# PPRP Application: Support for Cavendish Involvement in Phase 1 of the Magdalena Ridge Observatory Interferometer

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## Introduction and Case for Support Sections only

# 1 Introduction

## 1.1 Project history and context

The Magdalena Ridge Observatory Interferometer (MROI) is a world-class optical/infrared interferometer being built by collaboration between the New Mexico Institute of Mining and Technology (NMT) and the Astrophysics (AP) Group of the Cavendish Laboratory, Cambridge. Our (i.e. the AP Group's) involvement in the MROI originates from a request made by NMT in 2001 for us to assist them in designing a state-of-the-art optical/IR interferometer in New Mexico. After six months of negotiation, the Cavendish reached agreement with NMT in early 2002 that a collaboration could be initiated as long as the top-level science goals of the array were those that had been developed by the UK astronomical community for the Large Optical Array (LOA) JIF bid, concentrating on the unique science that would be obtained from an imaging optical/IR array located at a world-class site. In addition, it was agreed that the majority of the capital costs for the facility would be provided by NMT, with the Cavendish providing an in-kind contribution of interferometric design expertise.

Our participation, and long-term committment, in the MROI was the subject of a Statement of Interest submitted to the Science Committee in the late summer of 2002. The SC responded by recommending support for Cavendish participation via the Rolling Grants programme, but at our Rolling Grant submission in 2003, uncertainties as to how the MROI fitted into the UK's strategy for optical/IR interferometry and the future development of the VLTI made it difficult for the RAP to assess the merit of our proposal. Nevertheless we were awarded 2 years of Rolling Grant funding to continue our work with the MROI consortium and this was subsequently extended by a bridging grant to run until April 2006.

Throughout all of this period, the Cavendish has played a major role in the MROI project. Since January 2003, Dr David Buscher and Dr Chris Haniff have led the top-level system and technical design of the MROI, acting as joint System Architects for the array. We have signed a Memorandum Of Understanding between NMT and the University of Cambridge for the joint development of Phase 1 of the MROI which covers the construction of the full array infrastructure and correlator facility and six of the final complement of ten 1.4 m diameter "Unit" telescopes. The MOU formalises the guaranteed and free access to the array for the AP group for the first ten years of operations in lieu of its in-kind contribution to the project. We have also bid for, and been successful in securing, a $670k grant from NMT which covers some of the costs of designing, testing and integrating the production versions of the six delay line systems required for the array, and we have reached an in-principle agreement that the AP Group will perform a substantial fraction of the work on the beam combiners for the interferometer.

In the meantime, the uncertainties with respect to the UK's optical/IR interferometry strategy have been addressed through an AAP-led survey of the community by the UK Optical Interferometry Forum (OIF) chaired by Dr Melvin Hoare (Leeds). The OIF was charged with establishing the scientific priorities for the UK in optical/IR interferometry and determining a strategic view as to how these priorities might best be met through UK access to existing or planned facilities. The OIF's recommendations in 2004 were unequivocal: first, that the UK's interests were focused on an *imaging* interferometric capability and, second, that a route via an 8-element implementation of the MROI would likely be a more cost effective solution for the UK than any redirection of the VLTI development plan from its astrometric priorities.

Following feedback from this activity, we were encouraged to submit a further Statement of Interest to the Science Committee to support our MRO-focused design, construction and commissioning work up to the completion of Phase 1 of MROI, which is now expected to terminate in the autumn of 2009. Our proposal was assessed by the SC last year and we were recommended to bid for these funds through a PPRP proposal.

Our request differs from a standard "project" proposal to PPRP in a number of ways:

- The majority of the MROI project is already funded through American channels and is underway.
- Our involvement in the MROI has been supported at a modest level since October 2003 through the Rolling Grants line. Much of this current request for support is for the completion of work which will be more than 50% complete by the time of the start of any PPRP funding.
- Our request to PPARC is for a small fraction of the total project cost (<4%), but the UK's involvement in the MROI is absolutely critical if the project is to be completed in a timely manner and be a scientific success.
- Components of the Cavendish work packages described in this proposal have been part-funded directly by New Mexico Tech.

These points reflect the nature of our collaboration with NMT that has developed out of the prototyping efforts supported by our previous Rolling Grant. This has been negotiated on the basis of NMT securing the capital funds to deliver the MROI and on us securing PPARC funds to support our existing core design team in Cambridge at a roughly constant level. Should PPARC decide not to support the effort described here, our existing work packages, and our collaboration, would need to be renegotiated.

During our consultations with PPARC in 2005 it was agreed that our proposed request for funds to support our continued collaboration with the MROI fell somewhere between the remit of the PPRP and that of the Rolling Grants funding line. PPARC therefore requested that *at the same time* as making a bid to PPRP, we should make the identical request through our next Rolling Grant submission. This proposal thus represents one of the "parallel" bids PPARC have asked us to submit: we have submitted a request covering the same proposed work as part of the most recent Cavendish Astrophysics Rolling Grant application submitted in May 2005.

### 1.2 Project scope

In part because of the small size of our request to PPARC in comparison to the total US-funded costs of the MROI, it was agreed with PPARC that the scope of the "project" being proposed and assessed in this PPRP application should not be the whole of the MROI, but rather the specific work that the AP group is performing for the the MROI consortium during the period 2006–2009. Our proposal here thus requests funding only to support our continuing system design role in the MROI, the remaining design, prototyping and fabrication work associated with the two MROI work packages which have been assigned to the Cavendish, and to lead the commissioning of the MROI until September 2009.

In accord with our MOU with New Mexico Tech, this timeline corresponds to the completion of Phase 1 of the MROI. Our proposal here is *not* concerned with future stages of the project, which will augment the total number of telescopes and delay lines at the MROI from 6 to 10, and which NMT intends to fund through requests to state and philanthropic agencies and through collaborations with other institutes. Furthermore, the scope of this proposal also excludes any UK contribution to the operations costs of the array. We would expect to make a separate bid for such funds at a later date, e.g. closer to the time of completion of Phase 1 of the array, only if it were in the best interests of the UK community, as explained in subsection **??**.

# 2 Case for Support

## 2.1 Scientific case

### 2.1.1 Rationale

Interferometry is the only direct method for reaching the milli-arcsecond-level angular resolutions required to provide detailed observational constraints on many fundamental astrophysical phenomena. These include star and planet formation, accretion and mass-loss in all stages of stellar evolution, and the fuelling of black holes in the nearest active galactic nuclei.

In simple cases, where the underlying physics is well enough understood to permit a parametric model to be be useful in describing a source, a single interferometric measurement may suffice to distinguish competing theoretical scenarios, e.g. in measuring the apparent diameter of a hot star or establishing the mass of a dynamical companion through the precise determination of an orbit. However, for most problems, our understanding on small spatial scales is often rudimentary and is based on indirect signatures. In these cases interferometric *images*, which can only be obtained using arrays of large numbers of telescopes, provide the only reliable method for establishing the basic characteristics of a phenomenon and in identifying, and subsequently understanding, the physical processes governing what we observe. The primary role of the MROI is to deliver this latter capability, i.e. to permit the model-independent and spectrally resolved imaging of complex astronomical sources on angular scales between 0.5–100 milliarcseconds (see, e.g. Fig. 1).

In order to provide some context for our astrophysical interest in the MROI project we have provided below a brief outline of the major science foci of the array. This highlights the key science drivers that have driven the technical implementation of the array, but is only a subset of the full scope of scientific studies that will be possible with the facility when it is commissioned.

### 2.1.2 The MROI science mission

The reference science mission around which the MROI has been designed is based on the top-level science goals developed by the UK astronomical community for the Large Optical Array (LOA) JIF bid and the subsequent key science objectives defined in PPARC's 2003 Roadmap. More recently in 2004, the UK-wide OIF survey has re-affirmed these community interests. The top-level science goals for the MROI focus on three broad branches of astrophysics and include the key PPARC strategy themes of star formation & the formation and evolution of planetary systems and extreme environment astrophysics in nearby AGN. The three foci of the science mission are:

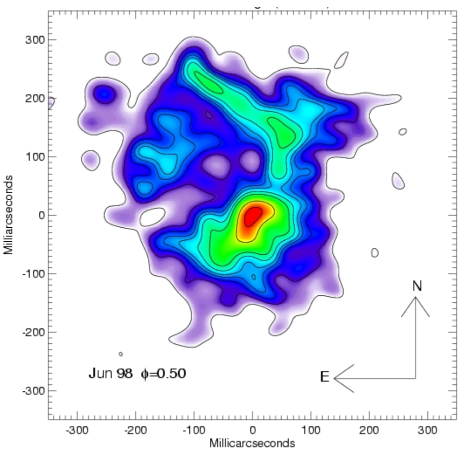

Figure 1: A 50 mas resolution interferometric image of the dust emission around the prototypical carbon star IRC+10216 in the K band. Prior to imaging at this angular resolution, the spectral energy distribution of the star had been modeled successfully assuming a uniform spherical distribution of dust. The lowest contour levels are at 1%, 2%, 3%, 4%, and 5% of the peak flux. This level of complexity characterises the type of imaging that the MROI has been designed to deliver and is comparable to typical images produced by modern phase-unstable radio arrays.

1. **Star and planet formation:** the detection and characterization of protostellar disks. Accretion, disk-clearing, fragmentation and stellar duplicity over all mass ranges. Stellar rotation in single stars and clusters.
2. **Stellar accretion and mass loss:** via winds, jets, outflows, explosive events and Roche-lobe overflow. Studies of examples in single and binary systems in themselves and as analogs for AGN jets and beams.
3. **Active galactic nuclei:** resolved imaging of the nuclear dust component of AGN, the broad-line-region (BLR), synchrotron jets and nuclear and extra-nuclear starbursts.

For each of these broad areas, the MROI design has been optimized so as to permit observations of multiple samples of targets at those wavelengths and angular resolutions most critical for advancing our current understanding.

For example, in the case of AGN, the design of the MROI allows for observations of all AGN with core magnitudes down to $H = 14$. There are of order 50 such AGN visible in the Northern sky and for each of these the MROI will be ideally suited for imaging observations of their purported dust tori in the K band. The inner edges of these tori are predicted to be roughly 1 pc from the nucleus (a limit set by the distance that dust grains can exist before they evaporate) which corresponds to 20 milliarcsec at z = 0.01, well within the MROI's resolution at this wavelength. The MROI will be the only interferometer with the sensitivity to address questions such as: What is the frequency of dust tori, what is the geometric distribution of the obscuring material, and how is this related to the predictions of magneto-hydromagnetic models? Similarly, the high angular resolution and short-wavelength capability of the MROI will offer a unique opportunity to investigate the broad-line-regions (BLRs) of the nearest AGN. At $z = 0.01$ a typical BLR radius of 1 light-month would subtend an angle of 0.2 milliarcseconds. One outstanding project will be to image the BLR in the H$\alpha$ line with coarse velocity resolution. This would constrain the kinematics of the emitting plasma, and hence address the long standing question of the relative importance of turbulent bulk motions and rotation. Furthermore, long-term monitoring of the BLR might be able to associate flux variations in the BLR with changes in its detailed spatial distribution. This would be an outstanding breakthrough in understanding the dynamics of AGN cores.

Much closer to home, the MROI will have the potential to reveal and map the inner regions ($\sim 1$ AU) of accretion disks round newly-formed stars, i.e. exactly those regions where Solar System analogs might form. The MROI will have the sensitivity to image the thermal dust emission from such disks down to radii of around 0.1 AU in the K band, where the apparent diameter of the discs will be 2 milliarcseconds for sources 100 pc away. Furthermore, the focus on delivering an imaging capability will mean that it will be possible to search for the presence of clearing in the disks as evidence for planet formation. At shorter wavelengths, scattered starlight from the disks will predominate and is expected to be detectable out to significantly larger diameters. At its highest angular resolution the MROI will permit unique diagnostic observations of magnetically-determined structures, such as the arcs along which material is supposed to be channeled from the inner accretion disk at around 5-10 stellar radii to the stellar surface. Theoretical models predict that the observational consequences of these features, e.g. gaps in the continuum emission, will be visible on milliarcsecond scales while others, such as the accretion arcs themselves will be detectable on sub-milliarcsecond scales in selected emission lines. For this application the unique snapshot imaging capability of the MROI will be crucial: a time series of images in the H$\alpha$ line would reveal directly the rotation rates of these accretion arcs and provide a direct measure of the shear forces involved. The existence of such magnetospherically-controlled structures has important consequences for the subsequent rotation rates of stars, which in turn drive their stellar dynamos, for disk clearing, and thus for the formation of the inner planets. Their confirmation, or otherwise, would represent a fundamental advance in our understanding of star and planet formation.

Studies of mass-loss in single and multiple stars are also expected to feature heavily in the MROI science portfolio. There is considerable interest in using the MROI to focus on the physics of mass loss in evolved stellar systems, both at the stellar surface, and in the cooler extended atmosphere where dust will condense. For both of these cases there exist major uncertainties since neither the structure of the extended atmosphere nor that of the stars are well understood. Stars at this late stage of their evolution are largely convective (and possibly chaotic) and their surfaces are believed to be dominated by a relatively small number ($\sim 50$) of giant convective cells. In addition, they can also pulsate strongly, but neither the cause of the pulsations nor their effects on the atmosphere, through for example, shock waves, are well understood. Even for the nearest such stars, the stellar surface and dust-formation radius extend to only 10-100 milliarcseconds, so that detailed studies require the angular resolution that only the MROI will provide.

Optical interferometric studies have already shown that the nearest evolved stars have asymmetric surface structures containing up to 10% of the total flux from the stars. The MROI will allow astronomers to make detailed surface maps of these stars for the first time, revealing the structures and temperatures of the hot-spots as well as their possible identification with convective cells. Establishing the topology of the cells, i.e. whether they form latitudinal rotational bands or banana-shaped segments along lines of equal longitude, as well as defining their timescales, will represent major leaps in our understanding of convection, a notoriously difficult problem.

Numerous classes of multiple stellar systems, such as classical and recurrent novae, symbiotic stars, and atmospheric eclipsing binaries will also be observable with the MROI and imaging studies with the array are likely to have a major impact. Classical novae will be ideal laboratories for studying mass accretion onto degenerate companions as well as the physics of thermonuclear runaways. These ejections are so energetic that spectroscopic measurements indicate that velocities as high as 1000 km/s can be attained. At best, radio observations can image the ejecta 80 days after the outburst, whereas observations with the MROI will be able to spatially resolve the optical and NIR emission from the ejecta only a few hours after an outburst. Roughly three nova outbursts are expected to be observable each year, offering many opportunities for detailed study. At later phases multi-wavelength imaging by the MROI will detail the shock structure in the ejecta and for the first time show if dust formation is associated with them.

Wider systems, where mass transfer is occuring from a giant companion, will also feature prominently. There are of order 10 recurrent novae and several hundred symbiotics systems known which the MROI will be able to detect and resolve. Their orbital periods range from 200-1000 days, and so at 1000 pc the typical binary separations will be 10 milliarcseconds. The binary separation and orbital parameters, the nature of the companion, the wind ionization geometry and the accretion disk geometry will all be observable with the MROI through imaging of the continuum and line emission. Radio data indicate that UV radiation from the white dwarf/sub-dwarf ionizes the molecular wind from the red giant. The MROI will be able to relate the radio emission directly to the location of the binary components for the first time. For some recurrent novae an accretion disk may also be present around the companion. Measurements with the MROI would then track the evolution of the shock structures caused by the passage of the companion, testing and enhancing our current models of astrophysical shocks.

As mentioned above, the previous paragraphs describe only a subset of the scientific studies possible with the MROI. All of the "bread-and-butter" applications of optical/IR interferometry such as the measurements of fundamental stellar parameters (i.e. masses, radii, and temperatures), searches for multiplicity, and monitoring the dynamics of stellar systems will continue to be possible though with larger samples at fainter limiting sensitivity and with greater temporal frequency.

### 2.1.3 International context

Three "facility class" optical/IR interferometer arrays are currently operational. These are the VLTI array on Paranal ($4 \times 8$ m fixed telescopes with an additional array of $4 \times 1.8$ m moveable telescopes), the Keck Interferometer on Mauna Kea ($2 \times 10$ m fixed telescopes), and the CHARA array on Mount Wilson ($6 \times 1$ m fixed telescopes). The UK has open access to the VLTI through its ESO membership, but must collaborate with US astronomers to use the Keck and CHARA arrays. Although all three of these arrays are either still in the process of being commissioned or have only recently moved into regular operations they are already being exploited for competitive astrophysics.

At the VLTI, key successes have included the resolution of the central dusty torus in NGC1068 (Jaffee et al, Nature, 429, 47, 2004), the detection of extreme photospheric distortion in the rapid rotator Achernar (Domiciano de Souza et al, AA, 407, L47, 2003) and the determination of an empirical mass-radius relation for low mass M dwarfs (Ségransan et al, AA, 397, L5, 2003). At the Keck array unique studies have been made on the inner disk properties of T Tauri stars (Eisner et al, ApJ, 623, 952, 2005; Akeson et al, ApJ, 622, 440, 2005) as well as AGN (Swain et al, ApJ, 596, L163, 2003) and eruptive variables (Lane et al, ApJ, 622, L137, 2005). Finally at the CHARA array, commissioning results have included studies of Cepheid variables (Merand et el, AA, in press, 2005) and rapid rotators (McAlister et al, ApJ, in press, 2005; van Belle et al, ApJ, submitted, 2005).

However, despite the recent burgeoning of scientific results from these arrays all three of them suffer from a number of critical shortcomings which set hard boundary conditions on

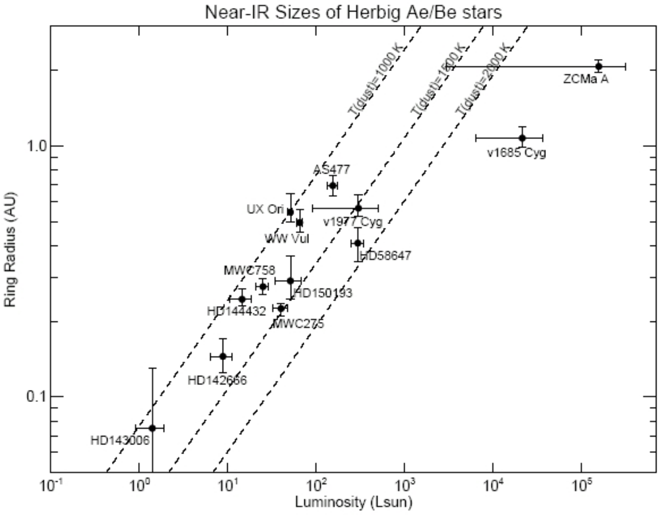

Figure 2: The radius-luminosity relationship for Herbig Ae/Be stars observed with the Keck interferometer by Monnier et al (ApJ, 624, 832, 2005). One reason for the small sample size is the limiting sensitivity of this survey: all of the targets have magnitudes lower than 8 at K, i.e. they are all at least 5 magnitudes brighter than the limiting sensitivity of the MROI.

their potential for useful astrophysics. The design of the MROI has focused specifically on these key shortcomings, and in all of these areas the MROI will have an enhanced capability over the VLTI, Keck and CHARA arrays.

1. **Sensitivity:** The MROI's limiting sensitivity will be at least a good as (if not better than) existing arrays by virtue of an optical design optimized for throughput and wavefront quality and a fringe-tracking beam combiner optimized for faint-source sensitivity.
2. **Imaging fidelity:** The MROI will deliver significantly more reliable images by virtue of its large number of telescopes, the detailed layout of its telescope stations, and its beam-combiner design.
3. **Angular resolution:** The MROI will have an angular resolution equivalent to the less-sensitive CHARA array and twice as great at the VLTI and Keck interferometers, both of which are fundamentally limited in expansion by the local topography.
4. **Complementarity with other instruments:** Because of its broad wavelength coverage (from 600 nm to 2400 nm) and multiple-array configurations the MROI will be a much more versatile interferometer that its existing counterparts. This will be particularly valuable for multi-wavelength studies combining data from other high resolution facilities such as the JWST, ALMA and MERLIN.

While all of these features will make the MROI the most advanced optical/near-IR interferometer worldwide, it is the first two of these (sensitivity and imaging capability) that have historically compromised the ability of existing arrays to delivering competitive astrophysics. It is the MROI's improvements in both of these key areas that makes its scientific potential so attractive.

### 2.1.4 VLTI context

Because the UK already has access to the VLTI, it is useful to provide some commentary on how the MROI, i.e. the underlying driver for our proposal, compares with that array, and to what extent this is reflected in any duplication of scientific or technical capability.

A detailed study of these questions was one of the key tasks of the AAP Optical Interferometry Forum which received presentations from the VLTI and MROI teams, consulted widely amongst the community and reported back to the AAP in 2004. The OIF concluded that the "majority of the science programmes suggested by the community would require imaging, and for any system to produce maps on a reasonable timescale". They continued in stating that "Such capability would require at least 6 telescopes" (c.f. the MERLIN array) "and ideally 8". In comparing an 8-element implementation of the MROI to the $4 \times 10\,$m (UT) $+4 \times 1.8\,$m (AT) VLTI the OIF identified two key problem areas:

- First, the feasibility, both technical and logistical, of securing access to the VLTI UTs for interferometric studies in concert with the smaller ATs.
- Second, the potential costs to the UK of funding the development of the VLTI to accomodate larger numbers of ATs and an associated beam combiner to handle more than 3 input beams.

As of 2004 there were no realistic plans for combining beams from the UTs and ATs together, nor for having any facility for combining more than three beams at a time. This implied that at best the VLTI as planned might be operated as a set of two independent 4-element arrays, neither of which would meet the UK community's needs for imaging complex sources on a reasonable timescale.

The specific costs to the UK associated with developing the VLTI to match the scientific capabilities of the MROI can be found in Annex 2 of the OIF's report (AAP(04)03). A number of different scenarios were examined by the OIF but having considered both these costs and the scientific data then available, the OIF concluded that the MRO route provided an optical/IR interferometer that was likely to be much better matched to the UK's scientific needs and be more cost effective in realising these than any VLTI route. Furthermore, they recommended that, were a cost effective development plan for the VLTI to deliver an 8-element imaging array not part of ESO's strategy, PPARC might wish to be ready to take up the MRO opportunity rapidly. In summary, the OIF's deliberations confirmed that the VLTI, while being located at a better site and offering access to the 10-20 $\mu$m window, did not as planned provide the capability to meet either the UK's scientific goals or access requirements, then estimated as 100 nights/year.

Since the OIF deliberations in early 2004, there have been changes in both the VLTI and MROI programmes. At the VLTI, a "recovery programme" was initiated in March 2005 to bring the infrastructure to a stable condition that would support the operational requirements of the astrometric instrument, PRIMA. This 24-month programme will address problems associated with the delay lines, the fringe tracking subsystems and with the environmental conditions within the delay-line tunnels all of which are now compromising the performance of the array. A decision as to how best to proceed is expected in March 2006, after which one year has been allocated for any required remedial action. The key impact of these developments has been an increased burden on the VLTI budget and a consequent rise in the risk associated with plans for any further enhancement of the array.

At the MROI, a major budget and schedule review took place in early 2005, following which a phased implementation plan was adopted. This means that Phase 1 of the project now envisages most of the array infrastructure but only 6 of the full complement of 10 telescopes being deployed by 2009. The capability of this 6-element implementation will clearly be reduced as compared to the 8-element array that had been assumed by the OIF: while its sensitivity will be identical to that of the 8-element counterpart considered by the OIF it will be roughly a factor of two slower in mapping complex targets. Nevertheless, even in this form the MROI will still be the world's most powerful imaging interferometer and will remain unrivalled in its ability to make model-independent images of astrophysical phenomena on a wide range of spatial scales.

These changes in the VLTI and MROI programmes do not alter the conclusions of the OIF in any significant way, and so their paper to the AAP remains a valuable commentary on the plans, capabilities, and relative costs of these two projects. Some additonal comments on the relative merits of the two projects are included in the paragraphs below.

### 2.1.5 UK role and influence

A key feature of our proposal here is the excellent match between the technical skills and scientific interests of our group at the Cavendish and the New Mexico-based MROI team. While the NMT-based staff have exposure to interferometric astrophysics through their proximity to and use of the VLA, e.g. the Array Operation Center for the VLA is located on the NMT campus, their desire to secure a partnership with an *experienced* optical interferometric group has allowed us to take maximum advantage of the historical investment by PPARC in the development of imaging interferometry with the COAST array. In the context of this proposal, our request exploits our significant experience in the design of delay lines and beam combiners, together with our particular expertise in the system architecture of complete interferometric arrays. These are unique competencies which could not have been developed without our in-house deployment of the COAST array and its role as a prototype through which both successful and unsuccessful approaches for the development of a true facility array have been explored.

The value of this experience has allowed us to negotiate a significant leadership role in the MROI programme, visible not only in the definition of the reference science mission for the array, but also in our technical role as system-architects for the array. This level of scientific and technical influence in a project to which the UK is making such a small ($< 5\%$) capital contribution is rare and uniquely attractive. In comparison to our relationship with the VLTI programme, the scientific benefits this partnership brings are threefold:

- Given our critical role in ensuring the success of the delivery of the MROI it is very unlikely that any adjustments to the top-level science goals for the MROI could be made in the near term without our agreement. This ability to maintain a close match of the array's capabilies to the UK's scientific interests despite our small capital contribution is particularly valuable.

- Our in-kind contribution to the design and development of the MROI brings with it free access to the array for approximately 30 nights per year for the first ten years of operations. Our group expects to collaborate with multiple UK-based groups to ensure that this time is exploited in the most scientifically valuable way.

- Our role as lead partners in the MROI prior to the engagement of additional partners (this is envisaged as a mechanism for funding telescopes 7 through 10 in the array) means that the UK is very well placed to bid for additional access to the MROI through a future subscription to operations costs. Importantly, though, this current proposal implies no UK committment to any such future expenditure.

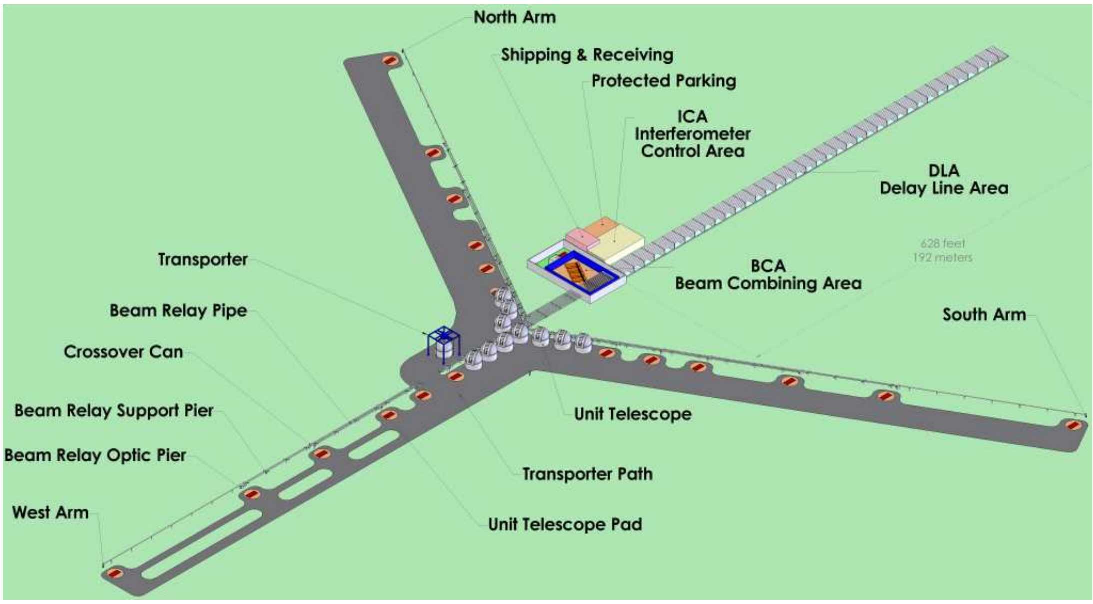

Figure 3: The schematic layout of the MROI. In this view, all 10 telescopes are shown together with a wheeled transporter based on a container crane design. Each arm of the "Y" shaped array is 200 m long, as is the building housing the delay lines.

## 2.2 Technical Case

Since 1985, more than a dozen optical and infrared interferometers have been built and operated successfully, in all the key astronomy wavebands from 400 nm to 12 microns, and with baselines of up to 640m. Thus optical/IR interferometry itself is not the unique feature of the MROI. As explained above, the scientific advantage of MROI comes primarily from the unique combination of its ability to make true images of complex objects and its faint limiting magnitude. Here we briefly outline how the design of the MROI reflects these scientific priorities.

The MROI is sited at 10,000 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 (in "beam combiners") 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 $R= 20$ to $R\sim5000$. 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 Figure 3.

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").

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 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, minimising 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, minimising 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 optimised multilayer antireflection 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.

This proposal is for work to be done by the Cavendish which will be directly related to the technical strengths of MROI, and also will draw on the technical strengths of the Cavendish team. The Cavendish will be responsible for the design of two of the key subsystems of the interferometer, namely the delay lines and the beam combiners, and will also be responsible for a number of remaining system engineering tasks and the final integration of the array.

The Cavendish design for the delay lines uses a total of only 3 reflections to achieve the 400m of optical path delay needed, which can be compared with the design at the Navy Prototype Optical Interferometer in Flagstaff, AZ, which uses more than 8 reflections to achieve the same effect. The resulting improvement in interferometric throughput is a significant component of the overall array throughput improvement, but requires considerable innovation at a system-wide level to meet all the technical requirements in a cost-effective manner and with low overall risk.

The beam combiner work package includes both the fringe-tracking beam combiner and the science beam combiners. Optimising the design of the fringe-tracking combiner will be critical to achieving the faint limiting magnitude goal for the MROI, and draws on our long experience of group-delay tracking techniques. In the case of the science beam combiners, a simultaneous optimisation both for imaging performance and for achieving good signal-to-noise ratios on faint objects is needed. Our design makes use of a fast optical switchyard which allows the best balance between these two goals to be achieved, building on the Cavendish experience in the design of compact stable combiners and on our familiarity with the trade-offs involved in imaging performance. Our design will allow the Phase 1 MROI to have factors of 2 and 6 advantage in instantaneous baseline and closure-triangle coverage respectively, and factors of 15 and 36 in the baseline and closure triangle coverage available within a few minutes, when compared with the best existing instrumentation at the VLTI.