SCIENCE OBJECTIVES AND COMMISSIONING OF THE MAGDALENA RIDGE OBSERVATORY INTERFEROMETER

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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 a description of the science to be undertaken with the facility, an overview and update on the status of the observatory and our progress towards first light and first fringes in the next few years.

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 in 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[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 2011. 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.

2. KEY SCIENCE MISSION

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 fundamental physics of mass-loss, mass-transfer, convection and pulsation in single and multiple stellar systems.

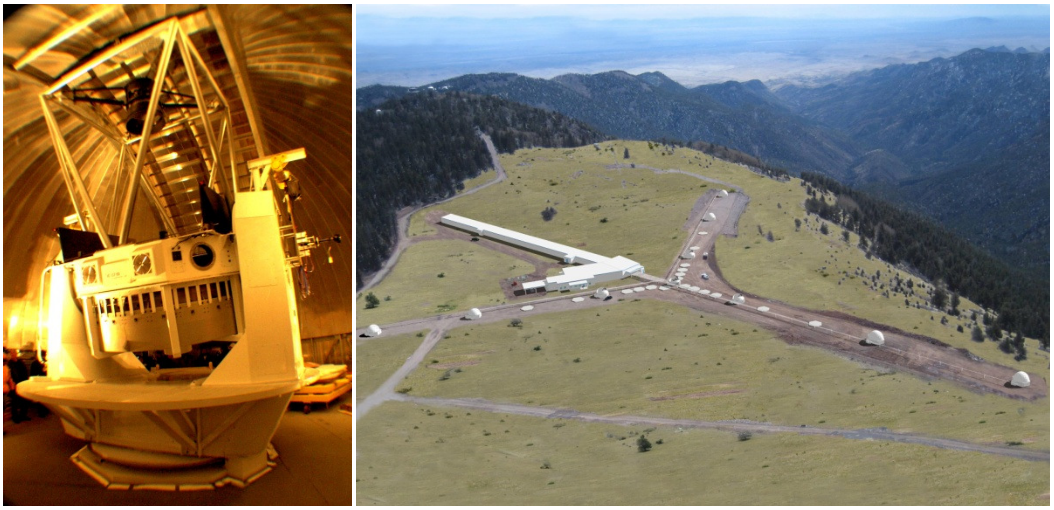


Figure 1. Two telescope facilities atop Magdalena Ridge. On the left is the fast-tracking 2.4m telescope which is now in operations. On the right is our architect's conception of the MROI facilities. The equilateral Y configuration with 28 pads is clearly visible to the right of the interferometric buildings.

2.1 AGN: While active galactic nuclei have been studied for many years, the advent of ultra-high-resolution interferometric imaging offers the prospect of gaining entirely new insight into the role they may play in galaxy formation and evolution. There are several interesting physical scales associated with these targets: the broad line region (BLR): characterized by Doppler broadened permitted lines (FWHM> several 1000 kms^{-1}) and formed in dense regions on sub 0.1pc scales; the narrow line region (NLR): where cooling is dominated by forbidden lines with FWHM < 1000kms^{-1}, extends from 1-1000pc; and the "circum-nuclear torus": purported to shape the observed properties of AGN through shadowing on scales between 1 and 50 pc. In nearby bright AGN ($z<0.01$) these different physical domains span angular resolutions from 0.5 mas to a few seconds of arc. However, it is those regions closest to the AGN that are of most interest and relevance to MROI science. Two of the main science goals that we will aim to address here include:

Constraining dust torus models: what is the frequency of dust tori, what are the geometric and physical properties of the obscuring material, and is it consistent with the latest clumpy models? Is the geometric distribution of the dust compatible with a "unified scheme"? Is the occurrence of a torus/disk axis co-aligned with the larger scale radio emission a frequent one, and what does it tell us about the validity of magneto-hydrodynamic models of outflows? Model-independent imaging will be crucial in interpreting observations of clumpy tori, which are not in general well-described by a small number of parameters.

Jet formation: the angular scales associated with accretion and coronal emission in even nearby AGN are far too small (<0.1mas) to be resolvable with MROI. However, for the nearest radio loud sources, the possibility exists to image the optical/infrared counterparts of synchrotron jets on scales some 5 times larger. While this type of study is at the limit of the MROI's angular resolution, it lies within MROI's sensitivity limit - which is tied to the near-IR magnitude of the AGN core, and not its jet – and so offers the prospect of a completely new window on AGN non-thermal processes.

2.2 Star and Planet Formation: Optical interferometry has already delivered important breakthroughs in the study of disks around young stars. In particular, the sizes of Herbig Ae, late Herbig Be and T Tauri objects have been measured to be 3-7 times larger than predicted by geometrically-thin disk models previously used to explain the SED measurements [2]. These interferometric size measurements have led to the development of a new class of "puffed up" inner wall models for the flared disk emission [3] & [4]. In this science area a sample of what we can address includes:

Constraining disk models: what is the inner disk geometry, including its vertical structure, and how does this vary with evolutionary and other physical status (e.g. with accretion rate)? How do disk properties change in hierarchical systems and what does this imply for disk stability and planet formation? Here the imaging capability of the MROI will be crucial to permit model-independent surveys. MROI will also improve on the inadequate sample size obtained thus far (Figure 2), obtaining images of several tens of objects in each sub-class.

Verifying accretion models: is there evidence for accretion onto proto-stellar surfaces from the inner disk edge and is this consistent with models for such processes? Existing interferometric arrays have made little progress in these areas, primarily because (i) much of the emission is expected in optical emission lines and (ii) the associated angular scales (corresponding to << 1 AU) are sub-mas. The combination of an optical capability and MROI's largest (340m) configuration offers the first prospect for confronting models with observational data.

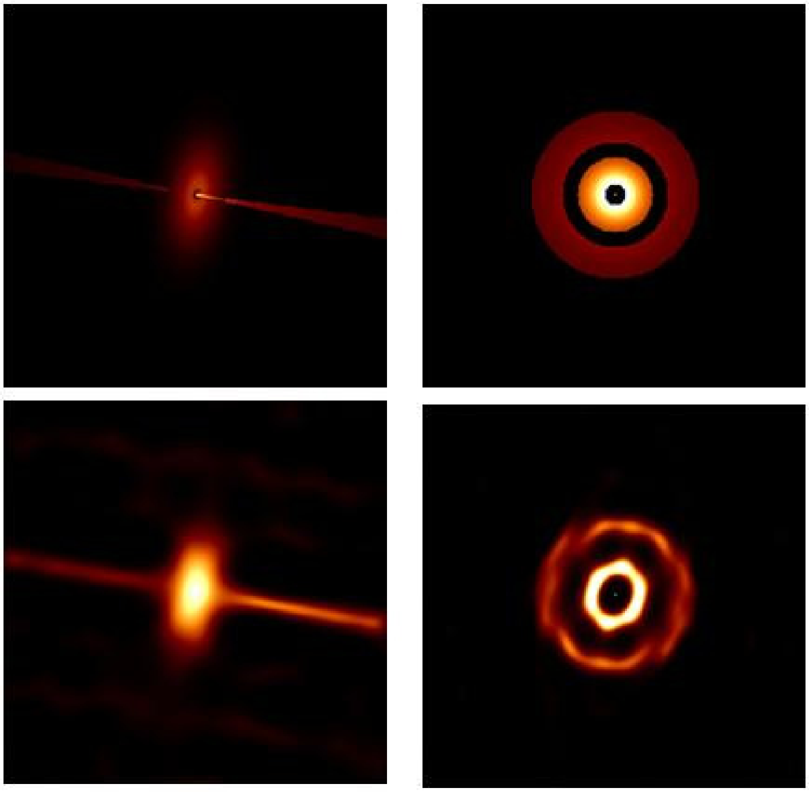


Figure 2: In the four adjacent panels, the top panels on L and R are "truth" images, and the bottom images are made with a 5-telescope MROI. On the left is an AGN with optical jets of excited material ejecting from the black hole, on the right is a young stellar object with a dust accretion disk, which has a dark clearing of material due to planet formation. Each simulation assumes an 8 hr observation, with calibrated data being secured at 20 minute intervals. Six spectral channels from 2.0 to 2.4 microns have been assumed, together with rms noise levels of 2% on the visibility amplitudes and 1° on the closure phases.

2.3 Mass-loss and Mass Transfer: Stellar evolution is fundamentally a cosmic-scale matter reprocessing and recycling program where the mass of the star and its membership of either a single or multiple stellar system determines the details of how the process will proceed. All the interesting astrophysics, however, is tied up in just these details. The physics of mass-loss, while generally poorly understood, is ubiquitous across the Hertzsprung-Russell diagram and accounts for many of the most complex and beautiful images in astrophysics: mass-transfer in interacting binary systems like cataclysmic variables and Wolf-Rayet systems, planetary nebulae resulting from bi-polar outflows in dying Asymptotic Giant Branch stars, and the remnants of supernova explosions. Optical interferometry has made contributions which advance our understanding of nearly all these phenomena, and this with just a few simple images [5] & [6]. In particular we will try to address some of the following fundamental questions:

Querying interacting systems: what are the details of the mechanisms behind mass-transfer in systems like cataclysmic variables and Algol binaries? Are Roche lobes detached/semi-detached and does this change with orbital phase? How does mass transfer trigger explosive events? Are angular momentum vectors in hierarchical systems co-aligned and how does this change with mass-transfer or the presence of accretion disks? MROI's unique re-scalable array (7.8-340 meters) allows for imaging at the wide variety of resolutions required to answer these questions from sub-arcsecond to sub-milliarcsecond scales.

Assessing dynamics in massive stars: what is the connection between stellar shape (i.e. non-spherical, rapidly rotating systems) and their wind structures? Do optical/infrared counterparts exist to X-ray and UV phenomena, tracing the shocks and hot winds? Are large-scale mass-loss/wind inhomogeneities due to stellar spots, pulsation, or some other mechanism? What is the origin of the dense equatorial disk in Be type stars and how is it involved in mass and energy supply to the disk and angular momentum transport? In these cases, MROI's ability to produce very-high resolution images in excited spectral lines will be key to solving many of these puzzles.

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.

3. PROGRESS IN SELECT INDIVIDUAL SUBSYSTEMS

Substantial design progress has been completed on nearly all subsystems of MROI. This owes, in part, to one of the guiding principles in the design of MROI which 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 (Figure 3), completed in February 2008, 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. The beam combining room-within-a-room concept (basically a thermally isolated inner facility) has been designed and fully thermally modeled and tested to meet our stringent thermal requirements. 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 remainder of the external site work and the installation of the first compliment of unit telescope and telescope enclosure foundations will take place over the next year.

Figure 3. The beam combining and delay line facilities for MROI. Note the 200m long portion of the building extending off to the left in this picture, which houses the delay lines. Light 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 have been designed by our collaborators at the University of Cambridge[7]. 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 between off-board computers and the cart itself, inductive power pick-ups and a carbon fiber assembly to maintain focal distance [8]. The delay line trolleys passed Final Design Review in March, 2008 and the first trolley will be delivered to the MROI facilities in late 2009 (Figure 4).

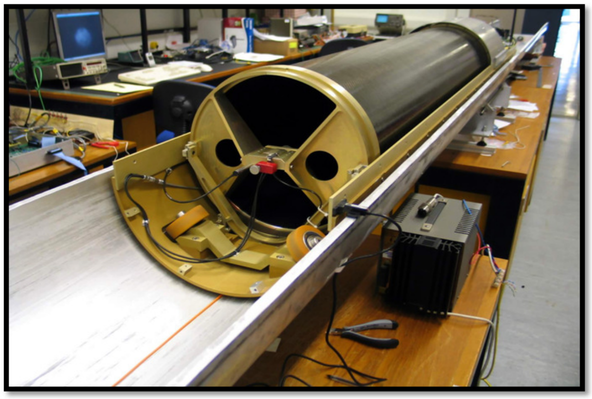


Figure 4. This is a delay line trolley at Cambridge from the Final Design Review in March, 2008. On the front of the cart one can clearly see where the stellar beams (top and bottom) and the metrology beams (left and right) enter the cat's eye assembly. Visible in the bottom of pipe (cut in half for ease of viewing) is the inductive pickup wire.

3.3 Telescopes 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 [9]. 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 [10]. The telescopes are capable of operating down to within 30 degrees of the horizon allowing us to obtain long tracks and excellent UV coverage. 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 (Belgium) (See Figure 5). We expect delivery of the first telescope mid 2010.

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 (7.8m on center). In 2009 we hired EIE (Italy) to design and supervise the build of the telescope enclosures. The design recently passed Preliminary Design Review and we expect the first enclosure in mid-to-late-2010.

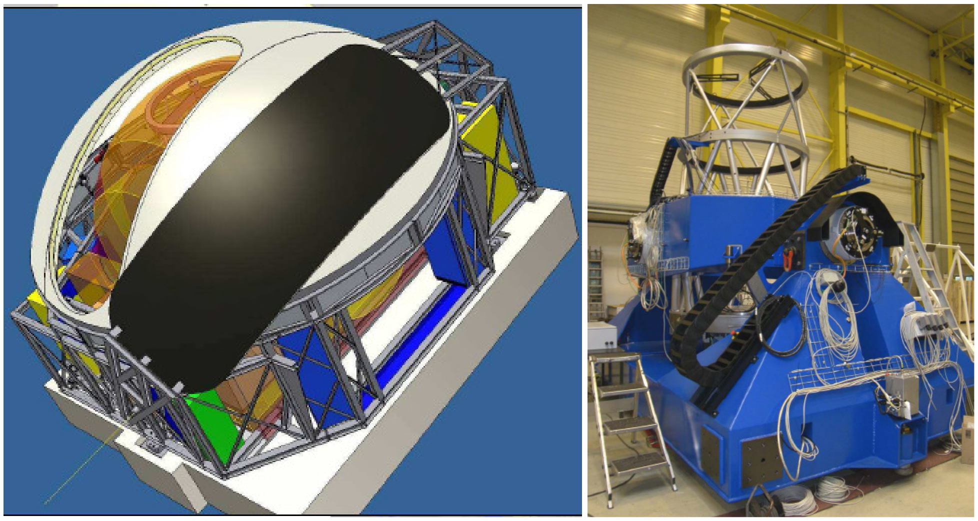
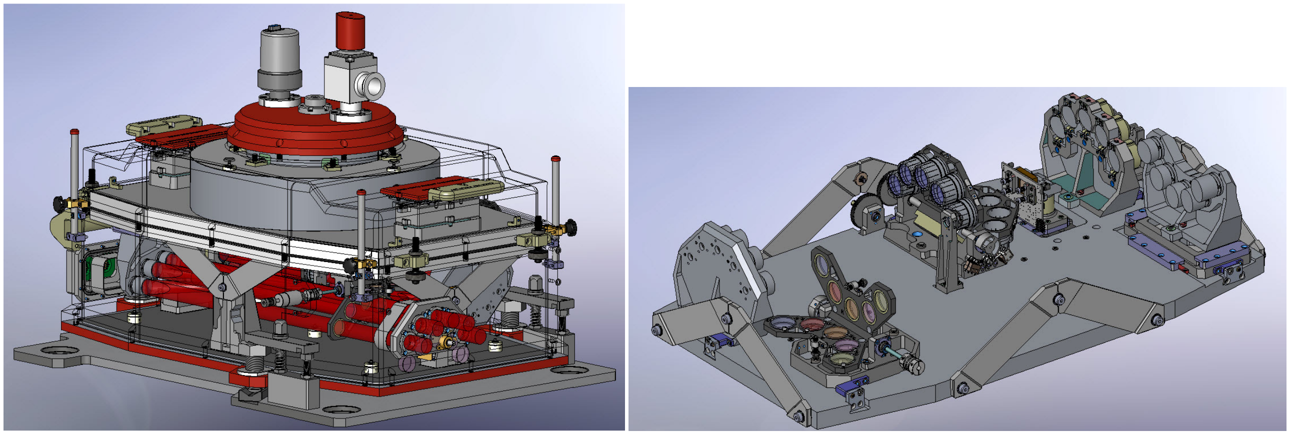


Figure 5. On the left is a telescope enclosure in the final design stages under the direction of EIE. On the right is an alt-alt telescope mount for the MROI 1.4m movable unit telescopes, being designed and built by AMOS. The Zerodur optics for the first six telescopes are being figured, polished and coated at OST, Albuquerque, NM. Pictures are courtesy of EIE and AMOS respectively.

<u>Fringe tracking – the heart of MROI:</u> 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 6), therefore utilizing only one infrared 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 currently being assembled in-house and integrated with electronics procured from Leach Electronics (San Diego, CA). The fringe tracking wavebands are H or Ks, depending upon which 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 commercially 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 are currently being custom coated with optimized coatings that address issues associated with intensity mismatch, s/p polarization differences and group delay differences between the beams to be combined [11]. Final design review for the fringe tracker is scheduled for the last quarter of 2009.



<u>Figure 6.</u> The design drawings for a fringe tracker liquid nitrogen dewar and optical plate. On the left, the initial dewar will accept 5 nearest-neighbor combined interferometric beams (seen in red entering the RHS of the dewar) and then performs the functions of spatially filtering, spectrally dispersing, and detecting the radiation on the array. Due to space limitations on the table, flipper mechanisms (seen in right-hand picture, bottom and middle) rather than wheels are one of the innovative mechanisms used to change filters and prisms.

<u>Control Software:</u> The MROI software system is composed of a collection of distributed systems managed by a centralized Supervisory System. These distributed systems correspond to the major functional divisions of the interferometer: Unit Telescope, Delay Line System, Automated Alignment System, etc. Each of these systems may themselves be structured as a collection of systems. Thus, the architecture supports hierarchically structured systems. All hard real-time control modules lie at low levels within these systems. Each type of system defines a set of high-level interface commands that are designed to completely manage that system, including collecting monitor and science data. These commands are implemented using gigabit Ethernet with a TCP/IP protocol. Software implementation and optimization for each of the various interferometric subsystems is ongoing, and in particular significant progress has been made for telescopes, delay lines, detectors, movable alignment mirrors and automated building control systems.

The Supervisory System itself is a collection of systems. It contains the following:

• **Executive**	Starts, stops, and monitors the global state of all active systems, including the Supervisory System;
• **Operator Interface**	The mechanism by which the telescope operator interacts with the Supervisory System;
• **Supervisor**	Manages one or more unit telescopes and other resources to support scientific observations, calibrations, or diagnostic testing;
• **Fault Manager**	Determines the significance of all faults and alerts and takes appropriate action to handle them;

Data Collector	Collects all software logs, engineering monitor data and science data from all active systems;
Database Manager	Manages all access to the permanent database, including accessing and updating configuration data, as well as reformatting data from the data collectors to be permanently stored in the database.

There is one Executive, Database Manager, and Operator Interface in the system. While the Data Collector functions as a unified system, there are many data collection instances collecting data from different systems, possibly running on different computers, and interacting with the Database Manager. There must be at least one Supervisor in the system but there may be more than one. For example, eight unit telescopes may be engaged in science observations, while the other two are doing calibrations having been moved to new stations. In such a case there would be three Supervisors running simultaneously. There is a Fault Manager for each Supervisor. It is a Supervisor that executes a science observing script, prepared with the Observation Preparation Tool.

All systems are extensions of a basic system that is implemented to provide what is common to all systems. For example, this basic system has the ability to communicate with its assigned Fault Manager, to generate faults and alerts, to communicate with the Database Manager and telescope operator, if necessary. It also implements a state model that is used by the Executive for system startup, initialization, operational mode, and shutdown.

The permanent database, which is implemented as a relational database, is a crucial portion of the Supervisory System and necessary to its operation. It is called the Monitor and Configuration Database and contains all system configurations, as well as all data collected during the execution of the system. A configuration is a specification of active computers, software and hardware systems. The database tracks changes in the system configuration over time and also tracks when a particular configuration is started and stopped. All configurations over time are permanently recorded in the database. In this manner one can always tell which telescope configuration generated particular system logs, monitor data, and science data. The specific properties of the relational database are well-hidden by a high-level interface implemented by the Database Manager. This database provides an integrated view of the total system and is intended to house all data needed to operator the telescope and store all data that are significant to its operation.

Fast tip-tilt system: The FTT 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 will not need higher-order correction for infrared observations (Phase A). We are still evaluating if there is an SNR advantage to adding AO for very-high spectral resolution modes in the optical as part of Phase B. 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 an ultra-low noise CCD for sensing the light, several of which are available off-the-shelf. Conceptual design 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.

Other Major Subsystems: There are many subsystems of the interferometer not mentioned above including the beam relay system, the telescope transporter and the beam compressors (Figure 7). Except for the primaries of the telescopes, all mirrors along the optical train are coated with protected silver, and all transmissive optics will 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. 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.

Turning mirrors and beam compressors for the MROI will operate in air in the beam combining laboratory. The compressors will reduce the 95 mm telescope beams exiting the delay lines to approximately 13 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.

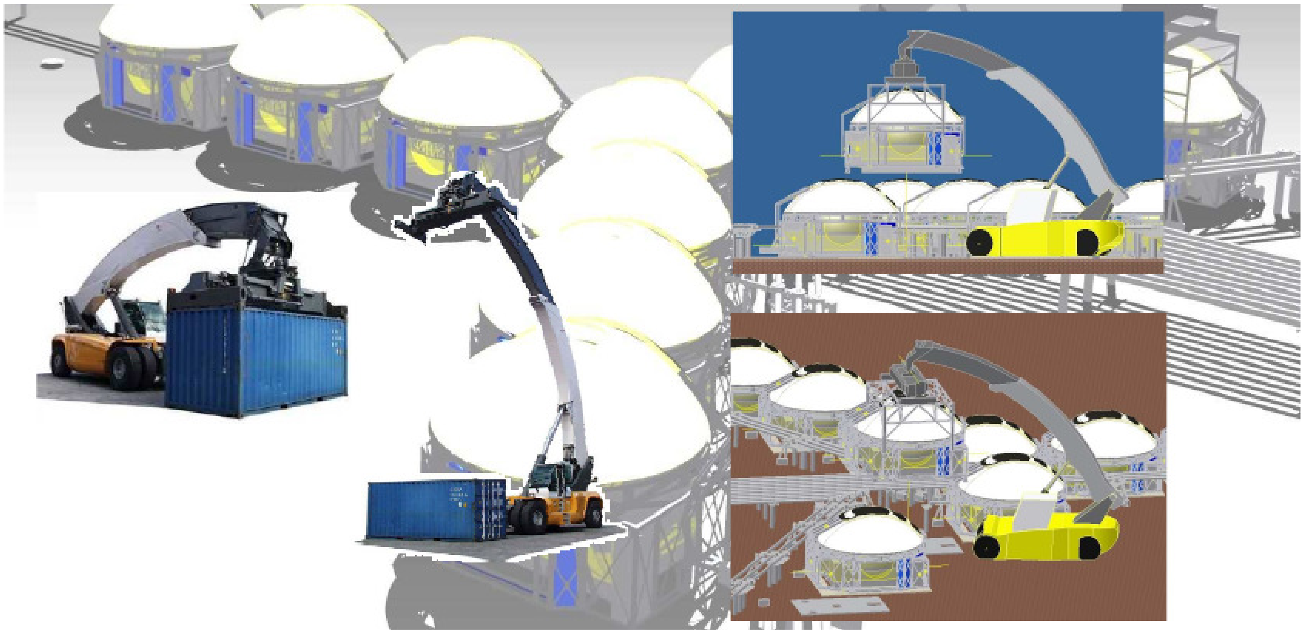


Figure 7. A view of the close-packed configuration of the Phase B interferometer. Included is a schematic of the telescope transporter, a modified reach stacker, which will be used to relocate telescopes along the beam arms.

The telescope transporter is a modified commercial crate reach stacker. The system is specified to lift the telescope plus enclosure and relocate it onto a kinematic pad within 4 hours. This will allow the entire interferometer to be reconfigured in a few days. This function is essential to the science program as it allows a “zoom” capability to match the interferometric resolution to the science cases of interest.

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 (H band) 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 the fifth Performance Verification Milestone (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 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 2011. Imaging demonstrations can begin in earnest once light from 4 or more telescopes is available to be combined on an imaging combiner. 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 (SWGs). 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, and 3) the initial formation of SWGs to address key questions and begin taking ancillary data needed to insure the success of the scientific commissioning activities. It is expected that all data from MROI will be written in OIFITS format 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.

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 2011. 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. After the 2010 delivery of telescope 1, we expect to receive subsequent telescopes about every 6 months and could therefore begin our open time phase as early as 2013. Our funding agreement with 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

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