Aperture-synthesis imaging with the mid-infrared instrument MATISSE

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ABSTRACT

MATISSE is the second-generation mid-IR interferometry instrument proposed for ESO's Very Large Telescope Interferometer. MATISSE will combine the beams of up to four UTs or ATs of the VLTI and will allow aperture-synthesis imaging in the L, M, and N bands with a resolution of a few milli-arcseconds. We report on detailed image reconstruction experiments with simulated MATISSE interferograms. Using model images as input for many of our simulations, we study the dependence of the reconstructions on the brightness and size of the target, the uv coverage, and several other parameters.

Keywords: interferometry, high-angular resolution, image reconstruction

1. INTRODUCTION

The main goal of MATISSE is to perform aperture-synthesis imaging in the mid-infrared spectral regime with unprecedented ($\sim$ 10 mas-) resolution. The VLTI with its four fixed 8.2 m telescopes and four relocatable 1.8 m auxiliary telescopes (ATs) provides the best infrastructure for this task nowadays. Since the end of 2002, MIDI has impressively demonstrated the feasibility of interferometric observations in the mid-infrared wavelength range with the VLTI. The two-beam combiner MIDI already gives the scientific community the possibility of high-angular resolution observations, although due to the lack of phase measurements, it is not able to perform imaging. Interpreting MIDI data always requires a-priori information about the structure of the object in form of a model. The parameters of such a model are then determined through MIDI observations. MATISSE will provide the opportunity to overcome the drawbacks of the lacking phase information of MIDI and will allow aperture-synthesis imaging.

In the last decade, several image reconstruction algorithms were developed for aperture-synthesis imaging with infrared arrays consisting of a small number of telescopes; for example, BSMEM (BiSpectrum Maximum Entropy Method; Buscher[1]), MACIM (Markov Chain Imager; Ireland[2]), MIRA (Multi-aperture Image Reconstruction Algorithm; Thiebaut[3]), Recursive Phase Reconstruction (Rengaswarmy[2]), BBM (Building Block Mapping Hofmann&Weigelt[4,5]). The performance of such algorithms was evaluated up to now in two blind tests initiated by the IAU Working Group on Optical/IR Interferometry[2,6] .

We demonstrate that the amount of interferometric data obtained with 3 or 4 telescopes is sufficient to perform aperture-synthesis imaging under realistic observational conditions. We report on detailed image reconstruction experiments with simulated MATISSE interferograms and the BBM method. We study the dependence of the reconstructions on the brightness and size of the target, the uv coverage, and several other parameters.

2. APERTURE SYNTHESIS IMAGING AT SIMULATED REALISTIC OBSERVING CONDITIONS

In this section we study image reconstruction with the Building Block mapping (BBM) method[4] using simulated interferometric data from observations (a) with 4 ATs during 3 nights, i.e. with 3 different array configurations.

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Wavelength	10.5 μm
Start of Observation	-4.5 hours of meridian
End of Observation	4.5 hours of meridian
Maximum zenith distance	60°
Time for one Data Point	1 hour
Detector Integration Time	900 ms
Total Integration Time for one Data Point	15 min

Table 1. Parameters used for the following MATISSE simulations.

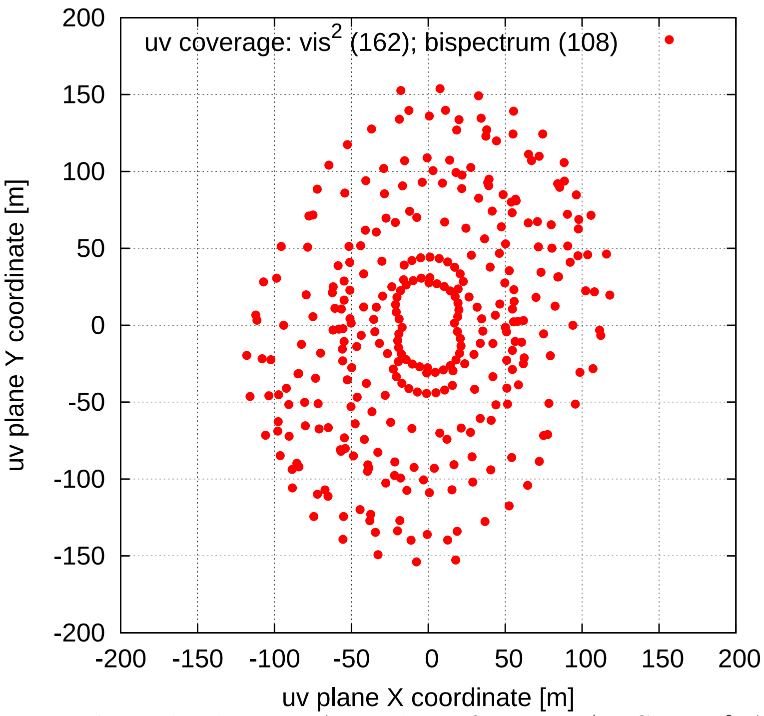

Figure 1. Simulated uv coverage obtained with 4 VLTI ATs and 3 configurations (DEC $= -60°$, AT stations: B5-D0-G1-J3, A1-B5-D1-K0, A0-G2-I1-J6).

2.1 Building Block mapping

The BBM method[4] was developed to reconstruct diffraction-limited images from the bispectrum of the object obtained with bispectrum speckle interferometry or long-baseline interferometry. Since the intensity distribution of an object can be described as a sum of many small components, our algorithm iteratively reconstructs images by adding *building blocks* (e.g. δ-functions) to a model image. The initial model image may simply consist of a single δ peak, to which components are iteratively added. Within each iteration step, the next building block is positioned at the particular coordinate which leads to a new model image that minimizes the deviations (χ^2) between the model bispectrum and the measured object bispectrum elements. An approximation of the χ^2-function was derived which allows fast calculation of a large number of iteration steps (see Ref. 4 for more details). Beside positive building blocks, also negative building blocks can be added to the reconstruction. Adding both positive and negative building blocks improves the convergence of the algorithm, when the positivity constraint for the final image is taken into account. Adding more than one building block per iteration step also improves the resulting reconstruction and the convergence of the algorithm. A regularization procedure, based on the maximum entropy constraint, is also included in the algorithm to find the smoothest best fitting image (see Ref. 5).

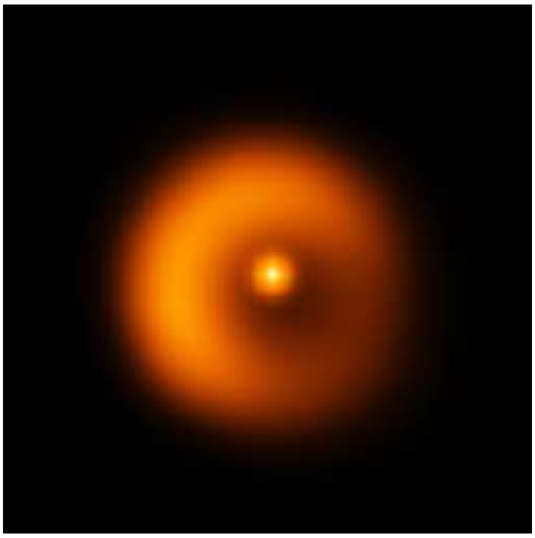

Figure 2. The target used for the MATISSE image reconstruction experiments was a model image of LkHa 101 (disk of a YSO) which was provided by P.G. Tuthill.[6] This target is named *Target1* in the following experiments.

Wavelength	10.5μm
Target declination	$-60°$
Number of interferograms per visibility value	1000
Average SNR of the calibrated squared visibilities	20
Total number of sky background photons / interferogram (ATs)	3.6×10^8

Table 2. Interferogram simulation parameter (see text for more details).

2.2 Simulation of interferometric data

A simulator allowing the generation of a large number of individual noisy interferograms was developed. This simulator generates 1-dimensional coaxial 2-telescope interferograms (MATISSE N band data). The interferograms are degraded by photon and sky background/detector noise, and a random piston. From 1000 generated 2-telescope interferograms the average power and bispectrum is calculated. Subtraction of the noise bias in the average power spectrum, photometric calibration, and calibration with an unresolved reference star yields the calibrated visibility. Since the bispectrum is the product of the fringe peaks of 3 different 2-telescope interferograms, the average bispectrum is free of any noise bias. For the simulations below, the number of sky background photons for a MATISSE observation with 4 ATs in N band was derived from MIDI data taken with 2 UTs in February and August 2004 during commissioning. The derived average number of sky background photons in a simulated 2-telescope interferogram (exposure time/interferogram: 900ms) is $\overline{\mathrm{M}} = 3.6 \times 10^8$.

In the following sections the quality of the reconstructed images was measured by the restoration error, which we defined as

$$\rho := \frac{\sqrt{\int |o_k(x) \otimes p'(x) - o(x) \otimes p'(x)|^2 dx}}{\sqrt{\int |o(x) \otimes p'(x)|^2 dx}}, \tag{1}$$

where $o(x) \otimes p'(x)$ is the computer object convolved with the theoretical diffraction-limited PSF $p'(x)$ of a hypothetical single-dish telescope with the length of the longest projected baseline as diameter, and $o_k(x) \otimes p'(x)$ is the reconstruction convolved with the same PSF $p'(x)$. The parameters for the simulation of one observation night with MATISSE is given in Table 1.

2.3 Quality of the reconstructed images as a function of the target size

Because of the sparse uv coverage, only relatively compact targets yield reconstructions with acceptable quality.

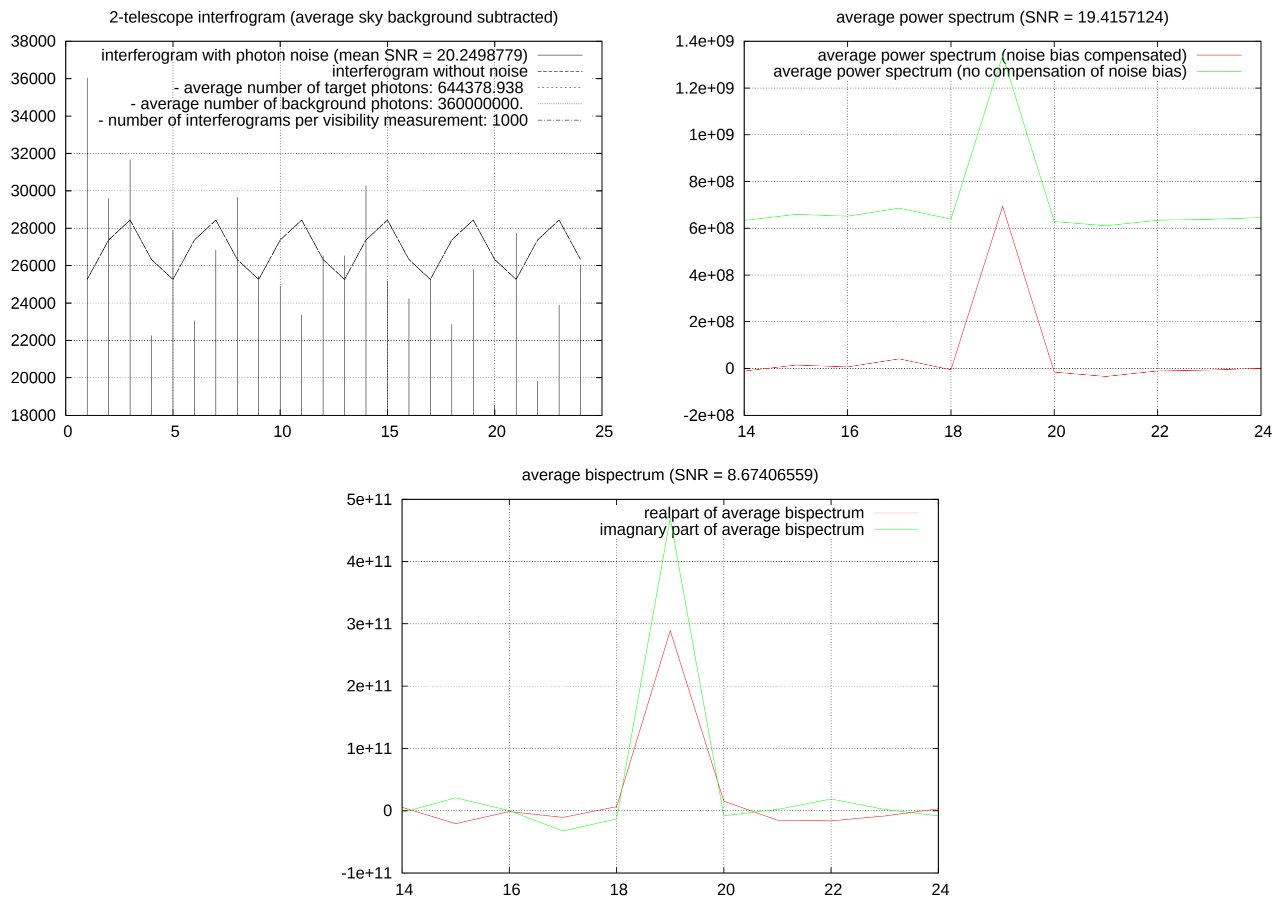

Figure 3. Simulation of the visibilities and closure phases: (top left) one of 1000 generated 2-telescope interferograms with sky background and target photon noise corresponding to an average number of 3.6×10^8 and 6.4×10^5 photons, respectively (solid line: interferogram without noise; vertical lines: pixel intensities of the interferogram including noise); (top right) average power spectrum calculated from the 1000 generated interferograms at the position of the fringe peak (central peak of the power spectrum is removed); (bottom) average bispectrum derived from the 1000 generated interferograms (calculated at the position of the fringe peak). In this example the average SNR of the squared visibilities is 20. In the average power spectrum (top right, green line), the noise bias is clearly visible. This bias-level is determined by a fit outside the fringe peak and then removed (top right, red line).

Observations with 4 ATs: The maximum baseline length is $\sim$ 150 m corresponding to a resolution of $\sim$14 mas at $\lambda = 10.5\mu$m. The discussed experiments were performed with the target shown in Fig. 2. The target is a model of LkHa 101 (named *Target1*) which was provided by P.G. Tuthill as one of two targets for the first SPIE image reconstruction beauty contest in 2004 (Ref. 6). Each of the simulated interferograms was degraded by sky background noise corresponding to a total number of 3.6×10^8 photons. The target intensity was chosen to get an average SNR of 20 for the calibrated squared visibilities. Table 2 gives a summary of the interferogram simulation parameters.

The theoretical objects used for the image reconstruction experiments were *Target1* with diameters of 60 mas, 86 mas, 112 mas and 125 mas. Fig. 3 shows for *Target1* with 86 mas diameter, (top left) one of the 1000 generated 2-telescope interferograms per data point, (top right) the average power spectrum with the fringe peak, and (bottom) the real and imaginary part of the average bispectrum.

Fig. 4 shows the resulting reconstructions: *Target1* with diameters ranging from 60 mas to 112 mas could be successfully reconstructed with restoration errors of 8.3% to 14.6%, respectively. The reconstruction of *Target1* with diameter 125 mas failed.

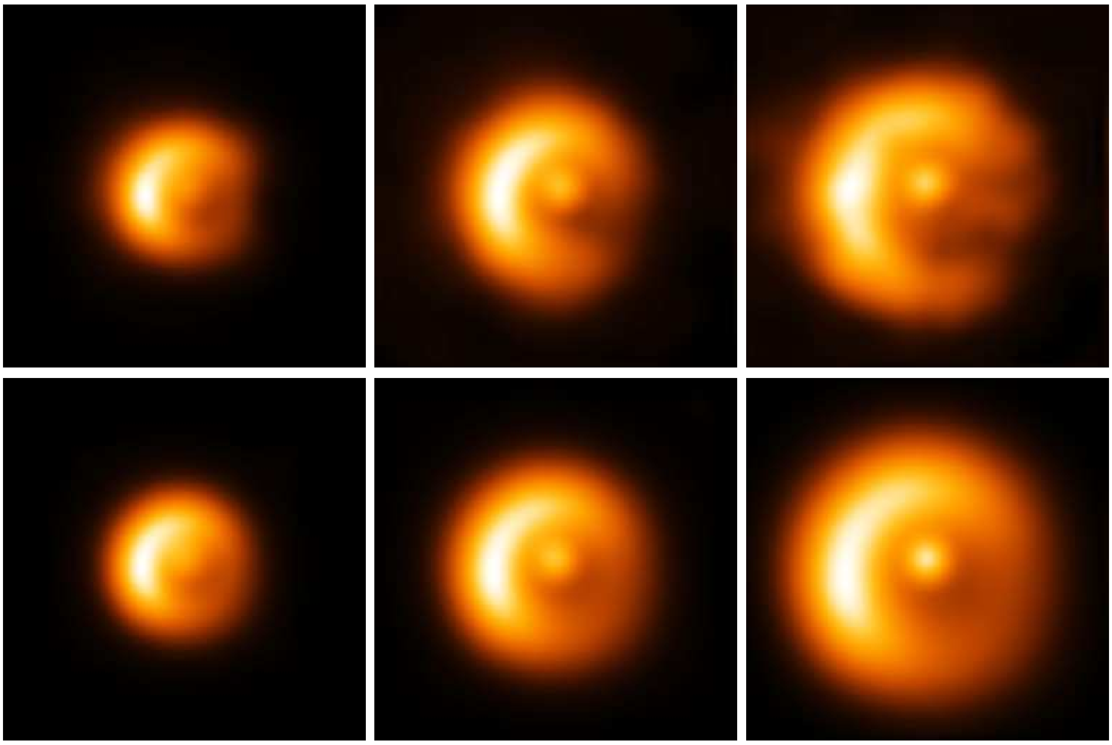

Figure 4. BBM reconstructions derived from simulated MATISSE data of *Target1* (disk of Herbig Ae/Be star LkHAlpha 101) for different diameters. The observation parameters are: 3×4ATs (uv coverage in Fig. 1), average SNR of the calibrated squared visibilities of 20. First row: reconstructions of *Target1* with diameters of 60 mas, 86 mas, and 112 mas (from left to right). The corresponding restoration errors are: 8.3% (60 mas), 11.8% (86 mas), and 14.6% (112 mas). Second row: the theoretical objects with the same diameters. All images are convolved with the PSF of a single-dish telescope with the dimension of the interferometric array.

2.4 Dependence of the reconstruction quality on the SNR of the simulated raw data

This study is based on simulated data obtained with 3 configurations of 4 ATs. The uv coverage is displayed in Fig. 1. The parameters to simulate one observation night are the same as listed in Table 1. The interferogram simulation parameters are the same as listed in Table 2, but different values of the average SNR of the squared visibilities are tested. The theoretical object is *Target1* (see Fig. 2) with diameters of 60 mas and 86 mas. Results: *Target1* with 60 mas diameter (see Fig. 5) can be reconstructed with acceptable quality (restoration errors between 6.7% to 13.8%) for all investigated SNR values between 50 and 7. The larger target, *Target1* with 86 mas diameter, can be reconstructed with acceptable quality (restoration errors: 7.5% – 11.9%) for SNR values between 50 and 17 only. For SNR values 15, 10, and 7 the image reconstruction failed.

2.5 Summary

The presented image reconstruction experiments were performed with 3 different 4-AT configurations. The following results were obtained:

- Observations with **4 ATs and 3 configurations can yield reconstructions with acceptable quality**.
- It has been shown that in the case of observations with three 4-AT configurations, a target size of ∼86 mas and a resolution of ∼14 mas, **the average SNR of the calibrated squared visibilities should be at least 17** (corresponding to an average error of ≥ 6%) in order to yield acceptable image quality (restoration error ∼8-12%). For smaller targets (target of size ∼60 mas) reconstructions with acceptable quality (restoration errors ∼7-14%) were obtained with an average SNR of the squared visibilities of 7, corresponding to an average error of ∼14%.

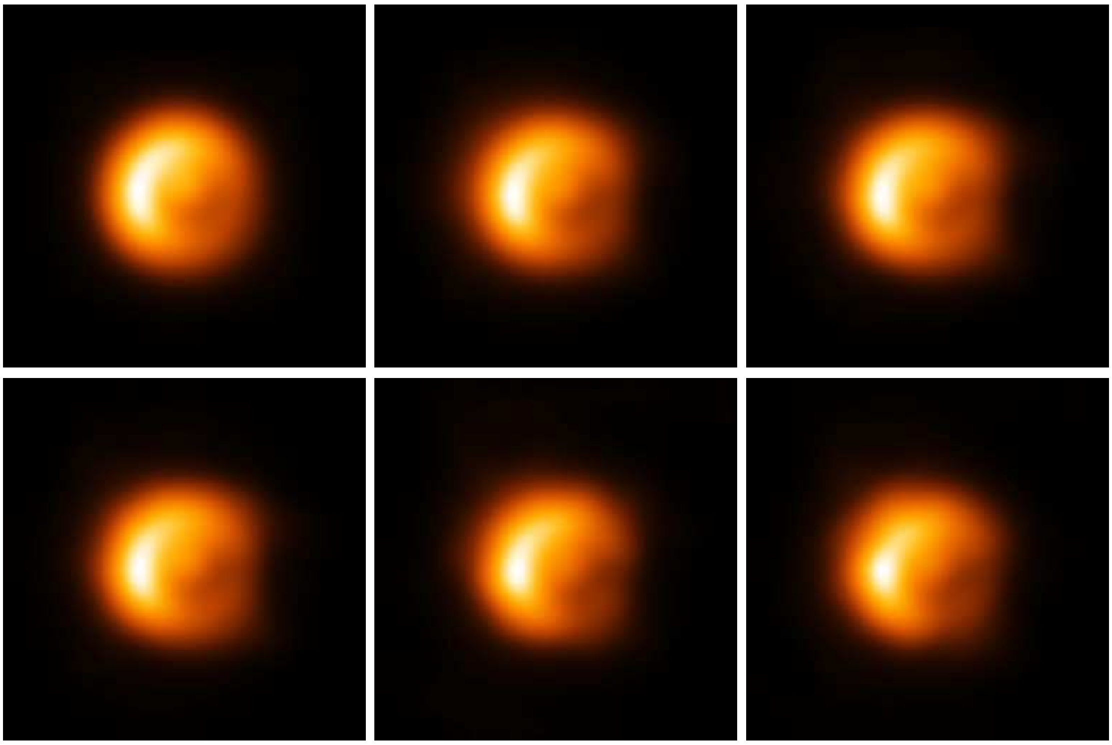

Figure 5. BBM reconstructions obtained from *Target1* with 60 mas diameter for different values of the average SNR of the squared visibilities. The simulated observations wer performed with 3×4ATs (uv coverage in Fig. 1). Top left: theoretical object *Target1*; the following images are reconstructions with average SNR = 50, 30, 20, 10, and 7 (from left to right, and top to bottom). The corresponding restoration errors are 8.4%, 6.7%, 6.8%, 13.8%, 12.6%; all images are convolved with a PSF corresponding to a single-dish telescope with the dimansion of the interferometric array.

- Furthermore, it has been shown that in the case of observations with 3×4 ATs, an array with resolution of ∼14 mas and an average SNR of the calibrated squared visibilities of 20, **targets with diameters up to ∼120 mas can be reconstructed** with acceptable image quality (restoration errors ∼8-16%, Fig. 4).

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