# Magdalena Ridge Observatory Interferometer: Imaging the Imagers

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*Abstract*— The Magdalena Ridge interferometer (MROI) is an optical interferometer that is currently (spring 2011) in the construction phase. All of the design work has been completed and the majority of the subsystems are being assembled. When completed, the array will consist of 10 fully transportable 1.4 m telescopes. These will support multiple array configurations, with baselines from 7.8 m to 350 m to give sub-milliarcsecond angular resolution. We assess the potential imaging capability of the MRO interferometer with regard to geosynchronous targets. We conclude that a significant proportion of GEO targets may be accessible and that it may be possible to routinely extract key satellite diagnostics with $7 \times 7$ pixel imaging. This would distinguish, for example, 70 cm features on a 5-meter satellite, or 30 cm features on a 2-meter satellite. [1 2]

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## 1. INTRODUCTION

The Magdalena Ridge Observatory Interferometer (MROI) project is an international collaboration between the New Mexico Institute of Mining and Technology (NMT) and the Astrophysics Group of the Cavendish Laboratory at the University of Cambridge in the UK to build the world's most ambitious optical/near-infrared imaging interferometer. The MROI offices are located on the campus of New Mexico Tech in Socorro, New Mexico, and the observatory site is located on a ridge just south of South Baldy in the Magdalena Mountains, about 48 km (30 miles) west of Socorro, at an elevation of approximately 3,118 meters (10,460 ft) above sea level.

The MROI has been designed to be the world's leading, high-sensitivity optical/near-infrared facility interferometer. It will comprise an array of up to ten 1.4-meter diameter unit telescopes (UT) arranged in an equilateral "Y" configuration. Each of these UTs will collect light from a celestial source and send a collimated, stabilized beam of light to a laboratory facility located close to the array. There, the beams will be path-equalized and superposed to generate interference fringes that encode information about the brightness distribution of the source. In this way, diffraction-limited imaging with an effective angular resolution given by the largest inter-UT separation will be realized.

The MROI's unit telescopes will be re-locatable amongst a set of 28 separate foundation pads, so as to give inter-telescope separations (i.e. baseline lengths) from 7.8 meters to 350 meters. At its shortest operating wavelength, the MROI will have a maximum angular resolution of approximately 0.35 milli-arcseconds. It will thus have the facility to resolve targets one hundred smaller than those resolvable with the Hubble Space Telescope (HST) or indeed by all ground-based optical telescopes that might be deployed in the next few tens of years.

From the outset, the MROI has been designed to satisfy multiple user communities. One of its core missions will be to provide a tool for the commercial, military and intelligence communities to support space situational awareness. This paper provides a first exploration of the MROI's capabilities in this role. In particular, we provide an introduction to the MROI, we discuss how well matched the sensitivity and speed of operation of the MROI are to the observation of typical GEO targets, and we provide an initial assessment of the diagnostic utility of interferometric imaging of such targets with an array like the MROI.

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[2] IEEEAC paper #1760, Version 1, Updated October 12, 2010

## 2. IMPLICATIONS OF KEY MROI DESIGN FEATURES FOR GEO IMAGING

The ability of the MROI to deliver a new and unique capability for the study of geosynchronously orbiting targets stems directly from its primary functional goal, which is to deliver model-independent images of the very faintest and complex astronomical targets, be they natural or man-made. This high-level functional goal is manifest in all elements of the MROI's detailed design, but can be most easily seen by comparing two metrics that quantify different aspects of the MROI's design.

The first of these relates to the overall sensitivity of the telescope, where the MROI has been designed to be much more sensitive than existing arrays. The design of each one of its eight sequential opto-mechanical subsystems has been optimized so as to maximize optical throughput, and to minimize signal losses due to uncontrolled spatial and temporal wavefront errors. Analyses of the global error budget for the array predict a fifty- to one hundred-fold (50–100) improvement in sensitivity over the current best optical and infrared synthesis telescopes such as the Keck, CHARA and VLT interferometers. The faintest targets that are routinely observable with these facility class arrays today have 2.2 μm (K band) magnitudes of between 7 and 10. This is some 3–6 magnitudes (i.e. between 40 and 600 times) brighter than the MROI design sensitivity of K = 13.

A second key feature of the MROI implementation is that its design allows for the very rapid and efficient measurement of the large volumes of visibility amplitude and closure phase data that are needed for model-independent imaging. In the past, the ability of interferometer arrays to image astronomical and other targets has been compromised significantly by the long time needed to secure enough data to allow unambiguous target imaging. Indeed in typical cases it is not unusual for several nights of observation to be required.

The MROI will overcome these limitations by using multi-way beam combiners to mix signals from between 4 and 6 telescopes simultaneously. This will immediately deliver roughly a ten-fold multiplexing advantage and will be coupled with a very high level of parallelized automation for the set-up and operation of the array.

As a result we expect that the MROI will be able to secure of the order of 100 calibrated visibility and closure phase measurements per hour in a minimum of five closely spaced spectral channels. This corresponds to an improvement in the speed with which images can be recovered – as compared with the observing efficiency of contemporary arrays – of between 10 and 100. Most importantly, by securing much larger samples of interferometric data than have hitherto been available, the images recovered will be much more reliable than has been usual historically.

Finally, the field of regard of the MROI telescopes and enclosures is an approximately 120 degree cone, so that the MROI will be able to image targets in the GEO belt from approx. the 64 degree West slot to the 150 degree West slot.

Apart from its enhanced sensitivity and higher operating efficiency, a powerful feature of the MROI will be its ability to tune its angular resolution – by factors of up to 25 – to the spatial scales of most interest for any given target. This "zoom" capability is a direct consequence of the multi-wavelength design of the MROI – it has been developed with imaging in all the atmospheric windows between 0.6 μm and 2.4 μm in mind – and the fact that its collectors will be rapidly reconfigurable so that the physical disposition of the array can be changed regularly.

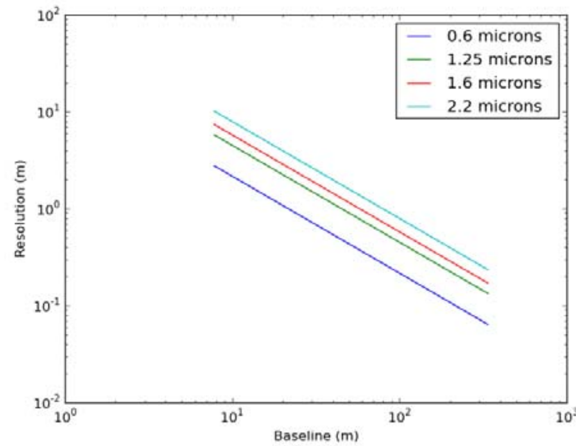


**Figure 1 - The relationship between the available MROI baseline lengths, the observing wavelength and the interferometric resolution (in metres) assuming a target in a geo-synchronous orbit.**

Figure 1 shows the relationship between the available MROI baselines and the sizes of the features that the interferometer will be most sensitive to at various wavelengths from 0.6 μm–2.4 μm for a geosynchronous target. The shortest wavelengths in this range are towards the red end of the visible spectrum while the wavelengths at 1.25, 1.6 and 2.2 microns correspond to the astronomical near-infrared J, H and K bands respectively. For example, with a 30 m interferometer baseline at 1.25 microns, a structure as small as roughly 1.5 m in size would be "distinguishable" in a reconstructed image. As Figure 1 makes clear, the range of spatial scales that, in principle, might be probed by the MROI spans roughly two orders of magnitude.

The multi-wavelength capability of the MROI is expected to be a particular advantage for at least two reasons. First, because it will be possible to switch the observing wavelength from the visible to the near-infrared during the night, it will not be necessary to spend any time in relocating the 1.4 m diameter array telescopes to alter the desired angular resolution (as long as the change needed is smaller than a factor of 4). Quite separately, the ability to secure data at wavelengths from 0.6 μm to 2.4 μm will allow the possibility of differential interferometry/imaging of targets with structures that have albedos that vary significantly over this range of wavelengths, for example gold and typical solar panel material. These extra diagnostic capabilities affordable through multi-wavelength observations will this be valuable both from a scientific and operational perspective.

The specific design details used at the MROI to deliver the enhanced capabilities outlined above are many-fold and a full description of these would be beyond the scope of this presentation. However, we list below a few details of the implementation adopted at the MROI which offer some pointers to the types of strategies we have adopted:

- The use of Unit Telescopes designed to exhibit very low levels of opto-mechnical and acousto-mechanical vibrations.

- The use of evacuated beam paths all the way from the unit telescopes to the beam combination laboratory. This eliminates turbulence from the light paths from the telescopes and removes the need for any optics to compensate for atmospheric dispersion.

- The use of separate wavelength bandpasses to monitor and/or control the interferometer sub-systems so that no light from the science target need be diverted from the science instrument. For example, for a science observation at 1.25 microns, light from 0.60–1.0 microns would be used to control the low-order adaptive optics (fast tip/tilt) systems, whereas light in the 1.65 micron window would be used to monitor and control optical path length perturbations.

- The use of a single stroke vacuum delay line system so as to reduce the number of reflections in the overall optical train. The MROI optical train has roughly 10 fewer reflections from the sky to the science instrument detector than a typical implementation at a contemporary facility array with no loss of functionality.

- The use of an automated end-to-end alignment system for the full optical train, used both before target observation begins, and subsequently in a real-time mode so that as an observation is being executed the effects of any slow opto-mechanical creep are eliminated.

To summarize, the MROI's sub-milliarcsecond angular resolution will offer an unprecedented capability for model-independent imaging of geostationary targets in comparison with what could be achieved with any single-dish telescope. For example, even a perfectly adaptively corrected 30 m-class telescope could only provide 1 m spatial resolution for geosynchronous targets. The MROI could in principle reach 10 cm resolution at the same 1 micron wavelength.

The increased sensitivity of the MROI, as compared to existing first- and second-generation interferometers, is also an outstanding prospect. The MROI will be able to image satellites as faint as magnitude 14 in the near-infrared H band: by comparison, no existing interferometer can even detect targets fainter than H = 10.

The larger number of unit telescopes in the MROI array (up to 10 can be accommodated in principle) will enable faster imaging than any existing interferometer, providing up to 100 times the number of images per night. Furthermore, those images will be reliable model-independent images of faint and complex targets whereas to date, imaging with optical/infrared interferometers has been largely confined to bright and/or simple targets or limited to fitting *a priori* models.

All of these key design characteristics result in the MROI being a potentially powerful tool for imaging both commercial and military geosynchronous satellites. In the following two sections we examine in more detail and concrete form what might be reasonably expected.

## 3. ABILITY OF THE MROI TO PROPERLY "IMAGE" GEO TARGETS

Evidence from the literature suggests (Payne 1998; Payne et al 2006) that roughly 50% of GEO satellites have K band (2.2 μm) magnitudes brighter than 12.5. Some examples of photometry of GEO satellites are provided in Figure 2.

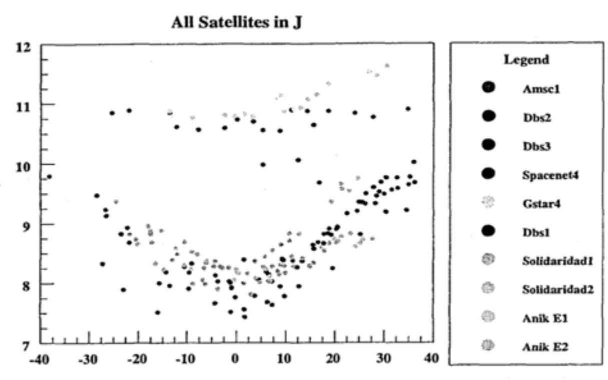


**Figure 2 - Measurements of infrared magnitudes of a number of GEO satellites from Sanchez et al (2000). In the H-band (1.6 micron wavelength) the objects were measured to be approximately 0.3–0.8 magnitudes brighter. The MROI, with an H-band limiting magnitude of 14, should be able to track fringes on all these targets, providing they have significant amounts of compact (< 5 m in size) structure.**

These J-band measurements reveal two classes of targets. The first show a characteristic brightening and then fading with increasing longitude, with excursions of as much as a factor of 10 (i.e. 2.5 magnitudes). A second class show much less variation in brightness, presumably due to a smaller contribution to the total brightness from large highly infrared-reflective solar panels that are altering their orientation with respect to the observer as a function of time. Importantly, in this survey of Sanchez, even the faintest targets had mean J-band magnitudes of approximately 11. The larger datasets of Payne and colleagues (1998, 2006) suggest that perhaps 50% of all GEO satellites will be visible with the MROI in the K-band, assuming the typical red colors seen by Sanchez which imply a median K magnitude of 12.5.

While the MROI will certainly be able to detect targets with a K magnitude of 12.5, a more important question is whether it will be able to properly provide reliable images of such targets. The ability of a ground-based interferometer to image a target depends crucially on how resolved the target is on the baselines that are being measured. For a "good" image to be recovered, the interferometer must secure data on long enough baselines that the smallest structures are appropriately resolved, but also on much shorter baselines so that the larger scale features of the sources are detected and recovered too. The range of physical scales of interest in the target – which might for example run from a few metres (the size of a typical main antenna) to 10 metres (the length of a large solar panel) – will thus act as important drivers for the amount and quality of data that must be secured.

At many long baseline interferometers this need to secure data on a wide range of interferometer baselines can be problematic. This arises primarily for three reasons:

- There may be too few unit telescopes to permit a wide range of inter-telescope separations to be realized without physical movement of them.
- Even with a suitable number of telescopes, it may not be possible to combine beams from all in an efficient way.
- The signal-to-noise ratio for measurements made with an optical/infrared interferometer is a strong function of how well resolved the target is. On baselines where the target is well resolved the S/N will be low, and so it may be difficult to secure reliable data.

At the MROI, the design of the array infrastructure has specifically been optimized to allow these difficulties to be overcome. Notably:

(1) The MROI will utilize up to 10 telescopes simultaneously, although its initial deployment will be with 6 unit telescopes only.

(2) As has been mentioned earlier, the MROI will utilize multi-way beam combiners so that as many inter-telescopes baselines can be interrogated at once as is reasonably possible.

(3) The MROI will incorporate a fringe tracker (a separate instrument from the science instrument), which will monitors the atmospheric disturbances on the shortest nearest-neighbor baselines and stabilize the array. This has been designed to operate at a flux level corresponding to $K = 13$, i.e. 0.5 magnitudes fainter than the median flux levels expected for GEO targets of interest.

It is likely that a reasonable fraction of targets will be compact enough to give high contrast fringes on the short fringe tracker baselines. At GEO, the term "compact" would imply that > 50% of the light comes from a region less than 5 meters across.

More extended sources could also be imaged successfully if they were correspondingly brighter, but some of the structure on scales above ~10 meters might be "washed out" due to over-resolution by the interferometer baselines. In addition, even fainter targets might be accessible if they were observable in the H-band (where the fringe tracker sensitivity is somewhat better), provided they were more compact.

In summary, we expect that overall a significant proportion of the GEO population is likely to be accessible to the MROI. These targets would be observable even when the solar panels are not glinting – allowing the whole target to be inspected without being blinded by the "glare" of a glint. Furthermore multi-color data would allow characterization of the targets.

A key feature of the MROI that we have mentioned earlier, but which deserves highlighting, and which underpins these unique capabilities is the use of a large number of array elements – up to 10 – simultaneously. Not only does this allow for robust monitoring and correction of the atmospheric perturbations (this leads to diffraction-limited resolution), but it compensates for the inability to use Earth Rotation Synthesis to fill in the Fourier (uv) plane when targeting GEO objects. The need to secure quasi-complete Fourier plane coverage in a few-minute "snapshot" is key when attempting to create images of time varying GEO targets. The MROI with its 10 telescopes will be unique in being able to collect such a high density of Fourier visibility and closure phase measurements in a rapid manner.

## 4. IMAGING WITH THE MROI

As with all interferometric synthesis arrays, the process of imaging is a post-observing procedure which takes as input a large number of fringe visibility amplitude and closure phase data, each of which corresponds to a measurement of the Fourier Transform of the target at a particular spatial frequency coordinate. An image is reconstructed by an iterative procedure which determines the most probable image consistent with the data. The reconstruction techniques have been developed and used routinely for imaging at radio, millimeter and optical/infrared wavelengths for many years now.

With the full 10-telescope complement of the MROI it will be routinely possible to make images containing $7 \times 7$ resolution elements. Depending on the precise array layout being used, these could distinguish for example 70 cm features on a 5-meter satellite, or 30 cm features on a 2-meter satellite. The first phase of deployment of the MROI with 6 telescopes would have a similar angular resolution but would be less able to separate out complex image structure.

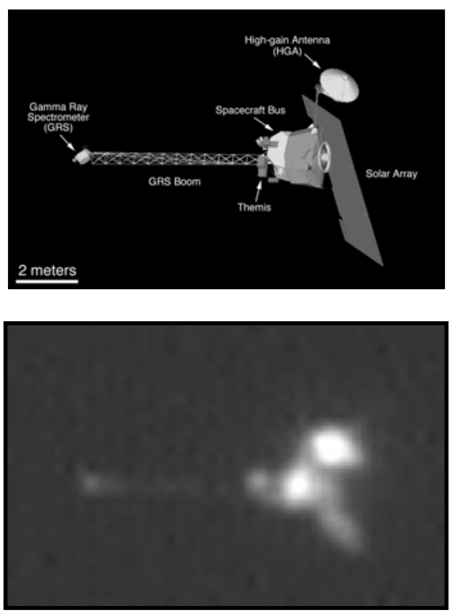


**Figure 3 - An idea of the type of imaging which might be possible with MROI. The top panel shows an artist's rendition of the 2001 Mars Odyssey orbiter while the bottom panel shows an actual image of the orbiter as taken by the Mars Global Surveyor from a range of 90 km. The resolution of this image is comparable to that which could be obtained from MROI at GEO range (36,500 km). The orbiter's size would qualify it as a "compact" object at GEO. Images courtesy NASA.**

In both cases, simultaneous imaging in multiple spectral channels to give a "hyperspectral" image cube would be available. This would typically provide 5–70 channels across either the 1.2–1.3 micron, 1.5–1.8 micron, or 1.9–2.4 micron wavebands. For a subset of targets it may be also be possible to extract key diagnostics on features as small as 10 cm, depending on the image structure and brightness.

Some initial hints as to what type and quality of imaging might be feasible with the MROI are shown in Figure 3 and Figure 4. The first of these shows an actual image of the 2001 Mars Odyssey Orbiter taken at an angular resolution comparable to that which would be achieved with the MROI if it observed a geosynchronous target. Most of the larger structures are easily visible, and it is clear that the presence and/or absence of certain key orbiter elements would be discernable from an image with this type of angular resolution. Such a target would be relatively compact in comparison to a large commercial communications payload.

Figure 4 shows a preliminary image reconstruction for a simulated observation made with a 10-element deployment of the MROI for a larger (26 m) satellite in geosynchronous orbit. A difference in albedo between the left and right circular antennae has been clearly detected in the reconstruction.

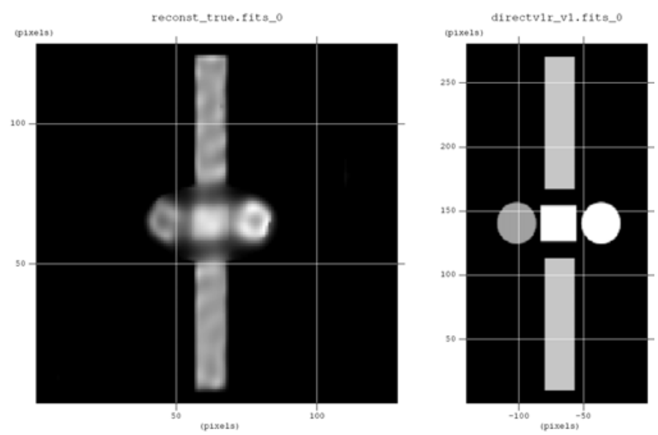


**Figure 4 - Reconstruction (left) and truth image (right) for a simulated 10-telescope MROI observation of a Boeing 601-bus geostationary satellite, similar to DIRECTV 1-R. The longest dimension of the satellite, spanning the length of the solar panels, was 26 meters. The simulated observation consisted of five 100 second integrations using 6-telescope sub-arrays of the most compact 10-telescope MROI configuration, using 5 spectral channels across the 2.0–2.4 micron (K band) wavelength range. The MROI's science instrument will incorporate a fast optical switchyard which will enable these data to be captured in ~10 minutes. The satellite brightness was assumed to be 8th magnitude at K band. An initial reconstruction (not shown) was made using a subset of the data and an uninformative prior image, and used to determine the orientation of the over-resolved solar panels. A more detailed prior image was then used to obtain the reconstructed image shown.**

To confirm these initial suggestive results, further studies including realistic simulations of satellite appearances at multiple infrared wavelengths will need to be undertaken. We expect to initiate such studies in the near term so as to permit more detailed predictions of the likely diagnostic capabilities (for example, detection thresholds, contrast ratios measurable, image fidelity, signal-to-noise etc) to be made.

## 5. CONCLUSIONS

We have outlined the capabilities of the MROI and have concluded that it offers an unprecedented new capability in GEO imaging. The MROI capitalizes on both significantly enhanced sensitivity compared with existing ground based interferometer arrays and also on significantly higher (> 10×) resolution as compared to any ground-based AO-corrected telescope likely to be deployed in the next 10–20 years.

The Magdalena Ridge Observatory interferometer leverages the designs of earlier arrays but combines their design knowledge with state-of-the-art sensitivity and a step change in the number of array telescopes which are combined together (from 2 or 3 to 10). It is this unique large number of telescopes, coupled with its high sensitivity and multi-beam combination that will allow snapshot imaging of GEO targets to become reality.

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## BIOGRAPHIES

***Chris Haniff*** *is a Professor of Physics at the University of Cambridge, UK. He has contributed significantly to the use of high-angular resolution imaging techniques in astronomy, in particular the application of aperture synthesis method at optical and infrared wavelengths. He is currently head of the Cambridge based team collaborating with New Mexico Tech on the deployment of the Magdalena Ridge Observatory Interferometer and responsible for the overall technical design of the facility. He has bachelors and masters degrees in Physics from the University of Cambridge, where he also studied for his PhD in Astronomy.*

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