[a], P. Festler[a], C. Jurgenson[a], R. King[a], D. Klinglesmith[a], K. McCord[a], A. Olivares[a], C. Parameswariah[a], I. Payne[a], T. Paz[a], E. Ryan[a], C. Salcido[a], F. Santoro[a], R. Selina[a], A. Shtromberg[a], J. Steenson[a], F. Baron[b], R. Boysen[b], J. Coyne[b], M. Fisher[b], E.Seneta[b], X. Sun[b], N. Thureau[b], D. Wilson[b], J. Young[b]

a – Magdalena Ridge Observatory, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM, 87801.
b – Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge, UK, CB30HE.

ABSTRACT

The Magdalena Ridge Observatory Interferometer is a 10-element 1.4 meter aperture 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 around 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 the next few years.

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

1. MAGDALENA RIDGE OBSERVATORY

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 interferometer. The 2.4 m telescope obtained first light on Oct. 31, 2006 and is currently moving into full operations. It is a superb instrument for the study of fast-moving objects and targets of opportunity, owing to its very high slew and tracking rates; its operations are currently funded 30% by NASA for Near-Earth Object follow-on studies[1]. The optical interferometer is being designed and built in collaboration with our partners at the University of Cambridge, Cavendish Lab. In this last development phase the interferometer is moving towards a first fringes date in late 2010. 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 for views of the two facilities.) 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.

Optical and Infrared Interferometry, edited by Markus Schöller, William C. Danchi, Françoise Delplancke
Proc. of SPIE Vol. 7013, 70130X, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.789859

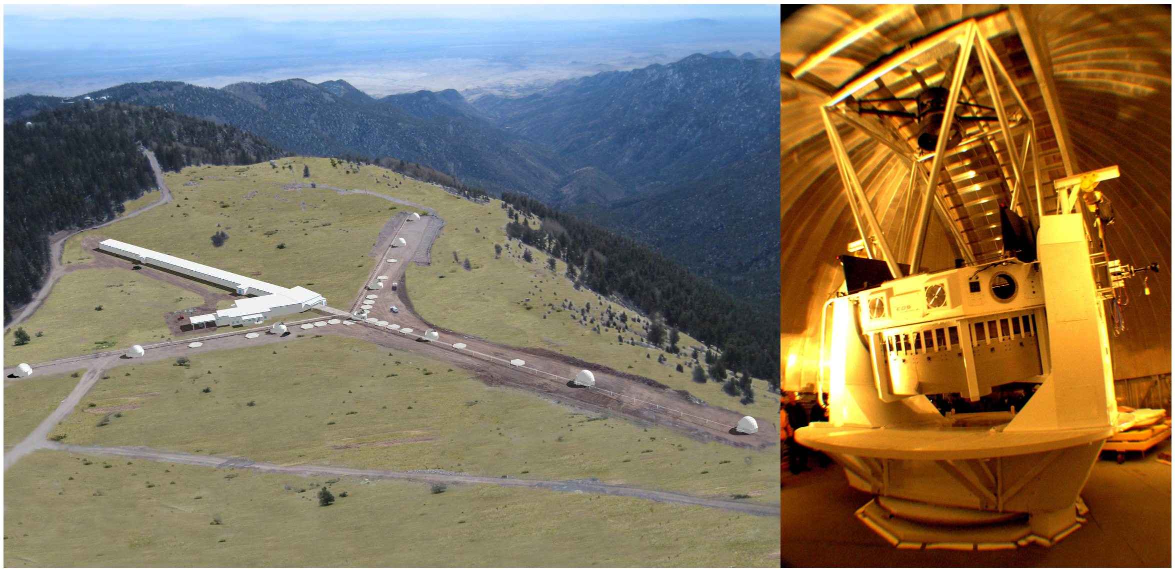

Figure 1. Two telescope facilities atop Magdalena Ridge. On the left is our architect's conception of the MROI facilities. The equilateral Y configuration with 28 pads is clearly visible to the right of the interferometric buildings. On the right is the fast-tracking 2.4m telescope which is now in operations.

2. KEY SCIENCE MISSION AND PERFORMANCE 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) a ubiquitous area of fundamental physics that is evident in processes like mass-loss, mass-transfer, convection and pulsation of single and multiple star systems. A more comprehensive discussion of the Key Science Mission basic objectives appears in previous SPIE 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, 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. Briefly, these PVMs cover the following: PVMs 1-3 include all operations necessary to obtain first light and direct it to a detector in the beam combining facility using a single telescope; PVMs 4-5 concern obtaining and stabilizing first fringes with the first two telescopes; PVM 6-10 discuss how to obtain and assess closure phase measurements and reach our ultimate sensitivity of 14th magnitude (H band) for fringe tracking; finally PVMs 11-13 are concerned with multi-telescope demonstrations including regular telescope relocation, baseline bootstrapping and snapshot imaging capabilities. As certain PVMs are reached and verified, science capabilities necessarily become available for MROI. Verification of each capability is considered as a part of each Science Verification Milestone, and these begin with PVM5 and the routine acquisition of stabilized interferometric fringes. (See below in Section 4.)

3. PROGRESS IN INDIVIDUAL SUBSYSTEMS

Substantial design progress has been made on nearly all subsystems of MROI since the last SPIE meeting in 2006. 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. We have addressed these requirements, along with those 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 received an occupancy certificate in February, 2008 (Figure 2). The remainder of the external site work and the installation of the unit telescope and telescope enclosure pads will take place over the next 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 the delay lines. Beams enter the building from the center of the 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 (to minimize reflections), 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[3]. The 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.[3] and Young et al.[4] in these proceedings). The delay line trolleys passed Final Design Review in March, 2008 and the first trolley will be delivered to the MROI facilities in early 2009 (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 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.

Figure 3. A delay line trolley is presented by three of our Cambridge collaborators during the Final Design Review in March, 2008. On the front of the cart one can clearly see where the stellar beams (top and bottom) and the metrology beams (left and right) enter the cat's eye assembly.

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[5]. The principal reasons for using this design are the low number of reflections (3 versus typically 7 for altitude-azimuth telescopes) 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[6]. The telescopes are capable of operating down to within 30 degrees of the horizon. They produce beams approximately 95 mm in diameter with 62 nm rms wavefronts and 92% throughput. Our telescope mounts are being designed and built by AMOS in Liege, Belgium (Figure 4) and more information about them can be found in their paper[7]. Final Design Review for the mounts is scheduled for October, 2008 and we expect delivery of the first telescope before 2010.

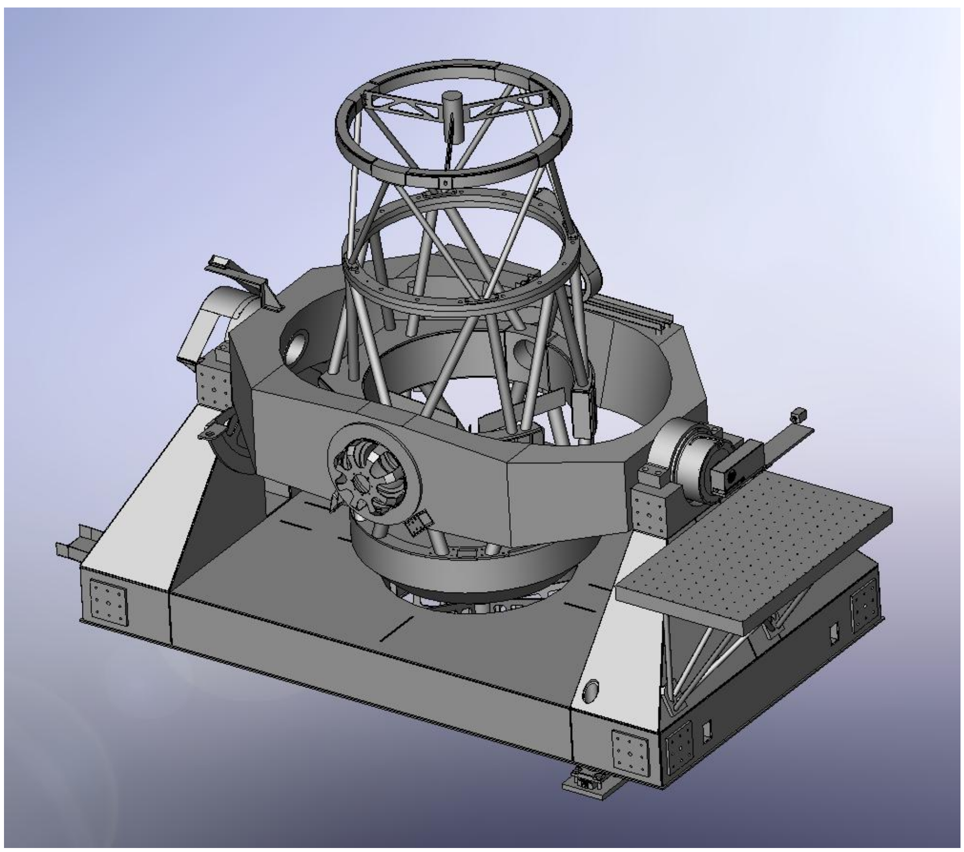

Figure 4. An alt-alt telescope mount for the MROI 1.4m movable unit telescopes. Notice the Nasmyth table on the right side of the mount where the atmospheric dispersion correctors and fast tip-tilt system will be stationed to correct the light before sending it into the beam transport system.

The optics for the telescopes are made from Zerodur in order to minimize surface changes with temperature. 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. Six sets of optics for Phase A are being figured and will be coated with aluminum (primary) and protected silver (secondary and tertiary) by OST in Albuquerque, NM (Figure 5).

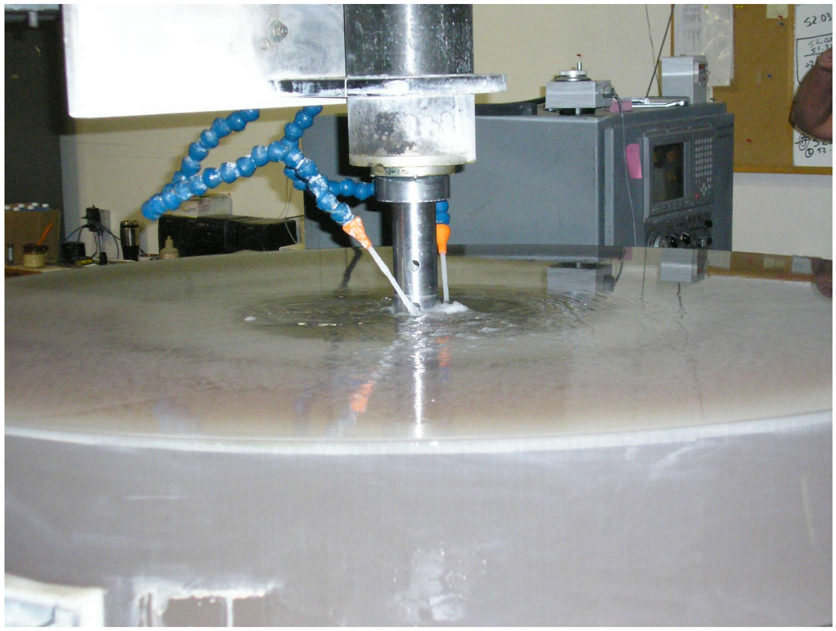

Figure 5. One of the MROI 1.4m primary mirrors being figured at the OST lab in Albuquerque.

The 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 (7.5m on center). We have made significant progress in designing such a system for MROI, having passed a conceptual design review in May of this year, and are convinced that enclosures meeting these specifications can be built and integrated with the telescopes being designed by AMOS (Figure 6). Given the timeline and activities for the observatory until first light, we have decided to let an RFP rather than pursue the final design internally. We expect to award this contract within a few months so that the first enclosure is available at the time of first telescope delivery, by early 2010.

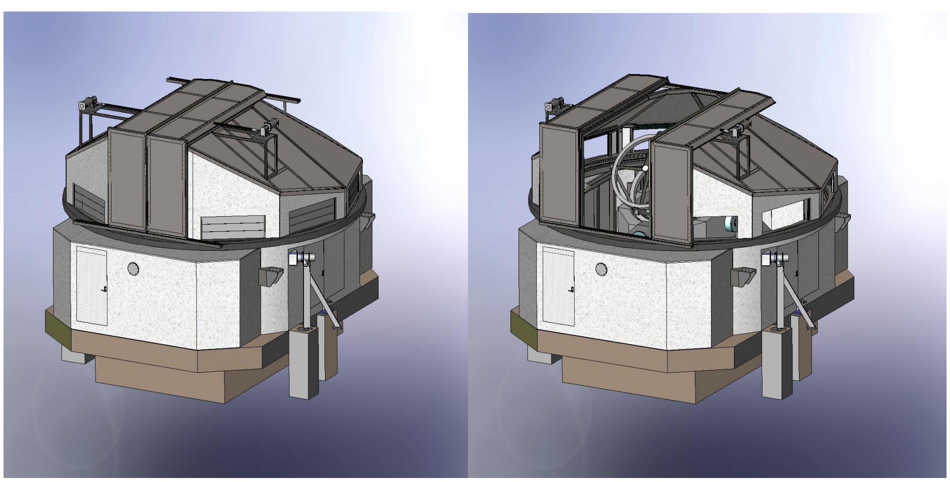

Figure 6. An internal conceptual design for the telescope enclosures. This design (left closed, right open) meets all the specifications for the facility and still allows telescopes to operate over their full field of regard, even in the close-packed 7.5m on center spacing.

3.4. Fringe tracker and fringe-tracking beam combiner

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 4 or 5 combined beams into one dewar (Figure 7), therefore utilizing only one detector, so that the Phase B version of the observatory will only require 4 dewars to collect all the light. Dewars and internal mechanisms are being designed and built in-house, with electronics likely to be procured separately. The fringe tracking wavebands are H or Ks, depending upon what science waveband is being used. Our current design includes the use of a PICNIC detector, but we are anticipating upgrading to a lower-noise 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 optics are Infrasil 301 and have custom coatings optimized to manage issues associated with intensity mismatch, s/p polarization differences and group delay differences between the beams to be combined. For more details on the fringe tracker see Jurgenson et al.[8] and for the custom coatings on the beam combiner optics Block et al.[9] both in these proceedings. Final design review on the fringe tracking system is scheduled for early 2009 with several long-lead items already being procured.

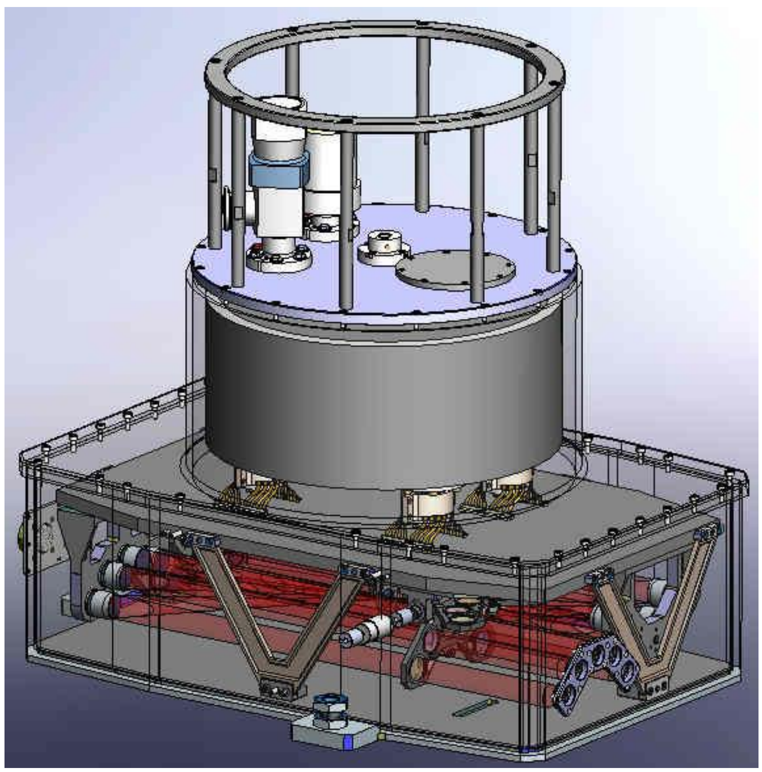

Figure 7. The preliminary design drawings for a fringe tracker liquid nitrogen dewar and optical plate. The dewar accepts 5 nearest-neighbor combined interferometric beams and performs the functions of spatially filtering, spectrally dispersing, and detecting the radiation on the array. Note that due to space limitations on the table, flipper mechanisms rather than wheels are one of the innovative mechanisms used to change filters and prisms.

3.5. Infrared science instrument

In mid-2007 we undertook a detailed design trade-study to consider various architectures of image and pupil plane combiners and associated detectors for the MROI primary IR science instrument[10]. These studies included considerations of throughput, SNR, design and alignment difficulty, calibration fidelity, risk, cost and schedule. Based on currently available focal plane array technologies, a pupil plane combination mixing 4 beams at a time was chosen as our lead concept for MROI Phase A deployment. The instrument would have two spectral resolution modes of about 30 and 300, with a higher resolution mode yet to be determined. A version of this concept was submitted to the 2008 NSF MRI program, but was unsuccessful. We expect to re-evaluate a few new design concepts based on recent developments in the fiber and array technology arenas and then have a conceptual design review of our favored concept by early 2009.

3.6. 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 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 which inject light into the system for end-to-end alignment of these non-powered optics. 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. For complete details see Shtromberg et al.[11] in these proceedings. The system has passed conceptual design review, with preliminary design to be completed this fall and final design review in the spring of 2009.

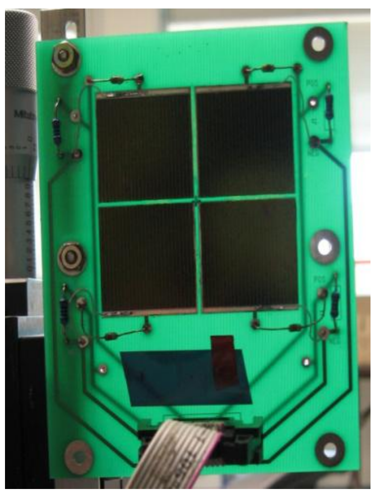

Figure 8. A photograph of one of our prototype quad-cells shear detectors used to align the 95mm beams at the telescopes and in the beam transport arms of the interferometer.

3.7. Control software

MROI software uses as its backbone Real-Time Control (RTC) software, which was designed at the Jet Propulsion Lab (JPL) and is used for both the Keck Interferometer and for various testbeds at JPL[12]. Modifications have been made to RTC by JPL so that it can be operated under real-time Linux, which is the primary operating system at MROI. A full copy of this new version of RTC and several training sessions were purchased from JPL in late 2006 and development of drivers for all of the subsystems at MROI is currently underway. The conceptual layout of the software is shown in Figure 9. In December 2007 a review of the software efforts at MROI by an external panel from NRAO confirmed that the work needing to be undertaken to fully automate the interferometer contains within it considerable effort, and advertisements for additional personnel to help in this effort are expected shortly. Software work will be ongoing for MROI throughout the life of the project.

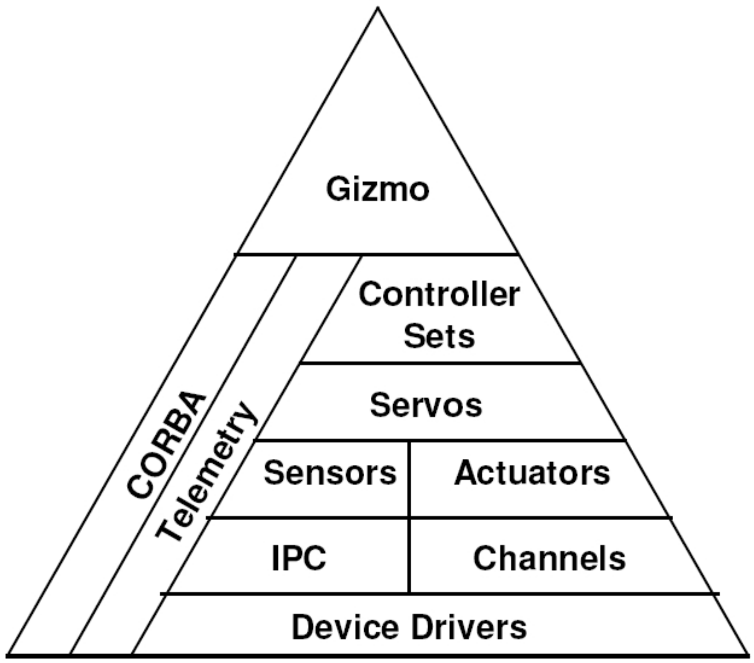

Figure 9. A conceptual diagram of the operation of RTC software structure within the MROI controls system. Notice the interdependencies at all levels and the ability for telemetry to capture information needed to track interferometer operations.

3.8. 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; this point is still to be determined for Phase B when optical operations begin. The specifications on this system are that it work at optical wavelengths (400-1000 nm in Phase A and 400-600 nm in Phase B if doing optical science operations) at rates up to 50 Hz for a closed loop 3dB bandwidth (with necessarily higher frame rates on the cameras). Sensing of stellar light using the fast tip-tilt system on the Nasmyth table is then corrected using the telescope secondary. We anticipate using a photon counting array for sensing the light, several of which are available off-the-shelf. Conceptual design review for this system is complete and we anticipate having an external group build, assemble and test the systems for us before integrating into the interferometer system.

3.9. 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 10). 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.

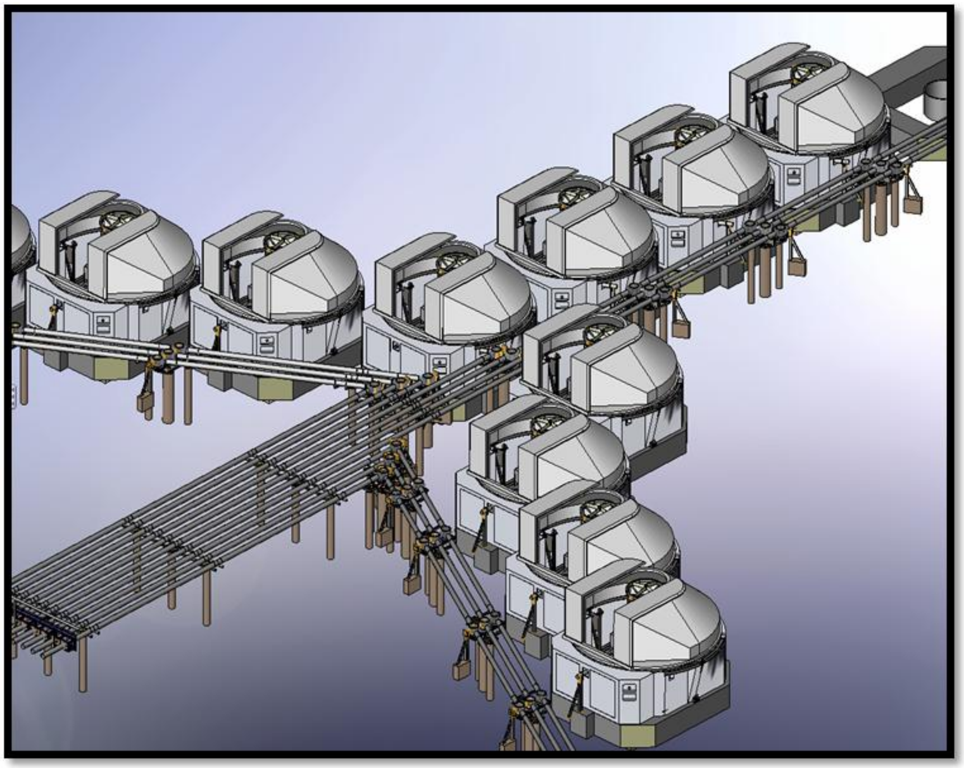

Figure 10. A view of the close-packed configuration of the Phase B interferometer. Note along the right side of the drawing the relay cans, which house the turning mirrors and portions of the automated alignment system.

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.

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 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 may be pumped down individually as needed for maintenance. The vacuum system is specified to hold at 1 millibarr 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.

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 with PVM5 when first 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 commissioning, 2) imaging demonstrations and 3) open time. The technical commissioning period extends from PVM5 to approximately PVM10 and concentrates on demonstrating non-imaging science capabilities of the array. This period is highly dependent on the timeline for deployment of the array, but is expected to start no sooner than late 2010. Imaging demonstrations can begin in earnest once light from 4 or more telescopes is available to be combined. 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 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[13], 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 late 2010. It is expected that all data from MROI will be written using the OIFITS format[14] 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 LIGHT

With first funding obtained for the observatory facilities in FY2000, we are still on an aggressive timeline to obtain first fringes by late 2010. 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. With the beam combining building now complete and the delivery of the first telescope expected by early 2010, we are anxious to obtain first fringes in 2010. We expect to receive telescopes about every 6 months and could therefore begin our open time phase as early as 2013. Our funding agreement with the Office of Naval Research and the Naval Research Lab has our funding continuing through the end of FY2012. Initiation of Phase B and the acquisition of hardware associated with the final 4 telescopes is highly dependent upon funding and partners, and we invite all interested parties to contact our Principal Investigator, Dr. Van Romero, for further information.

6. ACKNOWLEDGEMENTS

Special thanks goes to our PI, Dr. Van Romero, for his vision and initiation of the Magdalena Ridge Observatory project. We would also like to extend special thanks to our NM Congressional staff, and especially the honorable Senator Pete V. Domenici for his support all these years.

The Magdalena Ridge Observatory is funded by Agreement No. N00173-01-2-C902 with the Naval Research Laboratory (NRL). MROI is hosted by the New Mexico Institute of Mining and Technology (NMT) at Socorro, NM, USA, in collaboration with the University of Cambridge (UK). Our collaborators at the University of Cambridge wish to also acknowledge their funding via STFC (formerly PPARC) in the UK.

References

[1] Ryan, E. V. and Ryan, W. H., "The Magdalena Ridge Observatory's 2.4 meter Telescope: A New Facility for Follow-up and Characterization of Near-Earth Objects", Proceedings of the 2008 AMOS Technical Conference, Hawaii, in press (2008).
[2] Creech-Eakman, M. J., Buscher, D. F., Haniff, C. A. and Romero, V. D., "The Magdalena Ridge Observatory Interferometer: a fully optimized aperture synthesis array for imaging", Proceedings of SPIE, Vol 5491, New Frontiers in Stellar Interferometry, p 405, (2004).
[3] Haniff, C. A., et al. "The long-stroke MROI vacuum delay lines: from concept to production", Proceedings of SPIE, Vol 7013, this proceedings (2008).
[4] Young, J. S. et al., "Software and control for the Magdalena Ridge Observatory Interferometer delay lines", Proceedings of SPIE, Vol 7013, Optical and Infrared Interferometry, this proceedings (2008).
[5] Richardson, E. H., Grundmann, W. A. and Odgers, G. J., "Altitude-altitude Mounting for an 8-m Telescope", Proceedings of SPIE, Vol 1236, Advanced Technology Optical Telescopes IV, p. 897, (1990).
[6] Buscher, D. F. et al. "Polarization Fidelity in an Optical Interferometer", Proceedings of SPIE, Vol 7013, Optical and Infrared Interferometry, this proceedings (2008).
[7] Pirnay, O. et al. "Design of the Unit Telescopes of the MROI", Proceedings of SPIE, Vol 7013, Optical and Infrared Interferometry, this proceedings (2008).
[8] Jurgenson, C. A. et al. "Fringe tracking at the MROI", Proceedings of SPIE, Vol 7013, Optical and Infrared Interferometry, this proceedings (2008).
[9] Block, E. et al. "Custom near-IR beamsplitters and AR coatings at the MROI", Proceedings of SPIE, Vol 7013, Optical and Infrared Interferometry, this proceedings (2008).
[10] Baron, F. et al. "A high-sensitivity near-infrared science combiner for MROI", Proceedings of SPIE, Vol 7013, Optical and Infrared Interferometry, this proceedings (2008).

[11] Shtromberg, A. S. et al. “MROI’s automated alignment system“, Proceedings of SPIE, Vol 7013, Optical and Infrared Interferometry, this proceedings (2008).
[12] Lockhart, T. G., “RTC: A distributed realtime control system toolkit”, Proceedings of SPIE, Vol 4848, Advanced Telescope and Instrumentation Control Software II, p. 197, (2002).
[13] Festler, P. , Creech-Eakman, M. and Bakker, E. “LoCal Star: An MROI Calibrator Star Locator Program”, Proceedings of the American Astronomical Society Meeting, 211, 132.13, (2008).
[14] Pauls, T. A., Young, J. S., Cotton, W. D., Monnier, J. D., “A Data Exchange Standard for Optical (Visible/IR) Interferometry”, Publications of the Astronomical Society of the Pacific (PASP), 117, 1255, (2005).