The MROI's capabilities for imaging geosynchronous satellites

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Abstract

Interferometry provides the only practicable way to image meter-scale structure in geosynchronous satellites. This capability represents a unique commercial opportunity for astronomical interferometry, but to date no interferometer has been able to make an image of such a satellite. We discuss the challenges of imaging these objects and present results of sensitivity calculations and imaging simulations which show that the Magdalena Ridge Observatory Interferometer is likely to be well-suited to this application. Our preliminary results suggest that a significant proportion of GEO targets may be accessible and that it may be possible to routinely extract key satellite diagnostics with an imaging capability that would be able to distinguish, for example, 70 cm features on a 5-meter satellite bus and payload, 30 cm features on a 2-meter satellite bus or similarly sized structure, as well as precise quantitative information on much larger structures such as 10-m long solar panels.

Introduction

The Magdalena Ridge Observatory Interferometer (MROI) project is an international collaboration between the New Mexico Institute of Mining and Technology (NMT) and the Cavendish Laboratory at the University of Cambridge in the UK to build the world's most ambitious and sensitive optical/near-infrared imaging interferometer. The observatory site is located at an elevation of approximately 3,120 m (10,460 ft) above sea level in the Magdalena Mountains in southern New Mexico. One of MROI's core missions will be to provide a tool for the commercial, military and intelligence communities to support space situational awareness[1].

Imaging of most GEO targets is difficult with ground-based telescopes. At near-infrared wavelengths, even a 10m-class telescope with full AO correction is limited by diffraction to resolving scales of 8 meters or more at the distance of geosynchronous orbit. To achieve sub-meter scale imaging would require a diffraction-limited telescope at least 50 meters in diameter, clearly an unrealistic prospect in the forseeable future.

An alternative to large monolithic telescopes comes from interferometry with arrays of smaller telescopes. Astronomical interferometers such as CHARA and VLTI are now producing images with angular resolutions far exceeding those of a 50-meter telescope. However, there are two key problems that have hampered the use of interferometry in the GEO domain. The first is that most current interferometers are only suited to imaging relatively bright objects, brighter than the majority of GEO targets unless these are "glinting"[2]. The second is that most existing arrays do not have enough telescopes to make images of complex geostationary objects. The design of the MRO interferometer overcomes these limitations.

Key MROI design features relevant to GEO imaging

- Much better limiting sensitivity (K=13) than existing arrays, due to optimized opto-mechanical design with minimum number of reflections
- Model-independent snapshot imaging capability (10 telescopes in final deployment)
- Relocatable telescopes, allows angular resolution to be matched to the size of the target (minimum baseline 7.8 m)
- Baseline bootstrapping capability and dedicated fringe tracking instrument, for on-axis fringe tracking of faint resolved targets

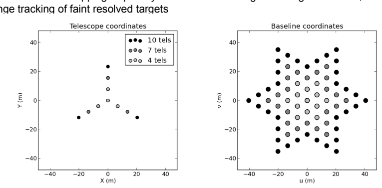

Figure 1 – MROI array layout (left) and instantaneous *u*,*v* coverage (right) for a target at the zenith.

Sensitivity match to GEO targets

We can estimate the apparent brightness of non-glinting targets illuminated by the sun by assuming an average reflectance and overall target size. Assuming a spherical and diffuse target with an average reflectance of 0.2, then at a wavelength of 2.2 microns a target with an overall extent of 3 m would have a K magnitude of 12, well within MROI's projected capability, and a 5 m diameter target would have a magnitude of 11, bright for MROI. These targets would be too faint to be imaged by other arrays, with typical published limiting magnitudes of 7–9.

Evidence from the literature (Payne 1998[3]; Payne et al 2006[4]) suggests that roughly 50% of GEO satellites have K band magnitudes brighter than 12.5. This is broadly consistent with our estimates, and suggests that a large fraction of GEO targets will be bright enough to be imaged with MROI.

Imaging performance

We have performed simulations of MROI imaging for two representative GEO targets. Simulated datasets were prepared by evaluating the discrete Fourier transform of suitably scaled model images at spatial frequencies corresponding to the assumed MROI interferometric projected baselines. Model images were simulated using the TASAT software[5]. The targets were assumed to have a constant structure across the spectral channels of the science beam combiner. The Fourier data were then used to generate "perfect" values of the relevant interferometric observables, i.e. squared visibilities and bispectra. Random errors were added to these values so as to properly mimic the signal-to-noise that would have been expected given various target magnitudes, the predicted interferometric performance, e.g. coherence losses due to jitter etc., and the assumed detector performance. In addition, uncorrelated calibration errors on the visibilities ($\Delta V^2/V^2$=0.02) and closure phases (0.8°) were added. We assumed the presence of a switchable science beam combiner which mixes 6 beams together simultaneously (using 192 pixels per spectral channel to sample the spatially-encoded fringes), and 4e^- readout noise.

The simulated squared visibilities and bispectra were saved in the OIFITS format[6] and used as input to the BSMEM image reconstruction code[7]. For each dataset, a two-step reconstruction procedure was employed, similar to that used for previous BSMEM entries to the IAU-sponsored beauty contests[8]. First, higher-spatial frequency data were removed and BSMEM run with a uniform disk prior image. High spatial frequencies and noise were removed from the BSMEM output image by convolving with a circular Gaussian and setting pixel values below a user-selected threshold to zero. The resulting image was used as a prior for a second run of BSMEM on the full dataset.

Figure 2 shows results of imaging simulations for a range of assumed target brightnesses and sizes relative to the angular resolution of the interferometer array. The satellite used for these simulations comprises a pair of large solar panels and a more compact central bus, this type of structure being a common one for GEO satellites. In all cases the most compact 10-telescope MROI configuration was assumed, with science data being secured in the astronomical K-band (2.0–2.4 micron). The K-band magnitudes used were 8 (somewhat optimistic for a GEO target, used to show the limiting effects of the Fourier-plane coverage for moderate signal-to-noise data) and 11 (a more realistic brightness). The MROI fringe tracking combiner is predicted to have sufficient signal-to-noise to track on the latter target effectively on the nearest-neighbour baselines, despite needing to operate at a shorter wavelength where the target is more resolved. The mean signal-to-noise of the squared visibilities measured by the science combiner in 100 seconds ranged from 4.8 (for the larger K=11 target) to 12.5 (for the smaller K=8 target). The mean closure phase error ranged from 1.5° to 54°. In the latter case there is a noticeable impact on the quality of the imaging (see middle left panel of Figure 2).

The major features of the satellite have been reconstructed successfully, including the shape and orientation of the solar panels and the main features of the satellite bus. Reconstructing meter-scale or smaller structures on the bus is inherently problematic for targets with a pair of solar panels spanning 20–30 m, as this range of scales exceeds that which a single interferometer configuration is sensitive to (set by the ratio of the longest to the shortest baseline). State-of-the art image reconstruction algorithms provide a degree of super-resolution (typically a factor 2 for moderate S/N) which mitigates but does not remove this difficulty. The issue could be addressed by combining MROI data with low-spatial frequency data from a filled-aperture telescope, by incorporating an *a priori* model for the solar panels (fitting for the unknown orientation), or, for smaller satellites, by using two different MROI configurations.

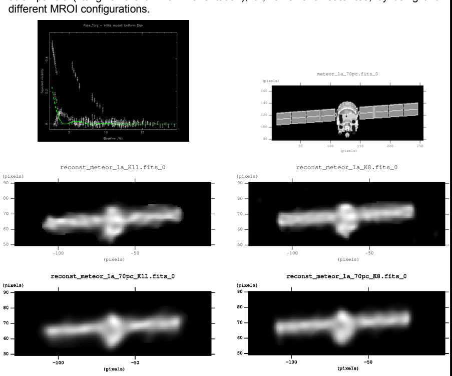

Figure 2 – Truth (top row) and reconstructed (middle and bottom rows) images for a simulated MROI observation of a typical satellite with a pair of large solar panels. A plot of the simulated squared visibilities against projected baseline length is shown at top left (a 10 m uniform disk is also plotted for comparison). Each simulated observation consisted of 5×100 second integrations using 6-telescope sub-arrays of the most compact 10-telescope MROI configuration, and used 5 spectral channels spanning the astronomical K band. Satellite brightnesses of 11th magnitude (left column and visibility plot) and 8th magnitude (right column) in the K band were assumed. The maximum extent of the target, spanning the long solar panels, was 23.7 m (middle row) and 16.6 m (bottom row) respectively. These sizes correspond to the typical size of large communications satellites, and to 70% of this size which is a better match to the spatial frequencies sampled by the most compact MROI array at K band.

Imaging performance (cont.)

For targets where the panels are comparable in size to the bus, imaging the details of the bus is more straightforward, as illustrated by the results in Figure 3. Here the satellite size was adjusted to match the resolution of the telescope array, and as a result the shapes of the bus and solar panel and the smaller-scale brightness variations across the bus have been accurately reconstructed. A greater degree of super-resolution is evident in the K=8 reconstruction owing to the higher signal-to-noise (by a factor of ~3 for the squared visibility data and ~20 for the closure phases) of the input Fourier data.

Further algorithm development to tune existing interferometric image reconstruction codes to better match the structural elements characteristic of geosynchronous targets (e.g. by using a more appropriate regularization than the maximum entropy approach used by BSMEM) is also likely to give superior imaging capabilities.

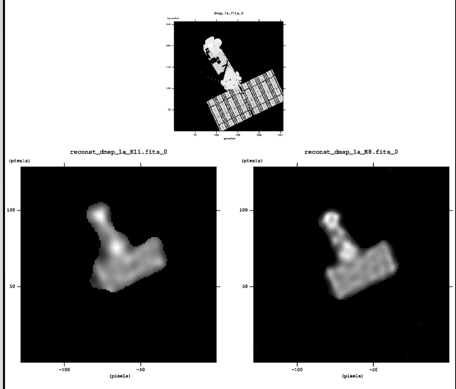

Figure 3 – Truth (top row) and reconstructed (bottom row) images for a simulated MROI observation of a satellite with a bus and solar panel of comparable size. Satellite brightnesses of 11th magnitude (left image) and 8th magnitude (right image) in the K band were assumed. The remaining simulation parameters were identical to those for Figure 2. The long dimension of the solar panel was set to be 11.9 m, approximately equal to the fringe spacing on the shortest baseline.

Conclusions

We have outlined the key design features of the MROI and have concluded that it offers an unprecedented new capability in GEO imaging. Preliminary simulations of satellite imaging with MROI are showing an impressive level of fidelity even without optimization of the algorithms for GEO targets. 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.

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