The Magdalena Ridge Observatory Interferometer: A Fully Optimized Aperture Synthesis Array for Imaging

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ABSTRACT

The Magdalena Ridge Observatory Interferometer will be the first facility-class optical interferometer optimized strictly for an imaging science mission. The array in its final form is envisaged to comprise ten 1.4 m aperture movable telescopes in a Y configuration, baselines extending from 8 to 400 meters, delay lines capable of tracking well-placed sources for 6 continuous hours, fringe-tracking in the near-infrared , and undertake science observations at both near-infrared and optical wavelengths. The science reference mission includes studies of young stellar objects, a full range of stellar astrophysics, and imaging studies of the nearest and brightest 100 active galactic nuclei. We will be staffing up to our full complement of personnel in New Mexico over the next year. Our goal for first fringes on the first baseline is 2007.

Keywords: interferometer; instrument design; imaging; MROI; COAST

1. INTRODUCTION

The Magdalena Ridge Observatory is a US Department of Defense-funded project being built by the New Mexico Institute of Mining and Technology (NMT) on Magdalena Ridge just west of Socorro, NM. It consists of two separate science instruments, a fast-tracking 2.4 m telescope[1] and an optical interferometric array (MROI). The interferometric array is planned to consist of ten 1.4 m telescopes in a Y configuration, operating in the optical and near-infrared (NIR). This facility-class array is intended to be optimized strictly for model-independent imaging. The main participating partners in the interferometer project are NMT and the Cambridge Optical Aperture Synthesis Telescope (COAST) group at the Cavendish Laboratory in the University of Cambridge. Our aggressive time-schedule for "first light" anticipates first fringes in 2007 and first closure phase in 2008. In section 2 we describe the site and its infrastructure. In section 3 we discuss the "vision" MROI instrument. Section 4 outlines our science reference mission and the requirements on MROI to meet these goals. In section 5 we discuss our technical progress to date. Finally, in section 6, we discuss our plans for staffing and our general schedule, including our phased approach for the build.

2. SITE DESCRIPTION

Magdalena Ridge is located 32 kilometers to the west of Socorro, NM at an altitude of 3230 m. The Ridge is the current site of the Langmuir Laboratory for Atmospheric Research[2] and was once considered by NRAO as a candidate site for the Millimeter Array.[3] The topography of the site is ideal for an interferometer, with a large flat meadow on the south end of the ridge which is mainly devoid of trees (Figure 1). Topographical measurements show elevation changes of less than 3 m across the planned array layout from the center of the array along any of its arms. The incoming winds are generally from the west-southwest, having traveled over a desert plateau (altitude 2200 m) for more than 100 kilometers before reaching Magdalena Ridge. The weather is typical for the southwestern US, including low humidity, a late summer monsoon flow and winter snows. For more detailed description of the weather conditions and ongoing site characterization work, see Klinglesmith et al. this conference.[4]

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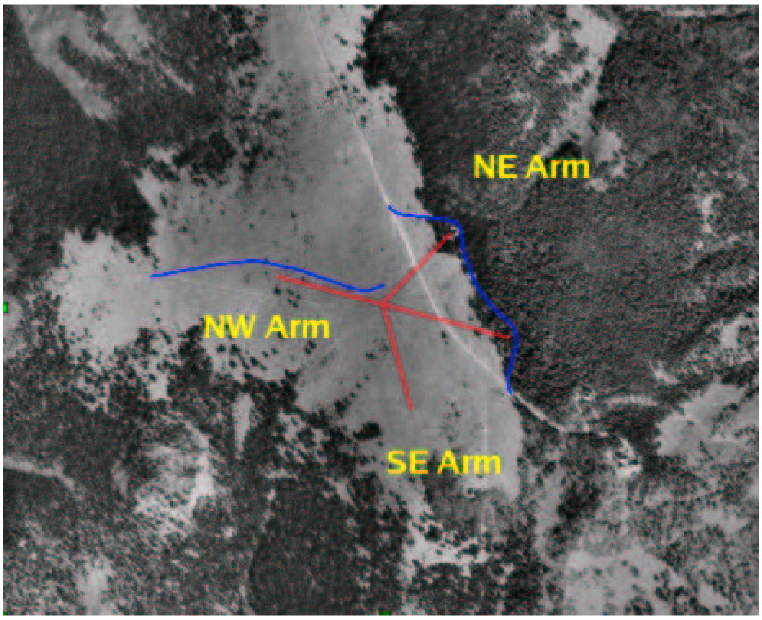

Figure 1. Photograph of the top of Magdalena Ridge with array arms and beam combining facility and new roads indicated.

The current infrastructure and facilities available on the Ridge include power, water and telecommunications running from the town of Magdalena and Water Canyon below. There is also an unpaved road to the summit, which has been recently rehabilitated with new grading and culverts. The Ridge property is maintained by NMT under a US Forest Service permit in the Cibola National Forest and an approved EIS was completed in February, 2004 for the new observatory facility, after which a permit to build was issued (see Westpfahl[5]). The current infrastructure upgrade will support 1 MW power, 200,000 gallons of water on site (both for potability and fire suppression), and ethernet, and is expected to be completed by mid-2005.

Ongoing characterization of r_0 and t_0 on the Ridge are taking place.[4] Preliminary results from a May 2005 DIMM campaign (14 nights of data) indicate that the median value of r_0 was 8.5 cm at 500nm and that the corresponding median value for τ_0 was 3.2 ms. These results are encouraging given that May is the windy season in NM. An "allsky" camera was installed in Nov 2003, and has shown that 67% of the 140 nights of data have at least 3 clear hours; 29% were completely clear. Seismic monitoring at the summit was conducted over a period of 8 months in 2003 as part of the thesis of R. Alvarado and shows the site to be intrinsically very benign for interferometric stability. For further details on the site monitoring program and intended additional tests, see Klinglesmith[4] from this conference.

3. MROI VISION INSTRUMENT

The Magdalena Ridge Observatory Interferometer is intended to be the first facility-class optical interferometer with a design that is optimized for model-independent imaging. This requires that careful attention be paid to throughput, wavefront quality and the impact of all design elements on the primary role of the array as an imaging telescope. Because we are pursuing an aggressive schedule toward first-light, we plan to employ technologies developed at other optical interferometers whenever possible, subject to the limitations of our design requirements and budgetary constraints.

The beam train for MROI has been designed with rigorous attention to throughput because its impact on sensitivity is a large driver for our science reference mission. The primary beam train consists of a telescope, atmospheric dispersion compensators (ADCs), vacuum beam transport, vacuum delay lines (DLs), a beam reducer, beam turning mirrors and pick-off dichroics to send light to various beam combiners and then to science and fringe tracking cameras (Figure 2). In total, there are only fifteen reflections in the primary beam train from telescope primary to detectors. A secondary beam train at each telescope contains the optical tip-tilt and tracking systems. No higher-order adaptive optics compensation is planned at this time.

The telescopes are designed to have modest aperture sizes (nominally 1.4 m) and are in an altitude-altitude configuration with an active secondary and driven tertiary (Figure 3). This configuration has been optimized to give a minimum number of reflections and a benign effect on the polartization state of the incoming light beams. After exiting the telescope, the 10 cm beam will be corrected for atmospheric dispersion using a traditional ADC design, a pair of articulated wedges. Light will then be picked-off via dichroics for tip-tilt compensation via the active secondary. For science observations in the visible, the 400-600 nm band will be used for this correction signal. When science observations occur in the infrared, the full 400-1000 nm band will be available for tip-tilt sensing.

After exiting the telescopes and ADC correction, the beams will enter a vacuum transport system. This system will likely consist of standard aluminum pipe pulled to a vacuum of about $1/1000^{th}$ of an atmosphere. The full array is intended to include one central and eleven kinematic pads on each arm at which to place telescopes. This array layout gives a large amount of flexibility in chosing the interferometer baselines, and five scalable configurations, each with a factor of two resolution advantage over the previous configuration, will be available. The minimum intra-telescope spacing will be 8 m, with the maximum baseline extending out to 400 m.

Vacuum transport will extend into the DL and beam combining facility (BCF). The optimal design of the building facilities is likely to be a traditional room-within-a-room design with suitable insulation and thermal inertia. We are currently finalizing design issues related to the overall thermal and vibrational stability of the building, and are aiming to realise an environment for the beam combiner optics that exhibits diurnal changes

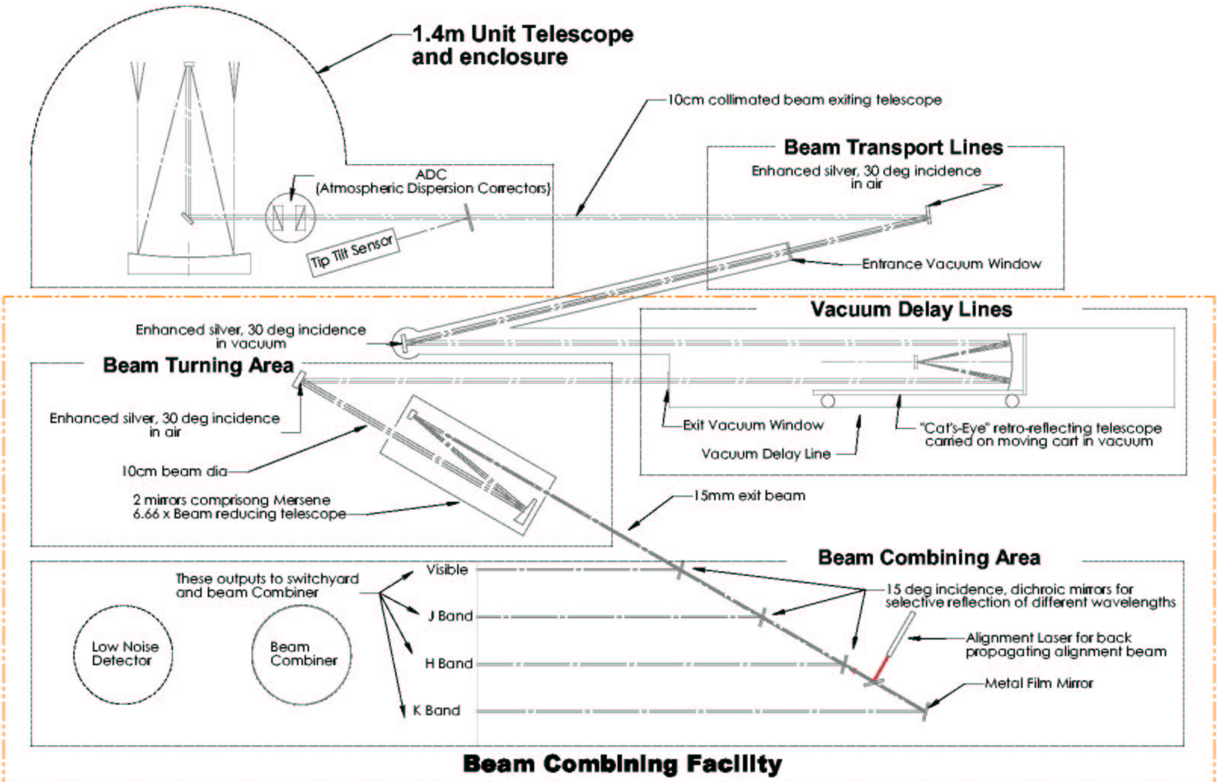

Figure 2. Schematic layout of all components within MROI. Note there are only 15 reflections from primary to detectors.

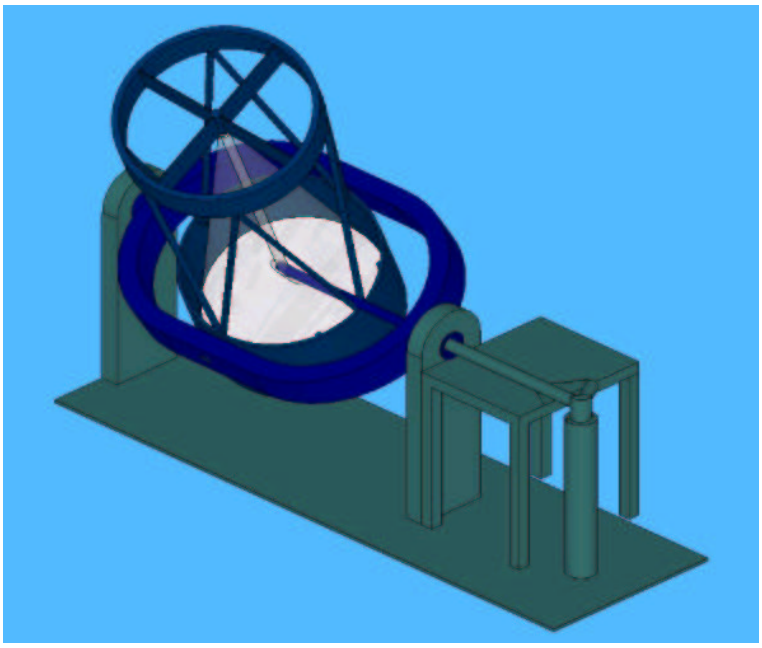

Figure 3. Altitude-altitude telescope design including optical table for the tip-tilt and ADCs.

in temperature of no more than 0.1°C.

After exiting the vacuum DL, the light beams will be further reduced to a 15 mm beam and then transported in air to beam combiners for either fringe tracking or science. The beam combiners themselves are expected to be built with bulk optics, as opposed to fibers or integrated optics. Fringe tracking will occur in the infrared, either at H (1.6 μm) or K (2.2 μm) band. Science will be performed from 0.6μm to 2.4μm with moderate spectral resolution and in narrow wavebands. Multiplexing several outputs onto a single detector, possibly via fibers, is still under investigation as we remain concerned about throughput losses in fiber-based systems.

In order to minimize spurious effects on the visibility due to possible source polarization, all reflections in the system will be at angles of less than 30 degrees, with the exception of the telescope tertiary, and then only for certain orientations of the system. We do not expect diattenuations of greater than 0.5% at 1.0μm wavelength for most pointing directions on the sky.

4. SCIENCE REFERENCE MISSION

The science reference mission for MROI contains three key elements: young stellar objects (YSOs) and planetary companion formation, astrophysics of many different stages of stellar evolution, and the study of active galactic nuclei (AGN) of nearby host galaxies. The goal is to produce model-independent images of these systems by taking advantages of the techniques of baseline and wavelength bootstrapping.[6] Below we outline each of the science cases briefly, and then describe the requirements this science reference mission places on our system.

4.1. Young Stellar Objects and Planetary Companions

The birth of stars is of central importance to astrophysicists, while the formation of planets is of fundamental interest to mankind at large. These phenomena are inextricably linked since planets form from the material left over in the star-formation process. The Hubble Space Telescope has been able to reveal the outer regions (> 10 AU) of accretion disks around new stars, and future millimeter arrays will analyze the physical conditions of cool dust enshrouded zones. With an imaging array like the MROI which operates in the visible and NIR, it will become possible to directly probe phenomena on AU-type scales. Theories of star formation predict that strong magnetic fields around young solar analogs disrupt the inner accretion disks of these stars at 5-10 stellar radii.[7]

Further, gaps and holes in these disks are predicted to be formed by companion objects (either stars or planets), and various disk structures are theorized, but only a limited number have been imaged (e.g. McCabe et al.[8]). The MROI will permit direct testing of many of these theoretical scenarios for the very first time.

Finally, the interactions of jets and disks in YSOs will greatly increase our understanding of the physical processes governing infall onto new stars. With high angular resolution studies in strong hydrogen emission lines it should be possible to discriminate between disk photoevaporation models, where line emission originates from several AU, and direct disk mass-loss scenarios, where radiation pressure forces drive material directly off the disk surface close to the star ($\simeq 0.1$ AU).

4.2. Stellar Astrophysics

At the end of a star's main sequence life, it enters a phase characterized by catastophic mass loss, convective motions of the atmosphere, and outflows that lead to 80% of the star's mass being returned to the galaxy. This also happens to be the least well understood phase of stellar evolution, as it is a multi-stage process governed by complicated and often chaotic processes such as convection, dust formation and pulsation. The MROI will give a first cut at understanding the structure of the extended atmosphere in which this mass-loss takes place: to quantify the number and locations of convective cells, to determine the modes of pulsation and the strength of the incident shock waves, and to determine the character of the mass loss outflow. These questions will be answered through a combination of high-resolution imaging and narrow-line imaging in key emission features which are known, in some cases, to show cyclic behavior.

These questions become more intriguing when a second star is present in the system, as is the case for symbiotics, and classical and recurrent novae. Predictable outbursts are observed in these systems and energetic ejections (as high as 1000 km/s) can be observed with spectroscopic measurements. Hundreds of these systems will be observable with the MROI and we expect detailed studies to characterize binary separations, orbital parameters, the nature of the companions, wind ionization geometries, accretion disk geometries and astrophysical shocks. We will also finally be able to tie the physics of the energetics in the radio frame to the location of the binary components.

4.3. Active Galactic Nuclei

The cores of Active Galactic Nuclei (AGN) and quasars, where gas and dust are believed to be spiraling in onto a massive black hole, are some of the most energetic and enigmatic objects in the Universe. Unfortunately, most of our current knowledge of these systems is indirect, through e.g. spatially unresolved spectra and variability studies of their broad emission lines and their optical/UV and X-ray continuum. The MROI is being designed to exploit the very compact continuum source (and the broad-line region in more distant objects) to permit imaging of the very central regions of more than 100 of the nearest and brightest AGN.[9]

The broad line region (BLR) is a fundamental component of active galaxy models. The technique of reverberation mapping has shown that the BLR in Seyfert 1 galaxies has an extended structure whose luminosity-weighted radius is a few light-weeks in Balmer lines (see, e.g. Peterson[10]). For the lowest redshift AGN, the MROI should be able to measure the size and shape of the BLR directly; and, since it is unlikely that the BLR has a hard edge, fainter emission may be detected on larger scales than reverberation mapping methods sample.

The existence of dusty molecular tori surrounding the cores of active galaxies is indirectly supported through spectroscopy and spectropolarimetry and is invoked to explain the division of AGN into the classes of Seyfert 1 and quasars, and Seyfert 2 and narrow-line radio galaxies. Despite being central to the favored AGN paradigm however none of these tori has ever been directly imaged. Because they are dusty and heated by a central continuum source, the are ideally detected in the NIR. While recent optical interferometric observations have begun to elucidate the structure of two of the nearest of these objects,[11] ,[12] all the conclusions drawn from these observations are based on a handful of visibility points. By imaging these tori directly with the MROI we will be able to answer key questions such as: does the torus really exist; if it does, what is its geometry; what does the molecular cloud distribution look like; what is the relationship between the torus geometry and the source luminosity; what is the temperature profile of the torus?

4.4. Overall performance requirements

The scientific questions above motivate many aspects of the design of MROI. First, the wavelengths needed to answer many of the questions about dust and energetics push us to NIR and optical wavelengths. Spectral resolutions needed to resolve the line features for the strongest lines are only moderate, i.e. R of a few hundred. Spatial resolutions, which are aided by working at shorter wavelengths, require that we be able to observe on angular scales from 10's of milliarcseconds (mas), down to sub-mas scales (e.g. gaps in YSO disks, 0.2-0.3 mas). This implies a need for baselines in the 8-400 meter range. The magnitude limits put the most challenging constraints on our system, including high throughput and wavefront quality, a minimal number of optical surfaces, and apertures capable of gathering enough light. To attain our goal of a statistical sample of AGN (over 100), the MROI must be able to group-delay-track on objects down to 14^{th} magnitude in the 1.6μm (H band). It is this requirement that primarily drives the choice of a telescope aperture of 1.4 m.

5. TECHNICAL PROGRESS AREAS

Optimizing *all* of the individual components of the MROI will be necessary to achieve our top level science goals, and as part of our design work we have been focusing on the most important of these. Brief reports on some of these are presented below:

5.1. Telescope and Dome Design

Our preferred telescope design for MROI is an altitude-altitude telescope (see Figure 3) with 1.4 m primary aperture, a focal ratio of roughly $f/2.5$ and an interferometric field-of-view of roughly ± 2 arcseconds. The primary will likely be aluminized, while the tip-tilt secondary and active tertiary will both be coated with protected silver. While this particular telescope design is familiar in laser-ranging applications, it has been used astronomically for decades in the European Southern Observatory's (ESO) 1.5 m Coude Auxiliary Telescope (CAT) at La Silla.[13] We expect to be able to locate the array unit telescopes within a 6 m diameter dome and hence realize our shortest spacing of 8 m without vignetting from neighboring telescopes. Traditional dome designs are currently favored, although a roll-off roof design has not been ruled out as yet. At the present our concept for the telescope transporter is to use in-situ wheels or a "boat-lifter" rather than permanent rails like the VLA. This decision is driven primarily by cost analysis. We are currently quantifying g-loading and repeatability characteristics associated with each transporter method and will down-select soon.

5.2. Coatings and Throughput

The COAST team at the University of Cambridge has been utilizing highly optimized coatings to increase throughput for their prototype interferometer. They have been able to design coatings with near identical performance for both s and p polarizations and have realized close to theoretical performance in actual devices. We have recently designed a new set of dichroic coatings for use at MROI[14] (Figure 4). These coatings are multilayer but utilize only two materials. The particular coating described here will deliver better than 99% throughput throughout the near-infrared (J, H and K bands) while reflecting well above 99% integrated reflectance from 600 to nearly 1000 nm.

The throughput for MROI is one of the most important parameters to track in order to attain our sensitivity limit of 14^{th} magnitude at 1.6μm (H band). We are optimizing our system to reach this goal by minimizing the number of system reflections, designing highly optimized coatings for our application, and using the lowest-noise detectors available (see below). Detailed reasonable (*not* ideal) assumptions about reflection losses in our system gives a 19% total system throughput using current technologies. With modest upgrades to certain components of the system (e.g. anti-reflection coatings on detectors to achieve better than 65% quantum efficiency) we expect to easily meet our design throughput goal of 20%.

5.3. Delay Lines

As yet, no DL are employed at any interferometric facilities that allow for both delay compensation and atmospheric correction at required bandwidths on a single carriage. For MROI development, this picture is further hampered by the very low number of interferometric facilities that employ any vacuum DL (currently only KI differential phase, CHARA and NPOI have vacuum DL) - again none of them in a single DL. Because of our high throughput requirements and long DL lengths, we have undertaken a design study to put both these functions into a single DL. As such, the COAST group at Cambridge is currently designing and testing a single-stage vacuum DL prototype that utilizes inductive coupling for power distribution and and radio frequency communication and control. The optical system envisaged is the standard parabola-flat (cat's eye) configuration, but the carriage utilizes wheels which run on the inside of the pipe, obviating the need for rails. The wheels allow for torsional control of the cart with respect to the incoming beam. An active secondary is employed for beam steering correction due to non-uniformities in the inner pipe surface. See Haniff et al.,[15] this conference, for more details of this design.

5.4. Beam Combiners

The beam combiners currently being considered for the MROI have been made from bulk optics (Figure 5). The combiners themselves are fabricated from a single piece of glass, which in the final phases of manufacture, is precisely cut, coated, and optically contacted. This type of beam combiner has the advantage of containing a limited number of degrees of freedom - so there is ease in alignment and calibration due to its intrinsic stability. It is likely that the science beam combiners (optical and NIR) for the MROI will accept 8 beams, with an external switchyard to permit rapidly switching in 2 more beams, producing a hybridized 10-way combiner (for a total of 10 telescopes). This will allow us to switch in a large fraction of the total baselines and closure phases for high observing efficiency. For more details on the optically contacted beam-combiner design see Haniff et al.,[15] these proceedings.

5.5. Detectors

The detectors required for MROI need to be both intrinsically quiet and capable of high readout rates. We will employ optical detectors for our tip-tilt sensing at each of the telescopes and optical science cameras capable of delivering moderate spectral resolutions in the BCF. The infrared detectors will be used in both the fringe-tracking cameras and in the science cameras, again with moderate spectral resolving power. To this end, we have identified at least two possible detectors that we might be able to use for the MROI.

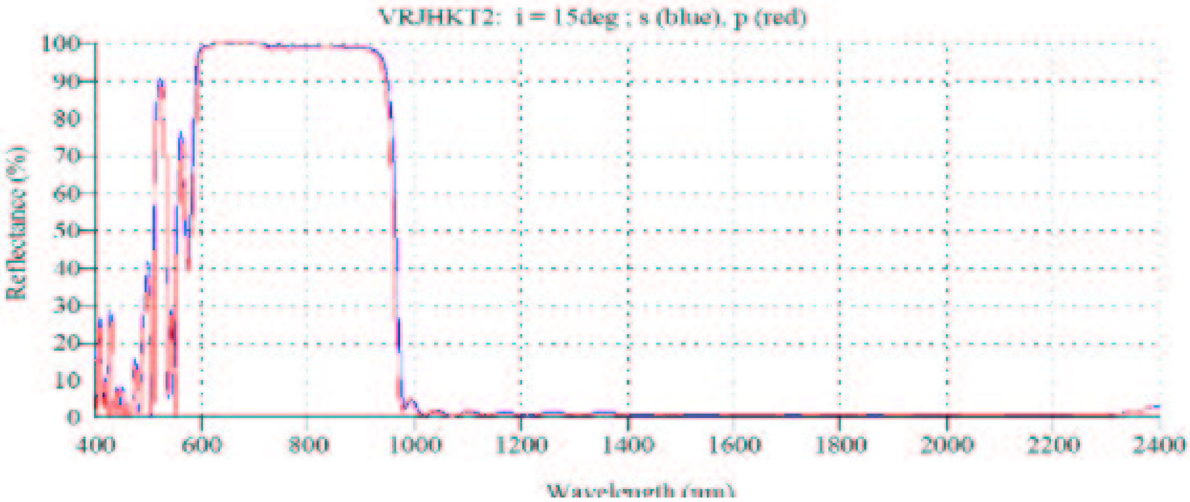

Figure 4. Newly designed multi-layer dichroic coating for MROI (see Hobson & Baldwin[14]). S and P polarizations overlay nearly exactly, indicating no difference in coating performance due to incident polarization.

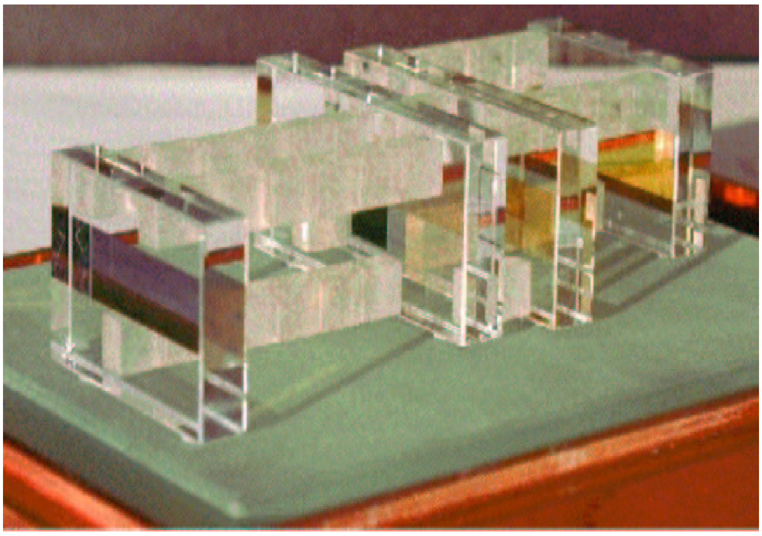

Figure 5. Prototype optically-contacted beam combiner on which MROI will base a hybrid design for an 10-way beam combiner. This beam combiner has a footprint of 10 by 15 cm.

The optical detector we will likely use is the E2V back illuminated CCD87 available off-the-shelf in complete systems from two companies, Andor and Princeton Instruments. This CCD has on-chip gain which delivers zero readout noise at any readout rate. Custom readout electronics are being tested at COAST to assess these detectors, and the first results from this system are reported in Basden et al..[16] The infrared detectors we wish to use are still under development. These are the Calico Adaptive Optics (AO) array being produced by Rockwell Sciences Center.[17] These arrays are specified to have 1 electron of read-noise at 500 kHz pixel rates. Eight designs for this device are currently under study at Caltech and ESO.[18] If the infrared array technology is not mature by the time we go for first fringes, our current fall-back position will likely rely on the Rockwell Sciences HAWAII or PICNIC array technology, which has been shown to achieve 3 electrons of readnoise at IOTA.[19]

6. PERSONNEL AND SCHEDULE FOR PHASED BUILD

6.1. Personnel

When completely filled, staffing for the MROI at NMT will include about 15 full-time equivalent positions. Our current staffing includes a full-time Project Manager (Mark Sirota), two System Architects (Chris Haniff and David Buscher), a Project Scientist (Michelle Creech-Eakman), and lead optomechanical and control engineers (Jonathan Kern and Thomas Coleman). We anticipate hiring our full complement over the next year in the following areas: electrical engineers, a camera systems engineer, controls engineers/programmers, postdocs and technicians. We also have access to the personnel resources of our partners in the COAST group at the Cavendish Laboratory at Cambridge.[15]

6.2. Phased Build

The description of MROI above presents our "vision" instrument. We intend to achieve this vision in a two phase approach. Phase A of the array will deliver 6 telescopes, baselines of up to 225 m, and will concentrate on infrared science. This phase of the build will, however, be inclusive of all our design goals outlined above. That is, all the coatings, glasses, beam transport, DLs, facilities, combiners and detectors implemented in Phase A will be fully compatible with the final vision instrument. Our Phase A schedule anticipates letting telescope contracts and beginning to build the BCF in early to mid 2005, receiving telescopes serially about 2 years thereafter, with first fringes in 2007 and first closure phase in 2008.

The second phase of delivery, Phase B, will be incremental, and will principally include procurement of four additional telescopes, optical science cameras, the extension of the baselines to 400 m and extension of the DL facilities to accommodate this extended delay range. The precise schedule for phase B is not yet defined and will depend upon the specific timeline for our future funding and partnership profile.

7. CONCLUSIONS

We have presented an overview of the design of the MROI, the first facility-class interferometer optimized primarily for imaging. Our science reference mission will concentrate on YSOs, AGN and complex stellar phenomena. The interferometer team at NMT will completely staff-up over the next year. Many of the most critical areas of the array design, including the design of the telescopes, the delay lines, the beam combiners, the detectors and coatings, have been under study for a while and clear routes forward have already been defined. We expect to start letting build contracts for the unit telescopes and the beam combining facility in 2005, with the first telescopes arriving in 2007 and our first closure phase predicted for 2008.

8. ACKNOWLEDGEMENTS

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