Magdalena Ridge Observatory Interferometer: An Overview of an Astrophysics Facility for Supporting SDA Efforts

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Abstract

The Magdalena Ridge Observatory Interferometer (MROI) was initially proposed in the early 2000s as an ambitious, long-baseline optical/near-infrared imaging interferometer for astronomy. Today, it is being developed through a collaboration between New Mexico Tech and researchers at the University of Cambridge, UK and funded by the Air Force Research Lab via a Cooperative Agreement with the university. When completed, MROI will comprise ten 1.4m aperture telescopes distributed in an equilateral-Y configuration at 10,500 feet altitude in the mountains of central New Mexico. The telescopes are used in coordination with each other, moved across 28 stations, allowing for baselines ranging from 8 to 347 meters. At the observing wavelengths in the optical and near-infrared, this translates to angular resolutions of 40 milliarcseconds down to 0.5 milliarcseconds. The telescopes are being built by AMOS in Belgium and are an alt-alt design, decreasing the number of reflections before injecting the collected light into the beam transport system. The enclosures are being built by EIE in Italy and both protect and are used to transport the telescopes between stations. The beam transport is accomplished in vacuum with active optical systems for beam steering. Delay compensation is done using custom delay carts developed and built by the University of Cambridge. The beam combining laboratory, completed nearly a decade ago, is built to support the full 10-telescope facility, and the overall architecture of the array aims to minimize vibrations and temperature excursions while exploiting a polarization preserving approach to beam transport and sensing. Beam combination is conducted in open air at near-infrared wavelengths for fringe sensing, and simultaneously in the optical and near-infrared for scientific measurements. These detector systems employ photon counting detectors for both fringe tracking and science, and use custom cryostats built by Universal Cryogenics in Arizona.

Introduction

As space telescopes reveal a once invisible universe, they also create the desire to understand how the universe functions. In order to address these “how” questions there has been a never-ending race to improve both sensitivity and resolution of the images we can record. This paper will discuss how the Magdalena Ridge Observatory Interferometer (MROI) will address these issues for ground-based observations. Mathematically, the resolution of a telescope is expressed as:

$$R = \lambda/D, \qquad (1)$$

where λ is the wavelength being observed, D is the diameter of the collecting device and R is the resulting resolution. New observational facilities aim to focus on minimizing R as much as possible. This simple equation quickly leads to two conclusions: (1) resolution improves as the wavelength is reduced; and (2) as the diameter of the light-collecting aperture increases. While enhancing R is simple in concept it becomes difficult in application. As λ decreases the atmosphere above a ground-based observatory increasingly distorts the image and as D increases, the costs of the facility rises non-linearly, typically in the range $\propto D^{2.5}$ to $\propto D^{3}$.

The MROI site is located at 10,500 feet in the arid southwest USA which reduces a significant amount of atmospheric distortion and it has been designed to operate at optical and near-infrared wavelengths. Its location and operational wavelength range result in a Fried’s parameter r_0 of

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approximately 10 cm (at 500 nm), with measurements indicating that the median seeing at the site is ~1 arcsecond, with the best seeing being as good as 0.5 arcseconds. The MROI has been designed to exploit these conditions as effectively as possible.

In conventional imaging instruments the size of the primary collecting surface for a telescope is increased to both improve resolution ($\propto 1/D$) and improve sensitivity ($\propto D^2$). However, for filled telescope apertures increasing D gives rise to substantial cost rises. An alternative approach is to use the technique first exploited by Michelson [Michelson & Morley 1887] to measure suspected differences in the speed of light. This Michelson technique relays on forming an interference or fringe pattern from two distinct sources similar to waves created in still water (Fig1).

Figure 1: Interference pattern from two sources in still water. The "fringes" created when the signals from each source interfere contain information about their origin.

The fact that the properties of the source of a radiation field can be determined by sampling and analyzing the field at different locations on the ground, implies than an alternative to constructing a large collecting aperture is to create an array of smaller apertures, each sampling the field at a different location. Measurements made by this "sparse" array can then be analyzed – by interfering the signals with each other – to infer the source brightness distribution. In this approach then, the problem of constructing a large monolithic telescope is reduced to designing a facility which samples the incoming field "representatively" enough to allow the source brightness distribution to be recovered unambiguously[1] (see Fig 2). The MROI has been designed as such a facility, and will consist of 10 unit telescopes that each have a 1.4m primary mirror and can be distributed over a region of order 350m in diameter. This combination will interrogate structures as small as 40 milliarcseconds when the telescopes are tightly spaced down to structures on 0.5 milliarcsecond scaled when the unit telescopes are spread out as far as they can be.

This approach to imaging has been used in radio astronomy for over 70 years and so many of its challenges – as well as the solutions to these – are well understood. The distinct difference between radio and optical interferometers is the wavelength. Radio interferometry is typically done at wavelengths that range from millimeters to centimeters, whereas optical interferometry is done at micron wavelengths. In particular, in the radio the signals can be easily manipulated (i.e., recorded and/or amplified) with modern electronics, whereas at optical and near-infrared wavelengths the Uncertainty Principle forbids useful amplification and requires that the signal from separate

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[1] This description hides to some extent the scope of this task, since the facility must manage not only the sampling of the field, but all the steps needed to analyze the measurements and reconstruct an image.

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telescopes be combined directly. Since the telescopes are configured on a surface the distance from each telescope to any combining location varies, requiring the signal from a near telescope to be delayed resulting in an equal pathlength of a far telescope. Once the pathlengths are synchronized, the signals can be combined to form a fringe pattern that can be recorded. The information encoded in this recorded signal can be combined with that from other fringe patterns from different pairs of receivers to form an image.

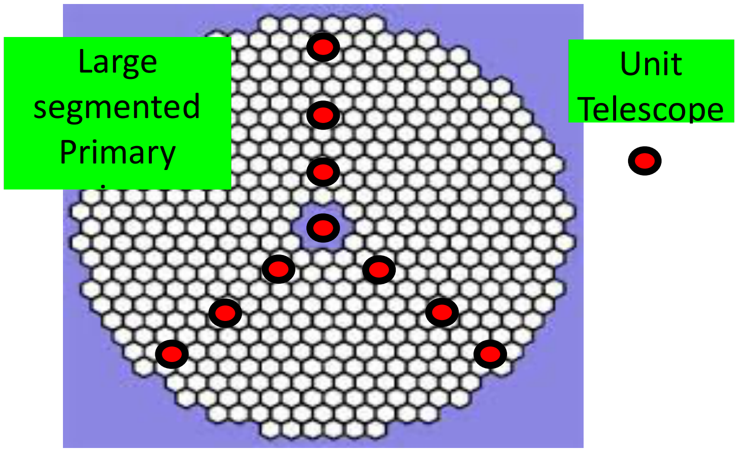

Figure 2: A cartoon showing how a large diameter segmented primary mirror might be mimicked by sampling its surface using a Y-shaped array of smaller sub-apertures (each of which corresponds to a Unit Telescope of the interferometric array. The signals from every pair of sub-apertures are required to be interfered and measured so as to infer the source brightness distribution. Many other distributions of unit telescopes are possible in principle: the particular selection adopted is a complex trade balancing costs, feasibility of implementation, and robustness against atmospheric turbulence.

The image forming process consists of combining independent measurements from pairs of telescopes. If a total of N independent visibility data are collected, an image with order N degrees-of-freedom can be reconstructed. If a 5 ×5 pixel image of an extended source is required, of order 25 independent visibility data need to be collected. In addition, the projected baselines used to secure these data should range in length by a factor of roughly 5:1.

In practice, optical/IR arrays struggle to collect data from targets with visual magnitudes much fainter than 8. This relatively poor sensitivity means that contemporary optical/IR interferometry has had a relatively small impact on extra-galactic astrophysics. The ability to routinely reach a limiting sensitivity of visual magnitude 12 or fainter would be a significant enhancement for astronomers. The MROI has been designed to provide this additional sensitivity.

The MROI Design

The MROI design flows down from a “key science program” that has been developed by the astronomical community. This key science mission includes studies of: 1) young stars and the earliest phases of planet formation, 2) a range of topics in stellar astrophysics centered on binary systems, mass loss/transfer, and time-varying phenomena such as pulsation and convection, and

3) the immediate surroundings of active galactic nuclei (AGN) in nearby galaxies. The MROI's anticipated sensitivity, closure phase precision and angular resolution needed for this ambitious astrophysics program is also uniquely useful for questions in space domain awareness (SDA). This is because both require high fidelity imaging of faint and complex sources in a model independent manner.

This shared goal has driven the particular architecture of the MROI and has affected almost all of its design choices. The design of the major elements of the MROI are presented below.

Array configuration: The cost of an interferometer increases approximately linearly with the number of telescopes, but the number of points sampled by N telescopes is on the order of N^2. Larger numbers of telescopes are thus preferred, but how should these be distributed on the ground?

When imaging sources with a mix of compact and resolved structure, an interferometer with a larger number telescopes is superior not only in imaging speed but also in the achievable image complexity. This is because in the presence of atmospheric turbulence the only reliable way to access baselines which give many pixels across such sources is to use the "baseline bootstrapping" technique [Pauls et al., 1998]. In baseline bootstrapping, multiple telescopes are arranged in a "chain", and in the chain on the shortest baselines the fringe visibility must high enough to allow fringe tracking and hence the measurement of atmospheric phase differences. This advocates for telescope layouts with short nearest-neighbor spacings, for which a Y is ideal.

The MROI infrastructure is designed for 10 telescopes but can operate with as few as two telescopes. When the telescopes are arranged in a Y-shaped configuration, the 10 telescope array can be viewed as a set of 3 "bootstrapping chains" each consisting of 7 telescopes, oriented at 120^o angles to one another. The ratio of the longest baseline in this array to the nearest-neighbor spacing is 5:1 and so this will allow approximately 5×5 pixel imaging on resolved-core objects. The primary array configurations are scaled versions of the "bootstrapping" array, with maximum baselines ranging from 40 m to 347 m and minimum baselines ranging from 7.8 m to 67 m. The array therefore allows access to angular scales with a range of 44:1.

Telescopes and adaptive optics: A critical factor in the sensitivity of an interferometer is the size of the "unit telescope". While a large telescope equipped with high-order adaptive optics (AO) might seem attractive, this is an expensive option for an array with many telescopes, and it precludes being able to pack the telescopes close together in order to sample larger-scale angular structure. In addition, high-order AO will only operate successfully if there is a bright reference available to sense the wavefront perturbations. The angular density of bright natural references (stars) is sufficiently low that the science target itself is most often the adaptive optics reference. Typical local active galaxies with near-infrared magnitudes of 14 have visible-wavelength magnitudes of around 16 and these are too faint to drive current adaptive systems. In this case, low-order AO is preferred. The best limiting magnitude is then realized using tip/tilt correction on telescopes of order $2–3r_0$ in diameter [Buscher, 1988b] and so, in the absence of laser guide star systems at each telescope, telescopes in the 1–2 meter size range provide close to the best possible interferometric sensitivity at optical and near-infrared wavelengths.

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Beam relay: At the MROI the light exiting the unit telescopes is sent to the beam combining laboratory as a set of parallel beams, where most of the path is in vacuum. The diameters of these beams need to be significantly larger than the Fresnel zone size in order to minimize the effects of diffraction. For propagation distances of order 1 km and a wavelength of 2.2 µm, this zone size is of order 5 cm. The propagation distances inside the beam combining laboratory are no greater than 20 m so smaller beams can be used in order to keep the size and cost of the more complex beam combination optics within reasonable bounds. A set of beam compressors between the delay lines and the beam combination optics serves to transform between these two beam sizes.

Delay lines: As mentioned above path compensation is required in order to equalize the path-lengths travelled by the starlight from the target to the detector. The path-length stroke required from these compensators scales with the size of the array. The approach adopted at MROI is to have a single-stage system introducing all the delay in a continuously-variable manner. This minimizes the number of reflections needed and at the same time avoids the switching overheads associated with the two-stage systems that have been favored in the past.0

Science instruments: The beams exiting from the delay lines are compressed and then spectrally split between a number of interferometric beam combiners. A visible-light combiner and a near-infrared (JHK) combiner can be operated simultaneously, and space has been left for a "guest" instrument which can substitute for one or other of these. These beam combiners are optimized for operation on faint sources, but at low light levels the signal-to-noise ratio of the fringes decreases as the number of beams which are combined simultaneously is increased. This is because the photons from all the telescopes contribute to the noise on all the baselines. Therefore, the MROI science instruments will be based on a number of parallel combiners, each of which combine a different subset of the beams. A beam "switchyard" will then allow the beams to be "shuffled" between combiners to allow all pairs of telescopes to be interfered with one another in rapid succession.

Fringe tracking: Fringe tracking is required to overcome effects of the random path-length perturbations introduced by the atmosphere. Fringe "co-phasing" attempts to compensate for the motion of the fringes at the sub-wavelength level while "coherencing" attempts to reduce the fringe motion to less than the coherence length of the light, which can be many microns. Fringe tracking in the MROI will mostly utilize the group delay method which is based on observing the phase differences between the fringes in multiple spectral bands. This allows fringe coherencing on sources about 10 times fainter than is possible with co-phasing methods [Buscher, 1988a] and so is the best way of achieving the MROI's faint-science goals. The MROI has been designed with a separate fringe-tracking combiner rather than using the science instrument to derive a fringe-tracking signal, because it allows each combiner to be optimized for a different role.

Alignment: Misalignments of the optical components in the interferometric beam train are a very common source of wavefront error in existing interferometers and can lead to significant losses in light throughput and fringe visibility. In many current interferometric arrays it is not unusual for optics to be realigned on a nightly basis to account for drifts which have occurred during the day. The MROI was designed from the start to allow automated alignment of the majority of the optical train in order to minimize time lost managing component drift and to increase the overall accuracy of its optical alignment. An automated system will inject multiple pilot beams both from the unit

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telescopes to the beam combiners and from the beam combing laboratory outwards, so as to permit real-time assessment and correction of any uncontrolled component movements.

Control software: Automated operation of an interferometer is critical to its scientific productivity, as large numbers of subsystems must work together to produce the interference fringes, and the cadence between observations is necessarily short to allow for observations of calibrator stars close in time to the target observations. A second critical feature for interferometers is continuous recording and storing of engineering data, as the calibration of the fringe visibility can depend on many variables within the system, and some of these can only be determined after the fact. For commissioning and operations, near-real-time display of data from multiple subsystems on the same console is essential to debugging operation of the system. The MROI's control software concept is based around independently-developed sub-systems forming a distributed whole, communicating over Ethernet. This system requires only a soft-real-time capability as the hard-real-time elements are confined mostly within active hardware subsystems such as the fast tip/tilt system. Real-time communication between subsystems is needed only between the fringe-tracker and the delay lines and this is provided by a separate dedicated communications link.

A key lesson learned from the design phase of the MROI was the importance of sticking to a focused set of scientific requirements despite programmatic setbacks and technical difficulties. The original vision of an optical interferometer for imaging faint and complex targets remains undiluted, and we believe this offers unique opportunities for scientific payback in the years ahead.

Current Status

Construction of the MROI site was started in 2005 with the installation of the basic infrastructure for the facility. During this initial construction the design of the instrument was concluded. The construction of the first unit telescope, manufactured by AMOS in Belgium, and first unit telescope enclosure, manufactured by EIE in Italy, was completed in 2017. These were delivered to the site in 2018. The project then experienced a shutdown during the world-wide pandemic and was restarted in late 2021. Currently the second unit telescope and enclosure are going through final factory testing and are scheduled to be delivered to the site before the end of the year. Fringes from this first pair of telescopes is expected in the second quarter of 2023.

Conclusion

The MROI has been designed to provide timely images of both deep space astronomical objects and manmade objects in earth orbit. Once complete, it will harness ten 1.4 m telescopes to conduct observations at wavelengths from 600 nm to 2400 nm. Its maximum resolution will be equivalent to that of a 350-metre diameter conventional telescope – something which could never be built in practice. Numerical simulations of the instrument indicate that MROI will provide insight on objects of interest in earth orbit. As an example of this capability, a simulated MROI image of a geosynchronous satellite is presented in Figure 3 [Young et al., 2016].

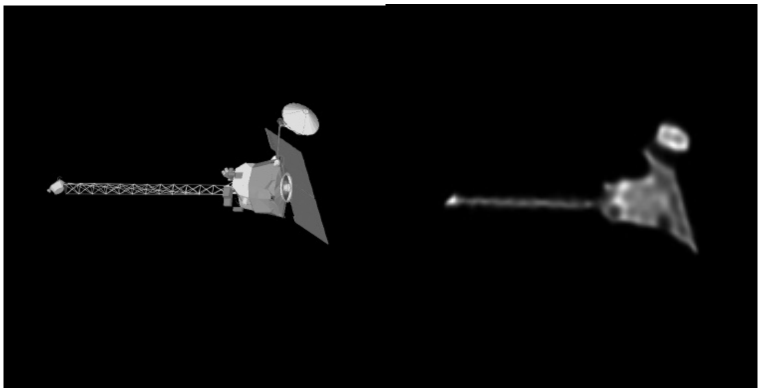

Figure 3: Left: “Truth” image of a solar-illuminated geosynchronous satellite. Right: Reconstructed image of the same satellite from simulated observations with the MROI using 10 telescopes in the most close-packed array. The satellite is 17 m in length and 35000 km away, so this is comparable to imaging a “quarter” from a distance of 50 km.

It is clear from the science case for the MROI that there are a large number of science targets for which imaging would provide critical new insights. Because these targets are complex in appearance, model-independent imaging is the only reliable and unbiased way to characterize them. Given the scientific importance of imaging, we have argued that a large number of telescopes is critical to providing a turnkey imaging capability, not only because this gives substantial increases in imaging speed and fidelity, but because for many objects the problem of tracking atmospheric phase perturbations can only be tackled with a “bootstrapping” array, which necessarily requires many telescopes. The MROI with 10 telescopes will thus be able to image “resolved-core” objects with of order 5 × 5 pixels across the image, a capability that will be unmatched by competitor arrays.

A second scientific focus of the MROI is that of sensitivity. Our analysis suggests that increasing the aperture size of the unit telescopes in the interferometer will have limited effect in improving the faintness of the targets which can be observed, and that concentrating on designing an efficient beam train which minimizes signal loss will be more cost-effective. Finally, this science case is used both to justify the requests for funding and to guide the design of the interferometer.

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