

New approach to very-high-resolution astronomical imaging

Michelle Creech-Eakman

The Magdalena Ridge Observatory Interferometer will produce extremely sharp images of faint astrophysical targets while minimizing reflections and wavefront aberrations to maintain sensitivity.

Astronomical objects are very distant, and so the angular sizes of many astrophysical phenomena are much smaller than can be resolved with conventional telescopes. Optical interferometry allows us to explore very small angular scales. Michelson and Pease first used interferometric observations nearly a century ago to measure the stellar diameter of Betelgeuse.¹ Since then, more than a dozen interferometers have been built worldwide to characterize the sizes and motions of stars and their environments. However, advances in technology have only recently allowed us to reconstruct physically realistic images of these objects rather than merely providing simple size measurements. We are ambitious in building the Magdalena Ridge Observatory Interferometer (MROI), with a mission centered on one primary goal: producing very-high-resolution images of faint astronomical targets.²

Stellar interferometry works by combining the light from multiple telescopes to form interference fringes. This requires a complex optical system involving multiple light reflections from the light-collecting surfaces to the detectors measuring these fringes. Each reflection adds aberrations to the observed signal and results in photon loss. For other interferometers, often more than 40 reflections are required before the interference fringes are measured. The MROI design minimizes the number of reflections to only 21, allowing scientists to observe much fainter targets than previously accomplished. In addition, the interferometer design (see Figure 1) capitalizes on having small-diameter (1.4m) movable telescopes, so that the array can be reconfigured easily to match the resolution needed for observations of a particular target, much like the operation of our larger radio counterpart, the Very Large Array.



Figure 1. Architectural rendering of the now-completed Magdalena Ridge Observatory Interferometer (MROI) delay-line facility and beam-combining laboratory (as well as the as-yet-unfinished telescopes) atop Magdalena Ridge. The telescopes will be movable onto 28 pads, with separations ranging from 7.5 to 340m.

Following starlight through the MROI beam train is instructive in understanding where the advances are gained. Starlight travels thousands of lightyears, only to be aberrated in the last few kilometers. Turbulence in the Earth's atmosphere causes corrugations in the incoming wavefront that must be flattened again before it can be interfered. These effects occur mainly in the form of low-order aberrations referred to as 'tip and tilt,' which can be removed after the wavefront has reflected off the telescope's primary mirror. Subsequently, the light travels along a beam train where a time delay is added to each telescope's beam (to track the object's sidereal position and remove small atmosphere-induced motions). This is done to achieve the zero

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optical-path difference (OPD) in the detecting laboratory that is needed to create the interference fringes. Finally, the beam diameters are reduced and the beams are mixed in a beam combiner (beam splitter), and then directed onto a high-speed infrared detector.

Most interferometers use traditional astronomical altitude–azimuth telescopes (subject to ~ 7 reflections) to direct the beams into the beam train and to the delay lines (DLs). If the apertures are large ($>2\text{m}$ diameter), an adaptive-optics (AO) system including several more reflections must be used to correct the wavefront. The MROI telescope design includes only three mirrors mounted in an altitude–altitude configuration, where the secondary mirror performs the tip-tilt correction.³ With our 1.4m apertures more closely matched to the atmospheric characteristics and using carefully optimized optical coatings and surfaces, we achieve 85% throughput and 62nm rms wavefront error: see Figure 2(left).

The principal functions of DLs are to add a time delay to the incoming signal to achieve the zero-OPD position at the beam combiner, and to correct for atmosphere-induced perturbations on time scales of typically $5\text{--}10\text{ms}$. This requires an interferometer to slew the DLs to the correct positions, detect fringes, predict the fringe motion, and command the DLs to track and intercept this motion to within a fraction of the detection wavelength (for the MROI this is at $1.6\mu\text{m}$). Our DLs do this in a single pass (three reflections), using a cart with compliant wheels which runs on the inside of the vacuum pipe.⁴ The optics are a cat's eye design, with a voice-coil assembly used to control the position at 100Hz to within 15nm , as shown in Figure 2(right), based on sensing using a HeNe interferometer. The cart is controlled using wireless transmissions and the power is picked up inductively along the bottom of the pipe. For many interferometers, these same steps are accomplished by folding the beams multiple times and running the carts on precision rails, often dragging cabling along. We save on as many as six reflections and many meters of steel.

The MROI fringe-detection method makes use of two separate beam combiners, one for fringe tracking and one for science combination, and employs the techniques of baseline bootstrapping and closure-phase application to produce images.⁵ In essence, light from shorter baselines (between the nearest telescope pairs) is combined on the fringe-tracker detector, dispersed at low resolution (~ 5 detector pixels), and read out quickly. This produces a clear signal, even for faint sources, which can be used to command the DLs. In the science combiner, the light from multiple telescopes is mixed so that the fringe contrast can be measured simultaneously on short and long baselines. This technique measures the closure phase (retaining the phase information in Fourier space in the presence of

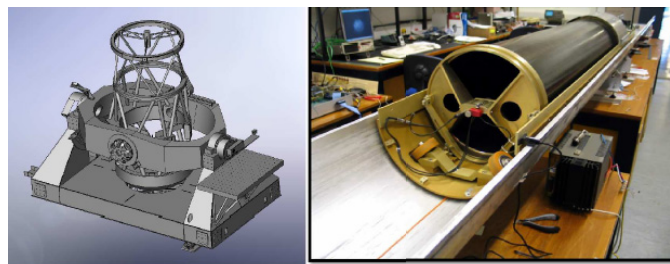


Figure 2. The Advanced Mechanical and Optical Systems (Liège, Belgium) design (left) for the MROI 1.4m altitude–altitude telescopes uses only three reflections. The table to the right of the telescope houses the tip-tilt sensor and the atmospheric-dispersion corrector. The DL cart (right) rides on the inside of a bisected vacuum pipe. The cat's eye carts, which use carbon-fiber tubes to maintain focal distance, are designed and built at the Cavendish Laboratory of the University of Cambridge (UK).

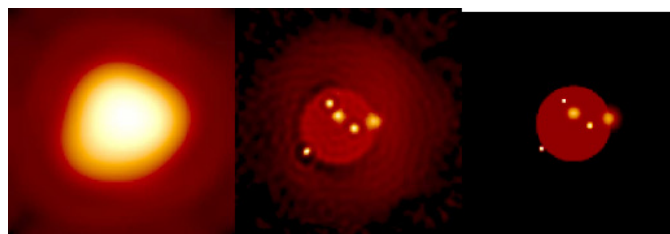


Figure 3. The left-hand panel shows a simulated image of a star taken with an 8m -class telescope with perfectly functioning adaptive-optics correction. At center, the same simulated image is shown taken with the MROI in snapshot-imaging mode using ten telescopes. Notice that the stellar spots (seen in the source image on the right) are only resolved in the interferometric image.

phase aberrations caused by the atmosphere), which can be used for image reconstruction. Because the number of baselines scales with the number of telescopes, N , as $N(N - 1)/2$, a ten-element interferometer allows for 45 measurements in each integration period. This combination of techniques produces much higher-resolution images than normally possible from the ground or from space. This can be appreciated readily by comparing a simulation of a perfect AO image from an 8m (diameter) telescope with an image from the MROI (see Figure 3).

With careful attention to system engineering and tracking of throughput and wavefront errors, the MROI will be able to track a $V = 14\text{mag}$ source at its principal fringe-tracking wavelength of $1.6\mu\text{m}$, fully five magnitudes (100 times) fainter than currently achievable with any other interferometer. The MROI

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is scheduled to receive its first telescope in 2009 and acquire first fringes in late 2010. Our team is located on the campus of the New Mexico Institute of Mining and Technology in Socorro (NM), which serves as the operations and construction center for the facility. Our major collaborators on this project are based at the Cavendish Laboratory of the University of Cambridge (UK). By 2013 we hope to be in routine operation with six telescopes. We expect to be producing cutting-edge high-resolution images of astrophysical targets, from newly-forming stars to the environments of black holes in other galaxies.

We acknowledge the vision of our principal investigator, Van Romero, in starting this endeavor and the strong support and funding for the MROI by our New Mexico congressional delegation, especially Senator Pete V. Domenici. Our Cambridge (UK) colleagues acknowledge the Science and Technology Facilities Council for their funding and support. The site's infrastructure was designed by the M3 Engineering and Technology Corporation of Tucson (AZ).

Author Information

Michelle Creech-Eakman

Department of Physics
New Mexico Institute of Mining and Technology
Socorro, NM
and
Magdalena Ridge Observatory
New Mexico Institute of Mining and Technology
Socorro, NM
<http://www.mro.nmt.edu>

Michelle Creech-Eakman is the project scientist for the Magdalena Ridge Observatory Interferometer. She has been a professor of physics at the New Mexico Institute of Mining and Technology since 2003. She was previously at the Jet Propulsion Laboratory and the California Institute of Technology, where she worked on the Keck and Palomar-Testbed Interferometers.

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