The Magdalena Ridge Observatory Interferometer: a high sensitivity imaging array

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ABSTRACT

The Magdalena Ridge Observatory Interferometer (MROI) is a US federally funded project to construct the world's most ambitious optical/IR (0.6-2.4micron) imaging interferometer at a 10,500ft-altitude site in New Mexico. In its initial phase it will consist of 6 telescopes, each 1.4m in diameter, separated by distances ranging from 7.5m to 340m. A second phase will upgrade the interferometer to a 10-telescope configuration, allowing a "snapshot" imaging capability. The MROI will deliver images with sub-milliarcsecond angular resolutions while simultaneously providing images over 5-70 spectral sub-bands. A key feature is that the array will have sufficient sensitivity to image a wide range of targets, including extragalactic targets and, potentially, geosynchronous satellites. We report on the design and current status of the array.

Keywords: aperture synthesis; stellar interferometry; instrument design; imaging; MROI

1. INTRODUCTION

The first generation of "facility" optical interferometers, including the VLTI and the Keck Interferometer are now on-line, allowing astronomers to do science at milliarcsecond resolutions. Between January and August 2006 alone, more than 29 papers with astrophysical results from interferometry have been published in the refereed literature (see http://olbin.jpl.nasa.gov/papers/2006.html for an up-to-date list), together with many more papers on the techniques of interferometry.

Nevertheless, there are significant gaps in the scientific capabilities of existing arrays. The most pronounced of these is the lack of a routine capability for making images of astronomical targets. The vast majority of astrophysical results from interferometers have so far come from fitting simple geometrical or physical models of objects to fringe visibility data. While model-fitting has undoubtedly resulted in valuable scientific insights, model-independent imaging is required in order to determine the validity of the models themselves.

A second area where improvement would be welcomed is in accessing faint targets. Ground-based interferometry is of necessity limited to observing relatively bright targets because of the requirement to take exposures shorter than the atmospheric integration time of a few milliseconds or tens of milliseconds. Perhaps surprisingly, the advent of interferometers which make use of 8-m class telescopes has not yet significantly improved the limiting magnitude of interferometers when compared with their 0.5-m class predecessors, but this is partly to do with teething problems and may reflect the compromise that 8-m class telescopes have to serve other roles than interferometry. What is clear is that interferometers which are able to observe fainter sources will be able to do exciting science which is not available in any other way. For example, only the brightest few AGN have been observed interferometrically, when it is clear that access to a representative sample will make a substantial difference to our understanding of the physical processes going on in the cores of these galaxies.

The Magdalena Ridge Observatory Interferometer (MROI) is an array which has been specifically designed to address these two problems. Grossly speaking, the design combines a large enough number of telescopes to

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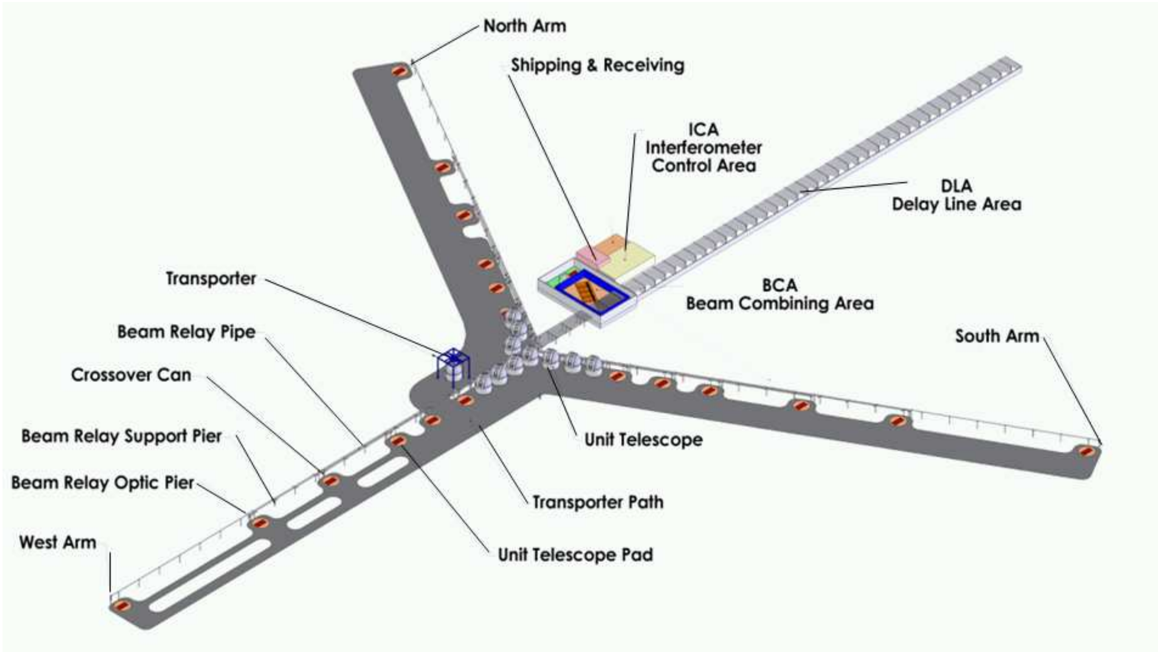

Figure 1. The schematic layout of the MROI. In this view, all 10 telescopes are shown together with a wheeled transporter based on a container crane design. Each arm of the "Y" shaped array is 200 m long, as is the building housing the delay lines.

achieve the required Fourier plane coverage for imaging, with a high throughput optical system and low noise back-end for sensitivity on faint targets. No other existing or planned array has this combination of features, and this makes the MROI a unique array for imaging science at high angular resolution. In this paper we briefly describe the major design features of the interferometer and give an indication of the types of science it will be capable of.

2. SYSTEM DESIGN

The MROI is sited at 10,500 ft altitude on the Magdalena Ridge, a dark site in central New Mexico which has frequent sub-arcsecond seeing. The basic design of the interferometer comprises an array of 10 telescopes, each 1.4m in diameter, feeding light via vacuum pipes to a central facility where appropriate optical path delays are introduced using delay lines and where beams from different telescopes are combined to make interference fringes. Different beam combiners will combine the light in different photometric bandpasses in the wavelength range from 600 nm–2400 nm. Each beam combiner will incorporate a spectroscopic capability to allow simultaneous interferometric images to be made in up to 100 spectral channels, with a spectral resolving power ranging from R=30 to R$\sim$1200. The telescopes are designed so that they can be relocated between a set of discrete stations which are arranged in a 'Y' configuration, with each arm of the 'Y' being 200 m long. This gives a maximum inter-telescope spacing (i.e. a maximum "baseline") of 340 m. A cartoon of the overall layout of the MROI is shown in Fig. 1.

While the maximum angular resolution of an interferometer depends on the maximum baseline, the performance of an interferometer in making high-quality images is dependent primarily on

- The number and *diversity* of the baseline vectors which can be sampled (the so-called (u, v) coverage).
- The number and diversity of phase-closure triangles of baselines (the "bispectrum coverage").

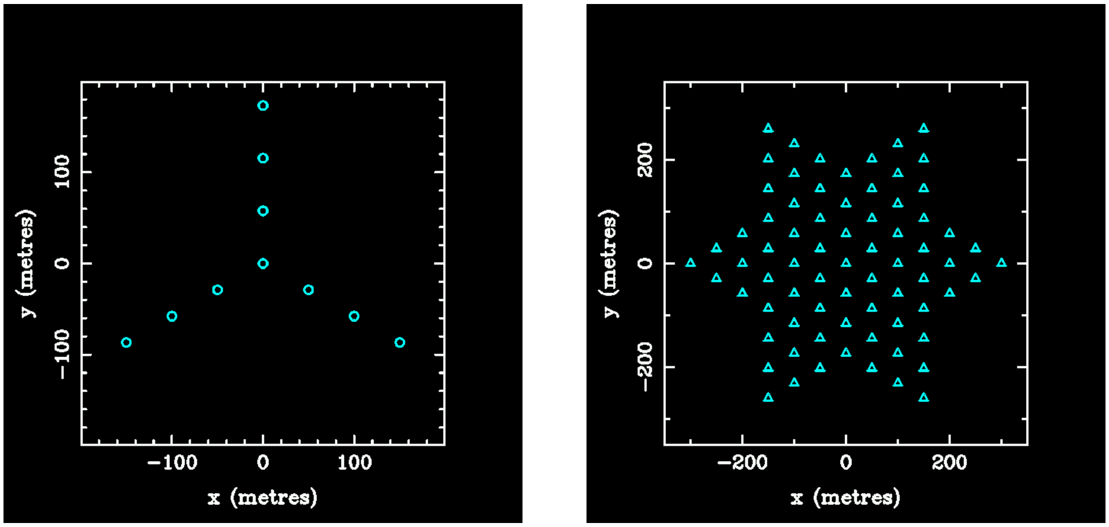

Figure 2. Telescope array configuration (left) and instantaneous (u, v) coverage for a source at the zenith (right) for the MROI array when ten telescopes are present. The array shown has maximum baselines of order 340 m, but scaled configurations with maximum baselines down to ∼40m are also available by relocating the telescopes. This scaling facility allows the tuning of the array to the scale of the objects being observed.

Both of these are strong functions of the number of telescopes which can be used simultaneously in the array.

The MROI, uniquely in the world, has been designed from the outset to combine the outputs from 10 telescopes simultaneously. Its nearest competitors, when they reach their maximum planned capacity, will be able to use a maximum of 6 telescopes simultaneously, and thus MROI will have the capacity to instantaneously sample a factor of 3 times more baselines and 3.6 times more closure triangles than any planned array. The instantaneous (u, v) coverage of the MROI is shown in Fig. 2 where it can be seen that "snapshot" imaging of many sources should be possible.

The number of baseline and closure-triangle points sampled is only part of the imaging advantage of the MROI design. A second advantage lies in the range of baselines that are available which translates directly to the range of angular scales which can be accessed by the array. The MROI telescopes are designed to be relocatable between a set of discrete foundations allowing the array to be "zoomed" between 4 different configurations (in the same way as the VLA), ranging from a compact array with minimum baselines of 8m to an expanded array with maximum baselines of 340m.

Equally importantly, the available baselines at the MROI can be arranged in a so-called "bootstrapping" configuration. In this configuration, the longest baselines are constructed from a "chain" of shorter baselines, which allows observations to be made of faint objects which have significant amounts of both large-scale and small-scale structure.

The other major factor in the MROI design is the limiting magnitude. Ground-based interferometers operating at optical and IR wavelengths are fundamentally limited in the faintness of the objects they can observe because of the effects of atmospheric seeing. When this is compounded with poor system throughput, this can severely limit the range and number of astrophysically-interesting targets which can be studied. The MROI will have a limiting magnitude comparable to or better than any other array worldwide due to combination of factors:

1. Fringe acquisition and tracking is performed by a dedicated group-delay fringe tracker using light from a different waveband from that used for science. Group-delay tracking gives about a 2.5 magnitude increase in limiting magnitude compared with phase-tracking techniques.

2. The telescope apertures (1.4m) are well-matched to the atmospheric seeing scale size at the optimum wavelength for fringe-tracking.

3. The MROI design approach stresses maintaining *interferometric* throughput (a decreasing function of the light losses in the system and — even more strongly — of the wavefront errors introduced by the optics) above almost all other criteria. This is reflected in:

   - An optical design which is radically simplified compared to most arrays, minimizing the total number of optical surfaces between the sky and the detector, and hence reducing both light loss and wavefront degradation.
   - The use of vacuum systems for both beam transport and delay lines, minimizing wavefront distortions due to air currents.
   - The use of a nightly automated optical alignment procedure, allowing strict quality control of the system wavefront errors.
   - The development of optimized multilayer anti-reflection and dichroic coatings.

4. The interferometer control system is highly automated so as to allow a large number of observations to be made per night with high efficiency. This improves both the amount of on-source time and the effectiveness of visibility calibration procedures.

More details of the MROI design can be found in Refs. 1 and 2. Below we report on the status and recent progress of the interferometer and its subsystems.

3. INTERFEROMETER BUILDINGS

An important part of the infrastructure of the interferometer is the Beam Combining Facility (BCF, see Fig. 3) which includes three components:

- A delay line area (DLA), which houses the optical delay lines. The DLA comprises the largest floor area in the BCF, being 192 meters long by 9.3 meters wide. This serves to protect from the elements the 10 delay line vacuum systems, each comprising 190m of 40cm-diameter pipes on 61 cm centers, together with room for access to the pipes. Thermal requirements on this area, a $\pm 1^{\circ}$C diurnal temperature change, are modest and these requirements are met with a thermally-passive single-skinned structure, insulated to R=40 on the walls and roof. The footings of the walls are insulated to R=10 to create a "thermally trapped" mass of soil beneath the building. This thermal mass contributes to a very long thermal time constant for the DLA which assists in filtering out the effects rapid thermal changes in the environment.

- A beam combining area (BCA) houses all the optics after the delay lines, including the the beam combiners and cameras, together with the beam compressors, the primary alignment system and other alignment aids. There are 3 $2\,\mathrm{m}\times 4\,\mathrm{m}$ optical tables for beam combiners, with a 4th table available for visitor instruments.

  The BCA has a number of stringent thermal requirements, primarily because all the optics are in air and so the effects of air temperature fluctuations on the optical wavefront and on the system alignment are critical. The BCA has a room-within-a-room design (similar to that used at the SUSI and CHARA interferometers) with an actively cooled outer room and a passive inner room acting as a thermal "low-pass filter". Thermal modeling indicates that this will meet our requirement for less than 0.1°C diurnal temperature changes within the inner room.

- The Interferometer Control Area (ICA) which includes the interferometer control room, offices, electrical and optical labs, shipping and receiving, and kitchen and bathroom facilities. On the far end of the ICA is the mechanically and structurally isolated mechanical room in which the HVAC, vacuum pumps and other large mechanical equipment is housed.

Great care is also being taken to provide a vibrationally benign environment for the optics. Measures taken to effect this include isolating all sections of the buildings from each other and moving vibration-generating equipment as far as possible from vibration-sensitive systems.

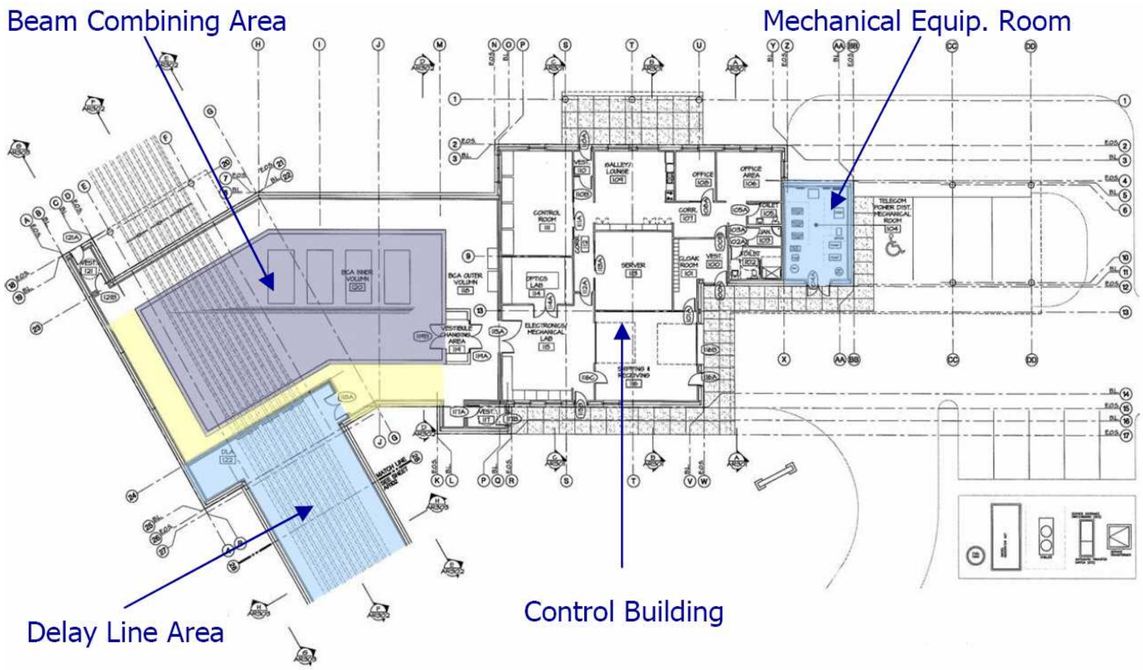

Figure 3. Architectural plan for the central part of the MROI Beam Combining Facility (BCF). The Delay Line Area extends below the figure for a total length of 192 m.

Included in the design work for the buildings is the "array infrastructure": the concrete supports for the vacuum transport pipes along the array arms, roadways for the telescope transporter, and telescope pads. There will be a total of 28 pads on the MROI site for the 4 configurations of the telescopes and approximately 200 concrete piers on which to support vacuum cans and pipes.

The architects selected to design the BCF were M3 Engineering and Technology Corporation of Tucson, AZ, who have extensive experience with astronomical facilities such as Gemini. A critical design review of the building design was held at NMT in March, 2006, and following this a bid package was released in May 2006. K. L. House Construction Co., Inc. of Albuquerque, NM was selected as the general contractor and Notice to Proceed was issued on August 5th, 2006. Mobilization of construction equipment began in the week of August 21st, with completion of construction expected in September 2007.

4. UNIT TELESCOPES

In order to achieve the increases in limiting magnitude required to access key science targets, we need to improve the "interferometric throughput" of interferometers, that is, we need to reduce the often large instrumental losses of both stellar light flux and wavefront quality which degrade the interferometric signal-to-noise ratio (SNR). One key factor in achieving low losses is to reduce the number of reflections of the optical beam between the sky and the detector to the absolute minimum. Each reflection degrades the interferometric throughput in 3 ways: it reduces the photon throughput due to reflection losses, it introduces high-order wavefront aberrations due to mirror figure errors, and it degrades the low-order wavefront quality by adding an extra surface which needs to be aligned (in tip and tilt for flat mirrors as well as focus and other degrees of freedom for curved surfaces). Remembering that the fringe visibility losses scale approximately as the square of the RMS wavefront error and the interferometric SNR scales as the square of the fringe visibility, we can see that the most deleterious effects of adding extra reflections are to do with wavefront quality degradation.

Fig. 4 shows a schematic of the optical train of the MROI. The total number of reflections experienced by starlight between the sky and the entrance of the beam combiner instrument is 13, which compares favorably with other interferometers. For example, the comparable value in the VLTI is 22 reflections[3] and in the Keck

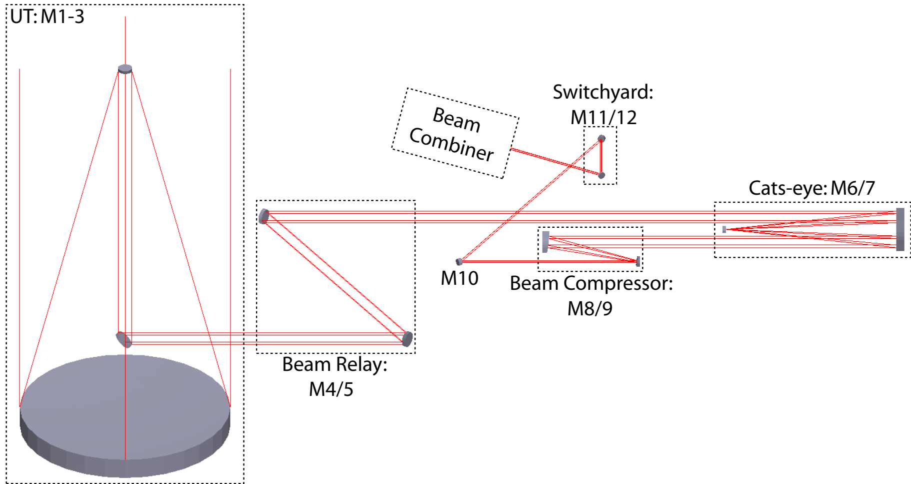

Figure 4. A schematic view of the optical train of the MROI, showing the reflective surfaces encountered by light going from a star to the entrance to a beam combiner. The light beam goes through only 13 reflections in this train (there are only 12 mirrors because the beam bounces off M6 twice)

Interferometer the starlight beam encounters 19 reflective elements *after* exiting the adaptive optics systems on the telescopes.[4]

An important part of minimizing the number of reflections in the MROI optical train is the fact that the telescopes (the "Unit Telescopes" of the array) require only three reflections to get from the sky to the horizontally-propagating exit beam, as a result of adopting an elevation-over-elevation design as shown in Fig. 5. This can be compared to the requirement for at least 6 reflections (typically 7 or 8 are needed in most practical implementations) to achieve a fixed horizontal exit beam for a more conventional elevation-over-azimuth design.

The diameter of the unit telescopes is 1.4 m, which is trade-off between the goal to reach targets as faint as 14th magnitude at H (1.6 microns wavelength) and the constraints of the atmospheric seeing when only tip-tilt correction is available. The relatively small size of the telescopes also aids in close-packing the telescopes to achieve a 7.5 m shortest baseline and in facilitating transportability.

An unusual component of the design is the requirement that the telescopes be relocatable within approximately 8 hours, so that the entire array can be reconfigured in a few days. The operational model for the array is to operate in different array configurations for different semesters, in a very similar manner to the VLA radio interferometer. The enclosures for the telescopes are designed to be relocated along with the telescopes, thereby affording protection during transportation and minimizing the total number of enclosures needed.

The RFP for the unit telescopes, enclosures and associated relocation system was reviewed by three independent experts before being released as an RFP (Request for Proposals) in Aug, 2005. Unfortunately, this RFP did not succeed in proceeding to a final contract with a vendor. The RFP is being restructured and will be re-issued in September/October 2006.

New Mexico Tech is committed to procuring 6 unit telescopes in the first phase of the interferometer construction. The aim would be to seek additional funding to purchase the remaining 4 telescopes in a second phase.

5. DELAY LINES

Another contributor to the goal of having an exceptionally low number of reflections in the MROI optical train is the decision to perform all the geometrical delay and atmospheric compensation in a single-stage delay line, in contrast to many other interferometers which have multiple delay stages in order to provide the large optical

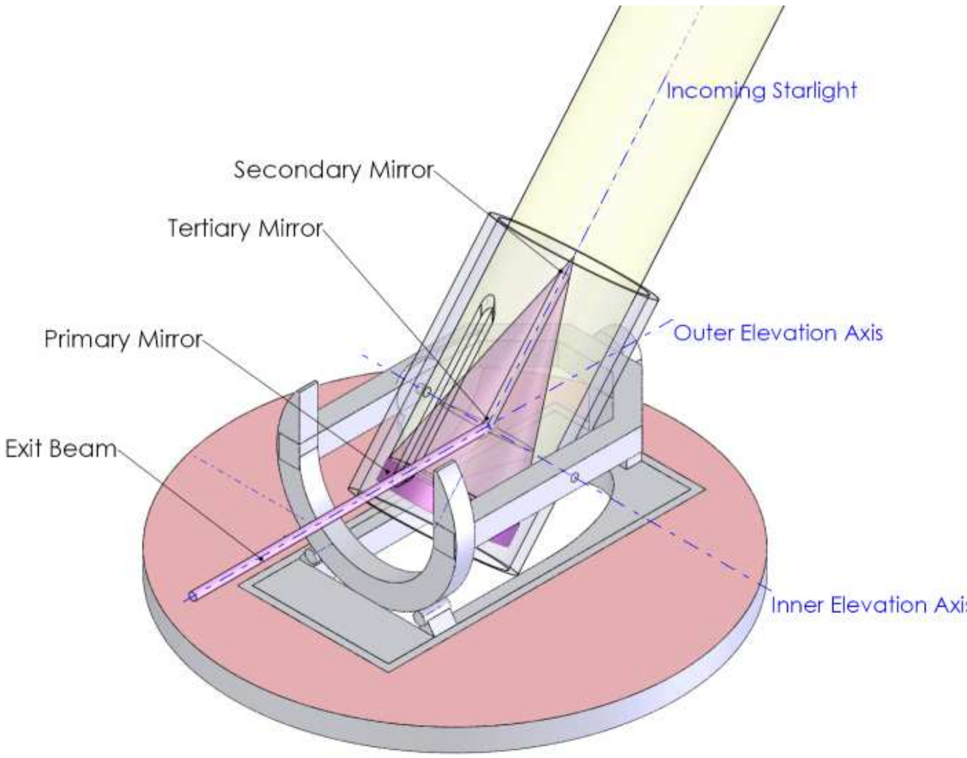

Figure 5. Cartoon of the unit telescope showing the elevation-over-elevation geometry.

delays of many hundreds of meters. These delay lines are being designed and built by Cambridge under contract to NMT and are discussed in detail in Ref. 5. Innovative features of the design include compliant wheels which run directly on the inside of the vacuum pipe and a steerable secondary which is capable of correcting for ± 5 mm excursions in the pipes straightness. Other innovative features included in the design are an inductive pick-up for power, which runs along a wire in the bottom of the pipe, and RF communication between the outside world and the moving "trolley".

Because this design is new to the optical interferometric community, two risk reviews were held to determine if the concept was feasible before moving ahead. In the first review in Nov, 2004, risk-reduction experiments were identified by Cambridge and an external team of experts to determine what parts of the concept were most risky or likely to fail. In the second review in July, 2005, the results of these experiments were presented to the external team. This team gave NMT a 'green light' to have Cambridge proceed with the prototype cart design. The prototype is now coming together: in particular the Cat's-Eye retroreflector is now complete and under test in the lab (see Fig. 7. We expect to take receipt of the first fully tested cart for MROI in October 2007.

6. BEAM COMBINERS

The 95mm collimated beams of light from the telescopes after pass through the delay lines and are then compressed to $\sim$13mm diameter. The light is then split spectrally between a number of beam combiners:

1. A near-IR fringe tracker
2. A near-IR science beam combiner
3. An optical science beam combiner

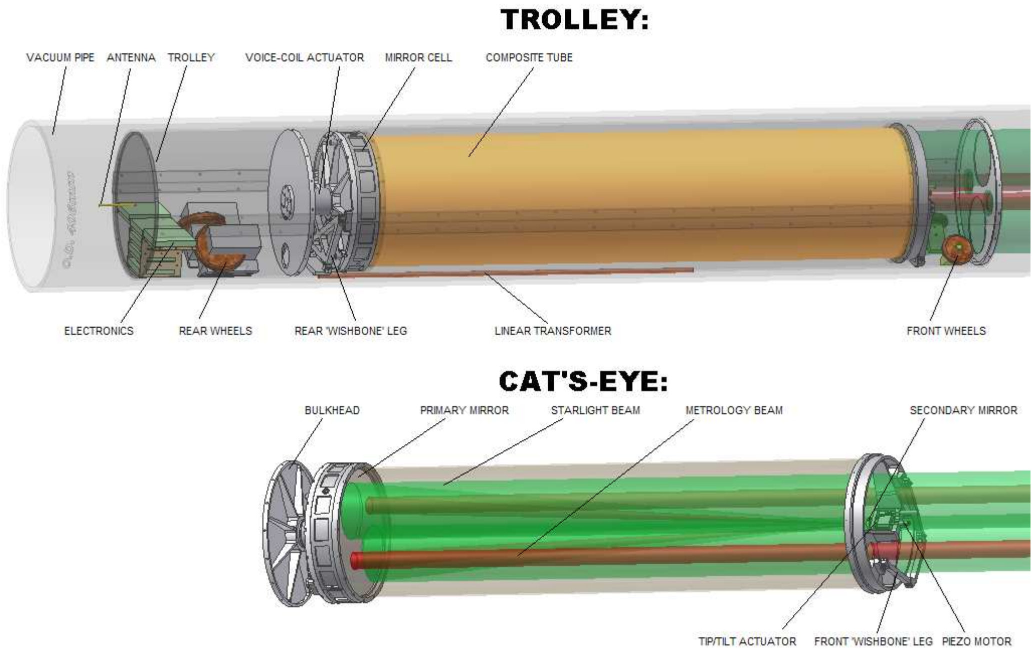

Figure 6. Concept diagram for the prototype delay line trolley, showing the physical locations and space envelope of the active elements. The top part of the diagram shows the complete trolley (comprising the Cat's-eye and carriage) inside the vacuum pipe, and the lower part is an expanded view of the Cat's eye. The diameter of the carriage tube is approximately 14 inches, and the approximate wheelbase of the carriage is 1.8 m.

The infrared beam combiner and camera designs are under study by NMT and Cambridge in collaboration. The fringe tracker beam combiner is optimized for group-delay fringe tracking, which allows tracking on sources approximately 2.5-magnitudes fainter than are accessible to phase-tracking systems.[6] It will be switchable between tracking in the H band (1.4-1.8 μm wavelength) and the K band (2.0-2.4 μm wavelength) in order to allow science operations in either the K band or the J and H bands respectively without having to share light between the combiners. Dispersion of the group delay fringe will be across approximately 5 pixels at H or K band.

Various pupil plane and image plane combinations using 4 to 8 way simultaneous combination for the near-IR science combiner are being studied, primarily at Cambridge(see Ref. 7. Camera designs for the optimal system to receive the interfered beams are being studied at NMT. These include 4 and 5 way bulk optics schemes to bring the outputs of the beam combiners into the cryogenic fringe-tracking camera (see Fig. 8).The cold portion of the camera will be optimized and baffled for thermal backgrounds as we expect to be operating in the thermal regime at K band (2.0-2.4 microns). The infrared science camera will have selectable dispersions with spectral resolving powers of roughly 30 and 300, and perhaps higher dispersion around 1200. Optimal schemes including grisms, gratings, prisms and cold fibers are still being investigated. Down-select of the optimal design for these systems will be held in Aug.

Optical beam combiners and cameras for science are not part of the first phase of MROI. We are investigating teaming options and external funding for these optical instruments.

7. DETECTORS

The detectors for MROI are integral to our successful tracking of 14th magnitude objects. Our current plans require us to reach 1 electron read-noise levels with arrays when multiply sampled (though we only lose 0.5 magnitudes when operating at 3 electrons read-noise). The infrared array market is on the brink of being able to

Figure 7. The Cat's-Eye assembly for the MROI delay line under test in the laboratory. The tube for the retroreflector is an approximately 1.2 m in length and 30cm in diameter, and built from carbon-fiber reinforced plastic (CFRP) for stiffness.

produce arrays of this capability in a repeatable way. Follow-on technologies to the Hawaii and PICNIC arrays are being optimized for wavefront sensing and infrared adaptive optics applications (Finger et al. 2004). We expect to let a common set of RFPs in a consortium with Gemini/NOAO and ESO for these devices in the summer of 2006, with anticipated delivery in about 18 months. For the optical science instrument, we expect to capitalize on the electron-multiplying CCDs currently available on the market.

8. CONTROL AND OFFLINE SOFTWARE

The need for a real-time, massively parallel control software architecture with which to run the distributed architecture of the MROI is a well-known issue for interferometers. Because we have the goal of making the MROI a facility-class instrument which is highly automated for efficiency, and available to general astronomers for use, it was important to pick a control software architecture that was capable of the multiple needs presented by such an optical interferometer. In March, 2005 a review and trade-offs of available software frameworks (including EPICS, and the software being used to operate the Keck Interferometer, ALMA and IOTA) for this task was made, and we decided to pursue the use of the Real Time Control (RTC) software developed by the Jet Propulsion Laboratory (JPL). This software has been used to run the Keck Interferometer, the delay lines on the CHARA array, and several interferometry testbeds at JPL. NMT has subsequently entered into an agreement with JPL to learn how to use the software, develop certain modules within the framework, and have RTC ported over to a real-time Linux operating system. The main advantages for NMT in this development are the lower cost of Linux-compatible hardware, the knowledge of a system already in use at other interferometric facilities, and the savings of many person-years worth of effort in its development. For more information on the original development of RTC see Lockhart.[8]

9. STAFFING

The MROI has moved forward tremendously in the last two years in many of its design and development efforts. Continuing on the current schedule, we plan to hire approximately 5 more employees (engineers, programmers and scientists) before the end of 2006. We also anticipate openings among the faculty in the Cambridge and

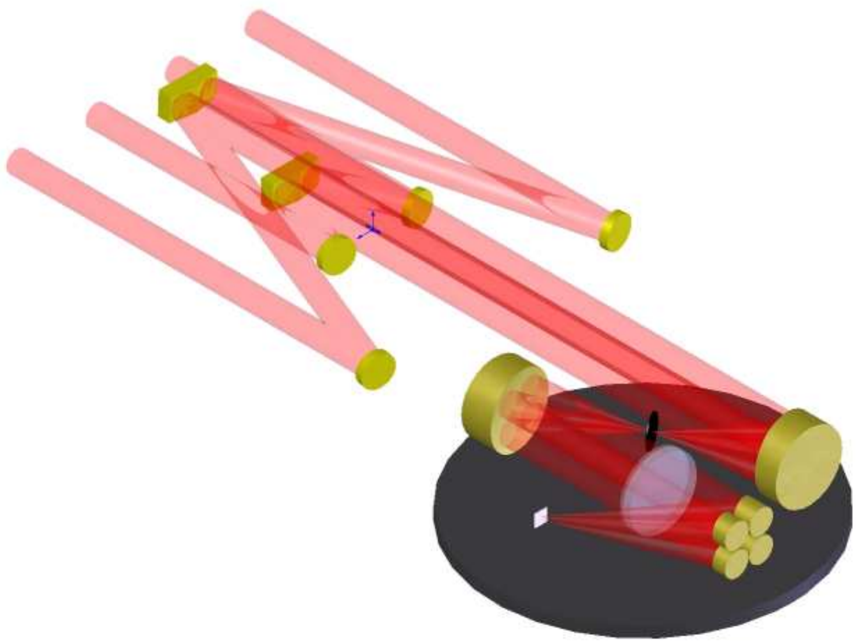

Figure 8. A conceptual design of a four beam feed system from the beam combiners into the Fringe Tracking cameras. The portion to the RHS over the dark circle is presumed to be on the cold surface and includes parabolas, a pinhole, a Direct View Prism and the array.

NMT Physics departments, with positions also available for postdocs and students in both locations. The total complement of FTE on the MROI team at NMT will be approximately 15, with another 6 FTE at Cambridge.

MROI will be the first facility class optical interferometer developed and optimized solely for an imaging campaign. We welcome community input for external design reviews and collaborations. Please contact Michelle Creech-Eakman, Eric Bakker, Chris Haniff or David Buscher for questions or further details. All contact information is available via the MRO website: http://www.mro.nmt.edu.

10. ACKNOWLEDGEMENTS

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