Imaging of Geostationary Satellites with the MRO Interferometer

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ABSTRACT

We discuss the capability of the Magdalena Ridge Observatory Interferometer (MROI) to image geostationary satellites. The MROI has a maximum baseline of 347 meters and therefore has an unprecedented angular resolution capability compared to current generation telescopes with primary mirrors up to 10 meters.

We have simulated the imaging capability of the MROI for the case of the geostationary telecommunication satellite Galaxy 12. Images were reconstructed for this satellite using the MROI close packed configuration (this mimics a telescope with a diameter of approximately 41 meters), when using light from the visible (600 nm) to the near-infrared (2.4 micron). Galaxy 12 is rather large compared to the minimum telescope separation (7.8 meters) available. The imaging capability will improve for targets about half the size of Galaxy 12 at a geostationary distance.

The expected visual magnitude of Galaxy 12 is about m_v=14. During a glint, this brightness can increase by a factor 10,000 to m_v=4. The glint is not only bright, but also very small in size, which makes fringe tracking on a glint relatively easy compared to full imaging.

Signal-to-noise computations show that MROI will collect enough photons such that it can image a geostationary satellite within a few hours, if the interferometer is able to bootstrap on a bright glint during that period.

1. INTRODUCTION

The emerging field of optical interferometry will enable imaging of satellites at a height of 36,000 km with a spatial resolution of less than 1 meter. The current generation of optical interferometers has baselines up to 300 meters, which is a factor 100 larger than a 3-meter single telescope. Since the angular resolution scales with baseline over wavelength, the increase in baseline translates directly to an increase in angular resolving power.

The Magdalena Ridge Observatory Interferometer (MROI) [1] will be a 10-element optical interferometer. Each telescope will have a 1.4 meter primary mirror and the maximum baseline within the array is 347 meters. MROI is currently under construction in New Mexico and is designed to meet multiple objectives: provide imaging capability for space situational awareness, to provide science capability to astronomers, and to train the next generation of technical workers [2].

Actual detection of fringes on geostationary satellites have been published [3, 4]. These detections have opened the field of high spatial resolution imaging of satellites using optical interferometers. As a result, we have simulated the performance of MROI to image geostationary satellites. These simulations start with a real image of a geostationary satellite and a model that uses simple geometric shapes to best represent the satellite. This model is fed to a simulator that takes into account the interferometer array configuration and computes the observables using estimates of the errors in the observations due to the intervening atmosphere (Fig. 3). Finally we use existing image reconstruction algorithms to compute a reconstructed image.

2. MRO INTERFEROMETER

For the MROI close packed configuration of 10 telescopes (Fig. 4), the minimum baseline is 7.8 meters, and the maximum baseline is 40.8 meters. The MROI fringe tracker will be sensitive for all wavelengths in the range of 0.9 to 2.5 micron and is optimized for fringe tracking in the H (1.49-1.78 micron), and K_s (1.99-2.31 micron) bands. Future upgrades are planned to extend the imaging capability to the visible band (600 nm to 1 micron). For additional details on the Magdalena Ridge Observatory we refer to the paper by Creech-Eakman et al. in these proceedings [1].

The observable for an optical interferometer is the complex visibility. This is the Fourier transform of the image, sampled at the spacing and orientation of the available baselines. The measured visibility is the amplitude of the complex visibility and ranges from 0 (fully resolved source) to 1 (for a point source). The phase of a fringe cannot be measured with the MROI first generation fringe tracker, only the amplitude. A science instrument will be required that measures the amplitude and the closure phases, in order to reconstruct images as presented here.

3. GEOSTATIONARY SATELLITES

Actual interferometric measurements on a geostationary satellite, DIRECTV-9S, have been reported [3, 4]. The Naval Prototype Optical Interferometer (NPOI), with an East-West baseline of 15.9 meters, was able to detect fringes at spectral wavelength between 500 and 850 nm. Measured fringe visibility squared are as high as 0.15 at 800 nm. Fits using a rectangular shape give best values for a width range of 1.24 to 1.44 meters, with a best fit of 1.34 meter. The NPOI measurements were made during a glint of the satellite that had a visual magnitude of 4.5. For this study we used the case of Galaxy 12 (which is very similar to Galaxy 13 in Fig. 5). This telecommunication satellite was launched on April 9, 2003. Galaxy 12 is about 26 meters by 9.3 meters (full length and width) and orbits Earth in a geostationary orbit. This translates to an angular size of 144 by 51 milli-arseconds on the sky as seen from MROI (at an altitude of 47 degrees, azimuth of 1.2 hours West from South, at a distance of 37,278 km). A glint on Galaxy 12, with a diameter of 1 meter, translates to an angular size of 6 milli-arseconds as seen by MROI. The satellite antenna dishes have a diameter of 2.67 meter, which translates to 15 milli-arcseconds on the sky. Visibility estimates for different segments of Galaxy 12 are shows in Fig. 1. For comparison we also made estimates for the case that Galaxy 12 was scaled down in size by a factor 2, and mimicking a micro-satellite (Fig. 2.).

Table 1. projected size and baseline for first null for specific structures on Galaxy 12. Baseline is computed for a wavelength of 2.15 micron (K-band).

Segment of satellite	Project size on sky [mas]	Baseline for first null [m]
Total length	144	3.7
Total width	55	9.8
Diameter of dish	15	36.6
Diameter of glint	6	97.8

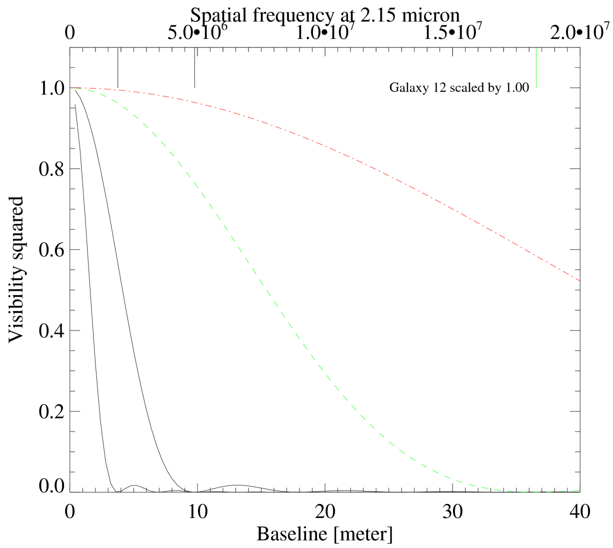

Fig. 1. Galaxy 12 at K-band (2.15 micron). The two solid lines represent the overall width and length of the satellite. The dashed line (green) is for a single antenna dish, and the dash-dotted line (red) is for the glint.

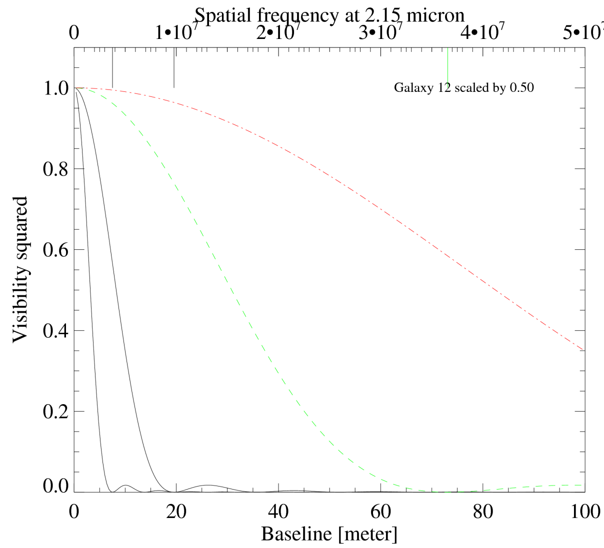

Fig. 2. Galaxy 12 scaled down by a factor 2 (50 % size reduction) at 2.15 micron (mimicking a micro-satellite). Same line coding applies as for the figure on the left. Note that the baseline scale is here up to 100 meters, compared to 40 meters in the left graph.

An indication for the required baseline to resolve these structures is the spatial frequency of the first null in the interferometric signal (see Fig. 1 and 2). The first null is at $B = 1.22\frac{\lambda}{\theta}$ for a uniform disk model with a total angular diameter of θ. The baselines for the first null are listed in Table 1. To sample the structures of Galaxy 12 properly would require baselines as short as 3.7 meters to sample the length of the satellite up to its first null at K-band. The minimum baseline of the MROI is rather large for this kind of application. For all other structures, the minimum MROI baseline of 7.8 meters is appropriate for K-band. Observing at longer wavelength could theoretically provide MROI with the correct spatial frequency to measure the larger structures. However observing beyond 2.4 microns becomes difficult due to the thermal background of the atmosphere and the optics.

4. SIMULATIONS

The goal of this paper is to demonstrate the most optimistic imaging capability for geostationary satellites with the MROI. Based on the angular size of the structures on the satellite, the MROI close packed configuration (Fig. 4) is the preferred setup. This is the most condensed configuration with the shortest baselines. For astronomical objects, the Earth rotates with respect to the sky, and this results in an object moving across the sky during the night. An interferometer uses this to increase the sampling of the uv-plane. This is referred to as Earth rotation synthesis. For a geostationary satellite this is not feasible as they remain at a fixed azimuth and elevation. To increase the uv-coverage we have added wavelength coverage from the visible (650 nm) to the near-infrared (2.4 micron).

Simulations were performed with software provided by the University of Cambridge, Cavendish group (UK). An observing strategy was computed with the program *obstrat*, visibilities were predicted for this strategy and the simplified geometric model of the target using the program *bsfake*. The output of these programs are the computed visibilities and closure phases. The image was reconstructed using the *bsmem* software package that uses a maximum entropy method to compute the reconstructed image [5, 6]. The process applied is visualized in the flow diagram of Fig. 3.

For all simulations we used 10 telescopes in the MROI close packed A configuration. This gives a total of 45 baselines. We assumed a 10-way science beam combiner so that all available baselines can be used for the simulations. We assumed ideal observing conditions given a noise contribution of 0.6 degree on the phases (0.01 rad) and 1% on visibilities on each discrete visibility measurement. Starting with a model (Fig. 6) at the appropriate dimensions on the sky for Galaxy 12. We note here that we have introduced asymmetry in the image by giving the different structures (dishes, solar panel, hub) slightly different intensities. Fig. 7 shows the uv-tracks. Fig. 9 shows the visibility squared computed for this set of parameters. These visibilities go as high as 0.3 for the smaller baselines for the small structures (unresolved structures: e.g. point sources), to close to zero for the larger baselines and the larger structures (resolved structures).

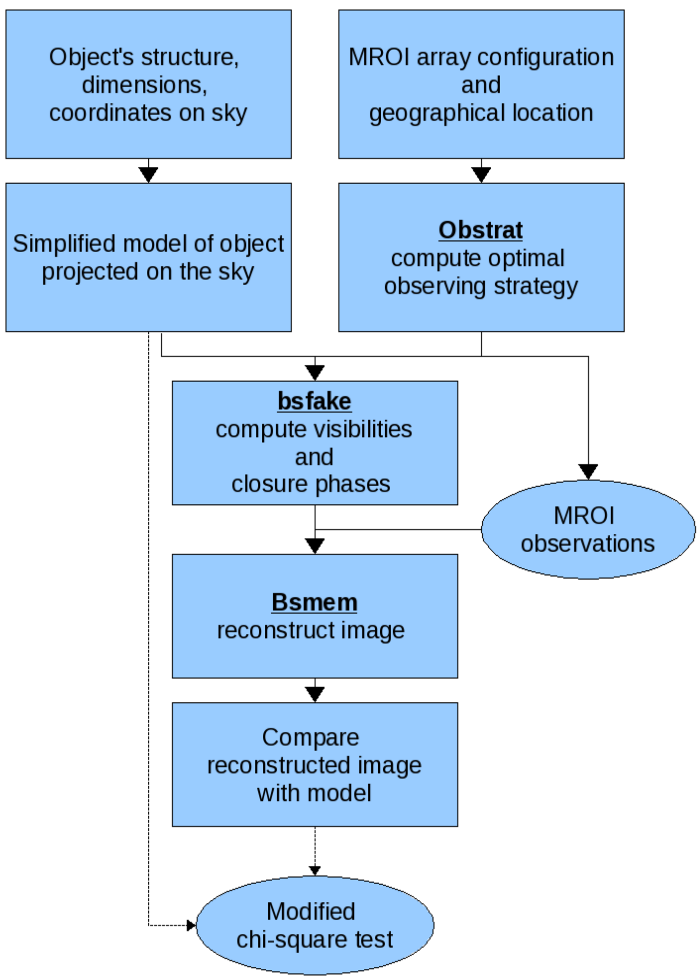

Fig. 3: flow diagram of the process applied for the simulations.

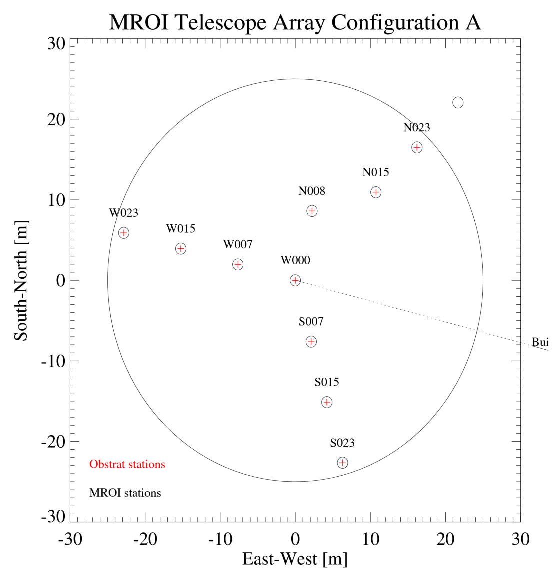

Fig. 4. MROI close packed array configuration. The circle is a 50 meter diameter representing a single dish telescope this size. The dashed line points to the location of the beam combining laboratory, which is at 32.5 m from station W000.

Fig. 5. Galaxy XIII/Horizons-1, similar to Galaxy 12 (courteously from Boeing).

We pushed the performance of MROI to its limit. Used its full wavelength coverage from 650 nm to

2.4 micron sampled at 0.1 micron steps (neglecting that the atmosphere is only transparent in selected windows) and assumed that the satellite looks the same over this wavelength range (it looks gray). For MROI to operate in the visible with its full aperture of 1.4 m diameter, adaptive optics would be required. The two radio dishes (East and West circles) are well identified (Fig. 8), and the Northern solar panel (ellipse at the top) is also visible. The fainter Southern solar panel is barely recovered. These simulations indicate that the MROI has the capability to image geostationary satellites. A critical aspect in these simulations is that the object is bright enough to be able to detect and track the fringes. This issue will be addressed in the section "signal-to-noise ratio".

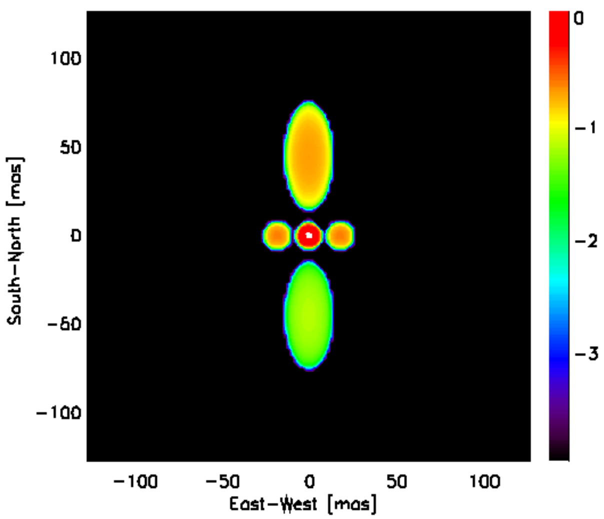

Fig. 6. model that represents Galaxy 12 as seen from MROI. The orientation of the satellites is arbitrary. Log color scale applied.

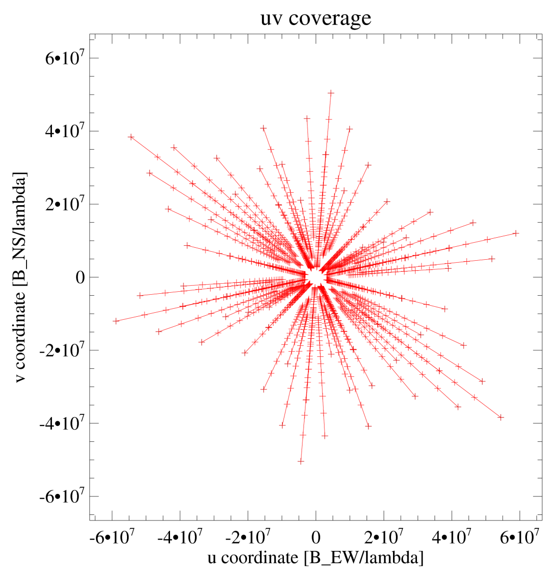

Fig. 7. uv-coverage for the MROI close packed configuration pointing towards the position of Galaxy 12. For each line, the crosses represent the wavelengths of the observations.

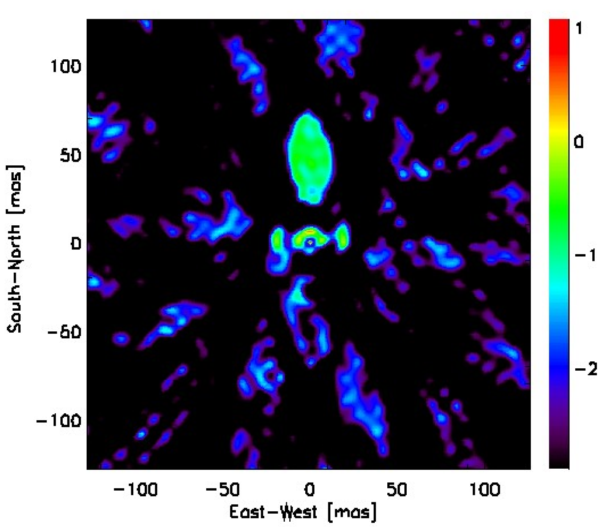

Fig. 8. reconstructed image for Galaxy 12. Log color scale applied.

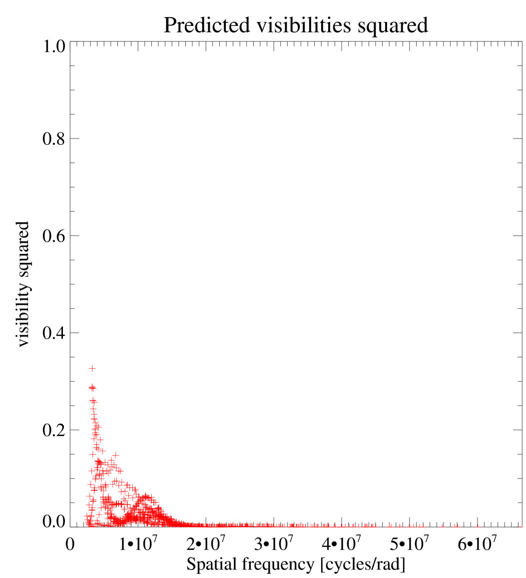

Fig. 9. predicted visibility squared for the model and the uv-coverage combination, for all 45

baselines, and 18 wavelength channels.

We will now investigate what size of geostationary satellite would lead to better reconstructed images with MROI. We started with Galaxy 12 at it's real projected size on the sky, and scaled dimensions down linearly with a scaling factor. All other parameters were kept identical.

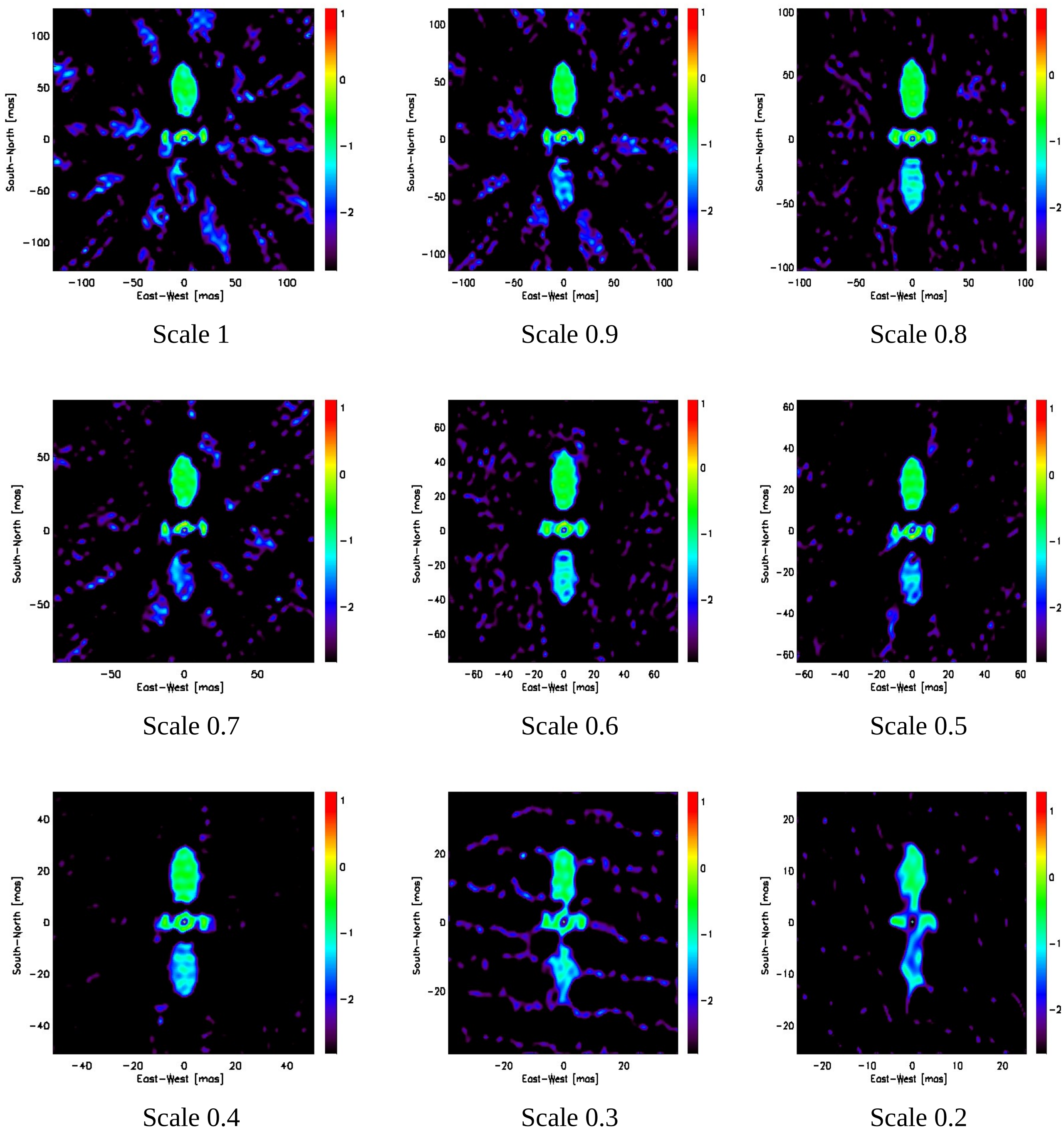

Fig. 10. sequence of reconstructed images for which the satellite has been scaled down in dimension from 100% to 20 % of its real projected size, 600 nm - 2.4 micron, bin size = 0.1 micron.

In an image sequence (Fig. 10) starting with the real projected size (scale 1) and decreasing this size in step of 0.1 (10 %), we notice that the reconstructed image first improves when reducing the size of the satellite, but then starts to degrade. For this satellite, based on a modified chi-square test, the best reconstructed image occurs around a scale factor of 0.5 (Fig. 11), which is half the size of Galaxy 12 at a geostationary distance. We follow the procedure described by Cotton et al. [6] to measure the quality of the reconstructed image relative to the model input image.

1. The image was centered using the center of gravity of pixel values for the inner region of the map;
2. Each submitted image and model were normalized using the sum of the pixel values in a box containing the satellite;
3. Subtract the normalized, logarithmic scaled model from the normalized logarithmic scale reconstructed image;
4. Determined the rms value over the center part of the map that contains the satellite;

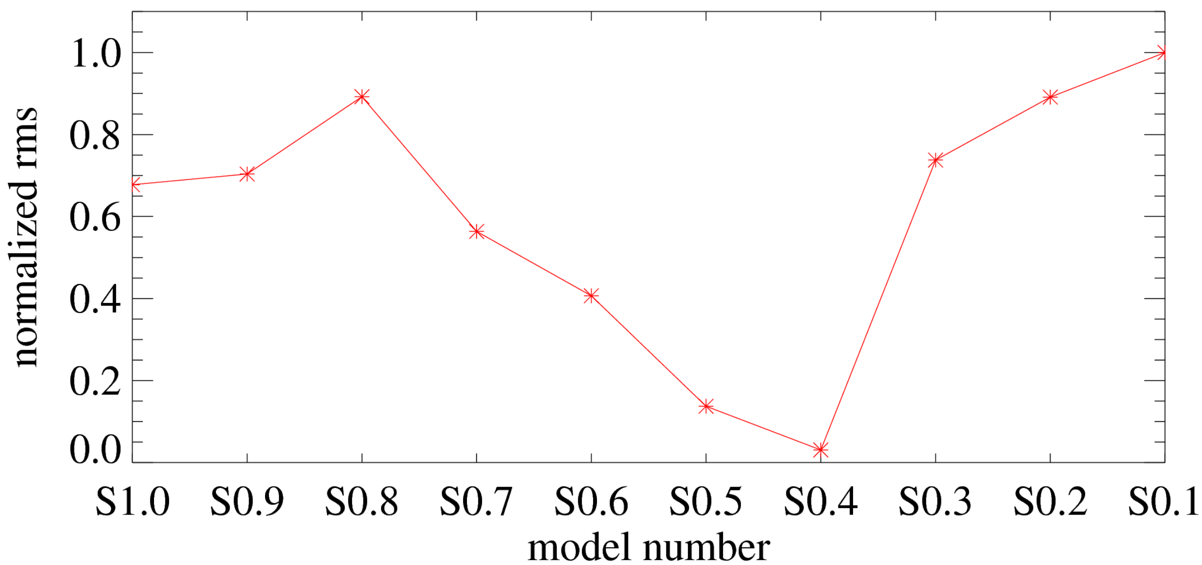

Fig. 11. modified chi squared test on reconstructed image to model images. Galaxy 12 was scaled down by factors 1, 0.9, 0.8 ... to 0.1 (10 % its original projected size).

A second sensitivity analysis was conducted to investigate the sensitivity for wavelength coverage. We increased the total wavelength coverage, and also the spectral resolution.

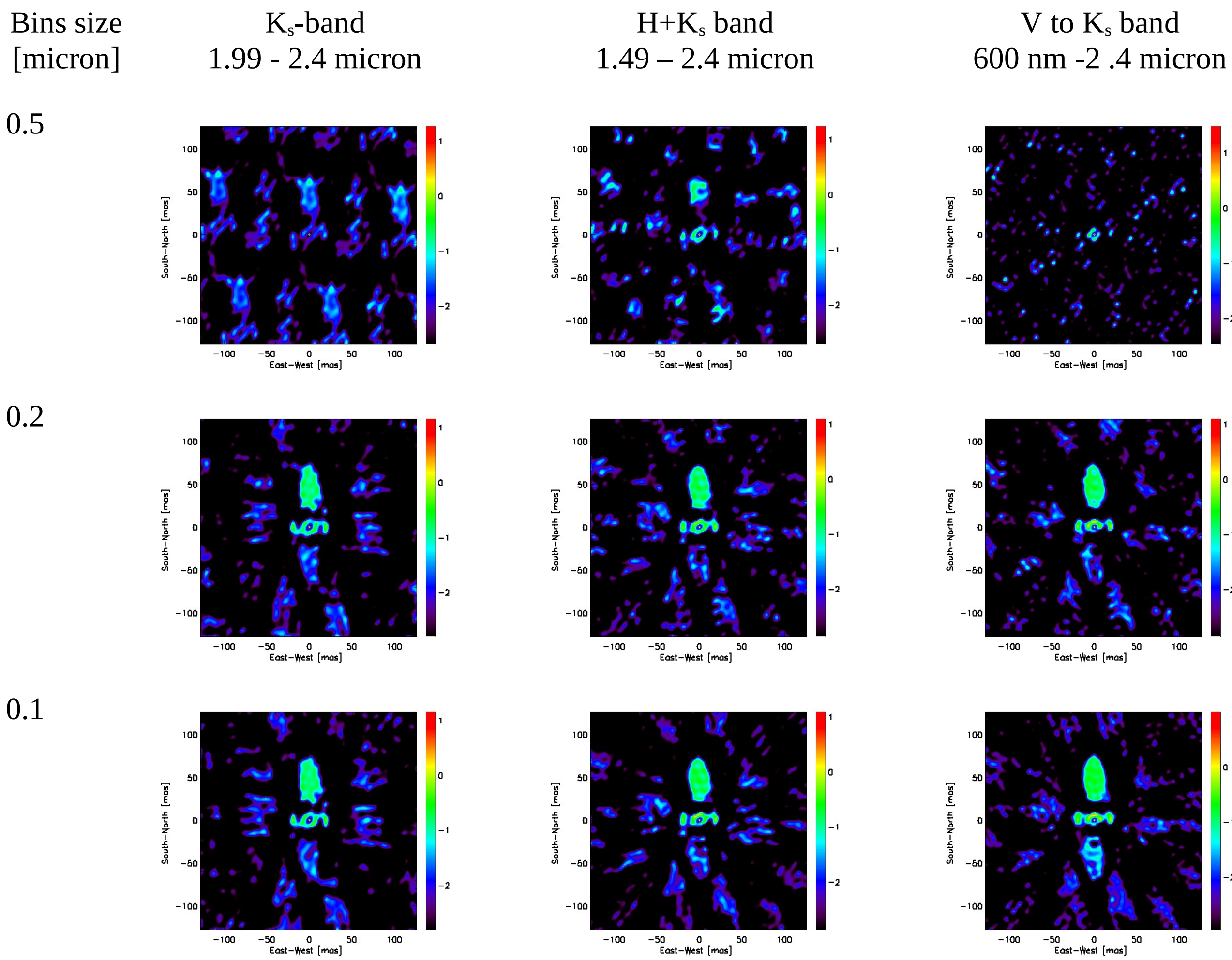

Fig. 12. sequence of reconstructed images for which the total wavelength coverage increases to the right, and the spectral resolution down.

We note the increase of performance from the upper left to the lower right (Fig. 12). The lower left being the same images as presented in Fig. 8. The initial capabilities of MROI is closest to the low spectral resolution (0.5 micron bins), and the limited wavelength coverage (K_s band).

6. SIGNAL-TO-NOISE RATIO

The fringe-tracking SNR is $SNR_{FT}=NV^2$, where N is the number of photons measured in one coherence time, and V is the visibility amplitude. Let us make several assumptions: the satellite reflects the spectrum of the sun, fringe-tracking takes place across the entire visible spectrum, the fringe visibility is $V^2=0.1$, and system throughput and visibility approximately matches the factors for the MRO interferometer (15% and $V^2=0.3$ for K_s band respectively). In order to image the structure of the satellite other than the glint, fringes must be observed on longer baselines. We will assume that a SNR=10 is required on the visibilities from the rest of the satellite in order to adequately image it. In that case we are operating in the high SNR regime where SNR_{IMG}=SQRT(N) V. However, the rest of the satellite is 10^{-4} times fainter than the glint, thus effectively reducing the satellite visibilities by a factor of 10^4. Because the glint also has non-zero visibility at long-baseline this requires observing the glint with a correspondingly greater SNR. In performing the calculations it makes no difference whether we consider observing the small visibilities of the satellite with a SNR=10 or whether we consider observing the larger glint visibilities with a correspondingly larger SNR. However, there are practical problems with separating the very large glint signal from the very small satellite signal which this SNR calculation does not take into account. Fig. 13 shows the computation of the imaging SNR requirements based on a simple model of two uniform disks: a bright disk with a diameter of 1 meter representing the glint, and a faint disk with a diameter of 10 meters representing the satellite. We assume observation in a single wide channel.

Table 2. Approximate required integration time to achieve SNR=10 in a single wide channel through a MROI-like aperture for selected baseline lengths. This assumes bootstrapping using the glint on the shortest baselines.

Visual Magnitude	10 meter	30 meter
13.5	Several hours	Several days
16.0	Many hours	Many days

Table 2 lists estimated integration times. From that it can be seen that detecting the signal to obtaining sufficient SNR at longer baselines required for imaging will require very long integration times (while fringe tracking on a glint). These number should be contrasted against a typical glint time of a few minutes only twice during the year. If observing at multiple wavelength (for example to synthesis multiple baseline lengths as an alternative to Earth rotation), the integration time will scale linearly with the number of channels chosen.

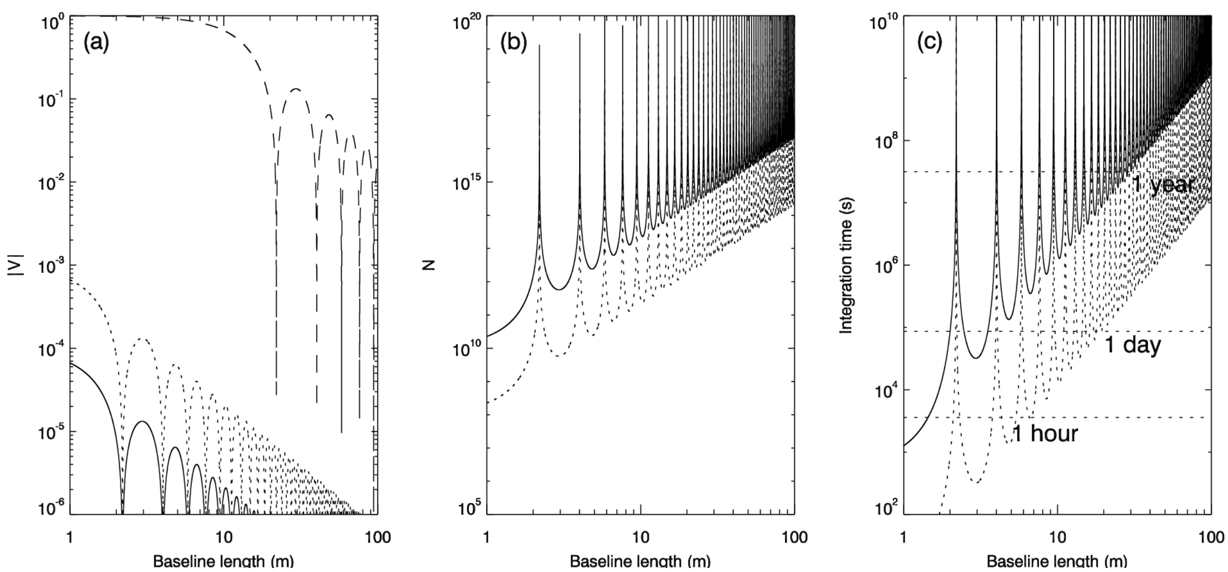

Fig. 13. imaging SNR for a satellite of diameter 10 meters with a 1 meter glint at 6th magnitude and the satellite 10^3 or 10^4 times fainter. Quantities relating to a 13.5th magnitude satellite are dotted, those relating to a 16th magnitude satellite are solid. (a) Visibility (V) of the satellite and the glint (dashed). (b) Required number of photons to achieve SNR=10 in a single wide channel. (c) Integration time through an MROI-like aperture. This assumes bootstrapping of the array using the glint on the shortest baselines.

7. DISCUSSION

1. Homogeneously illuminated geostationary satellites (without a glint) the size of Galaxy 12 (10 by 30 meters) can be imaged with an optical interferometer (e.g. MROI) operating from the visible to near-infrared, with a minimum baselines of 8 meters, assuming that the satellite is bright enough to perform fringe tracking and obtain sufficient imaging SNR in a reasonable amount of time;
2. A glint on a satellite that raises the flux on a small segment of the telescope (1 meter squared) by a factor of 10,000 can easily be detected by MROI;
3. Increasing the uv-coverage by Earth rotation synthesis is not possible with geostationary satellites. Observing at different wavelengths allows to have radial tracks of uv-coverage and will improved the image quality. This will work if the spectral characteristics of the satellite are the same over the range of wavelength used;
4. MROI in its close packed configuration is better suited to observing satellites about half the size of Galaxy 12 with typical dimensions of 5 to 15 meters at a geostationary distance;
5. Preliminary estimates suggest that integration times of several hours will be required on typical passively illuminated satellites in order to obtain sufficient SNR on imaging baselines, while at the same time bootstrapping the array using the bright glint on the shortest baselines.

8. REFERENCES

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