Comparison between closure phase and phase referenced interferometric image reconstructions

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ABSTRACT

We compare the quality of interferometric image reconstructions for two different sets of data: square of the visibility plus closure phase (e.g. AMBER like case) and square of the visibility plus visibility phase (e.g. PRIMA+AMBER or GRAVITY like cases). We used the Multi-aperture image Reconstruction Algorithm (MiRA) for reconstructions of test cases under different Signal-to-Noise Ratios (SNRs) and noisy data (squared visibilities and phases). Our study takes into account noise models based on the statistics of visibility, phase and closure phase. The final images were then compared to the original ones by means of positions and fluxes. For astrometry, the precision is typically of tens of miocroarcseconds and, for the photometry, typically of a few percent. Although both cases are suitable for image restorations of real interferometric observations, the results indicate a better performance of phase referencing (V^2 + visibility phase) in a low SNR scenario.

Introduction

In optical interferometry, data is obtained in a sparse coverage of the Fourier plane, not in the form of an image. By means of visibility and closure phase information and supported by physical models, modern optical interferometers yield the possibility to obtain reconstructed images of real objects. The Phase-Referenced Imaging and Micro-arcsecond Astrometry (PRIMA) dual-feed facility and the GRAVITY experiment (7734-33) will offer a phase referenced imaging mode, where data consisting on spectrally dispersed visibilities and phases can be used to generate images. Therefore, two scenarios for interferometric image reconstruction arise from current facilities: *power-spectrum* (*square of the visibility amplitude*) + *closure phase* data and *power-spectrum* + *absolute phase* data. We devised a simple method to perform a formal comparison between images belonging to both cases.

Setup

A synthetic image of a cluster of eight stars was built with the freeware programming language `Yorick`. The cluster was used to create several Optical Interferometry FITS exchange format (OIFITS) files, each corresponding to a different set of SNR and noisy data. All files were used as input to MiRA. A set of optimal parameters (initial guess, number of steps and regularisation) was found and kept for all the restorations, allowing one to compare the resulting images under the same conditions. Using `Starfinder` and `SExtractor`, the astrometry and the photometry of the images were measured. We computed the distances and the relative fluxes between each element of the cluster and the brightest star. These data were used to evaluate the quality of the reconstructions and to compare the images with the original one.

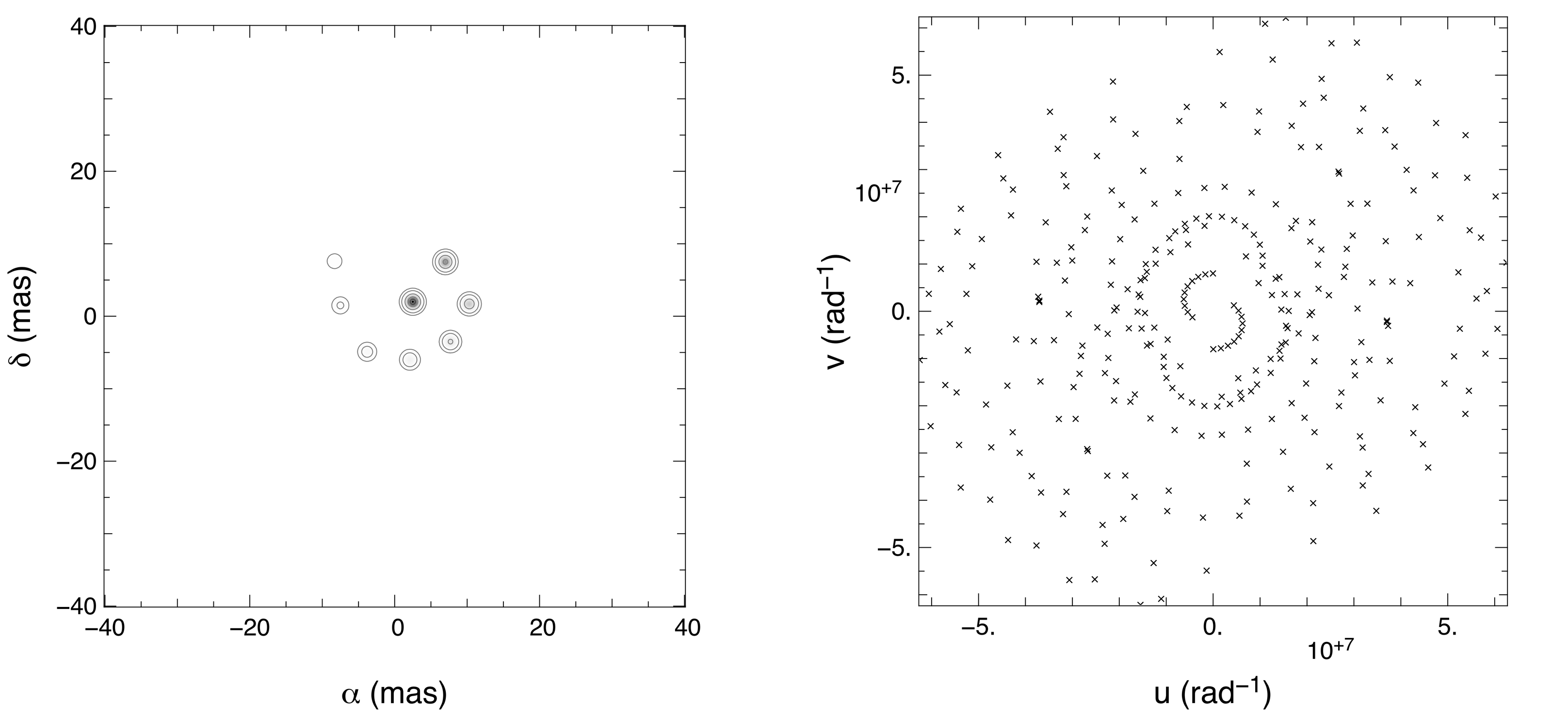

Figure 1: Contour plot of the synthetic cluster of stars used as a model for the reconstructions (*left*) and uv-coverage with the VLTI interferometer (*right*). The simulated stars are discs with a Gaussian intensity profile. The cluster is approximately 22.4 mas wide and is embedded in a FOV of 80 mas × 80 mas (500×500 pixels); the pixel size is approximately equal to 0.16 mas. The contour levels are at 1, 10, 40 and 90%. The uv-coverage corresponds to a 6 ATs configuration (A0-B1-D2-G1-J2-M0).

We consider three scenarios for the SNR, which is controlled by the total number of photons N reaching the array of telescopes: $N \sim 10^7$, $N \sim 10^5$ and $N \sim 10^3$ photons. The errors for the power-spectrum and closure phase, in photon and detector regimes, were based on the work developed by Tatulli and Chelli (2005). For the absolute phase, the errors were calculated according to the model of Colavita et al. (1996). For the power-spectrum, the detector noise regime is considered ($N \ll 1$), while for the closure phase, both the photon ($N \gg 1$) and detector noise regimes are taken in to account. Some approximations were implemented: Strehl equal to 1 and Strehl error equal to 0 (fully adaptive optics corrected), transmission in the optical fibre equal to 1 and the fraction of light selected for photometry at the output of the beam splitter was neglected. All errors were randomly added to the data by means of an uniform distribution. For each group of three realisations corresponding to a specific number of photons, we computed the mean of the medians of the SNR of the power-spectrum (V^2), phase (ϕ) and closure phase (ϕ_3) data points.

	$N \sim 10^7$	$N \sim 10^5$	$N \sim 10^3$
V^2	396.25	39.69	3.93
ϕ	875.0	87.7	9
ϕ_3	3	1	1

Table 1: Mean of the medians of the SNRs of the power-spectrum (V^2), phase (ϕ) and closure phase (ϕ_3).

Image Restorations

For each SNR scenario, three OIFITS were generated and a corresponding image restored. MiRA was configured under a positivity constraint, using a edge-preserving smoothness regularisation and a normalised image. The images are squares of 500 pixels length (100 mas) and the pixel size equal to 0.20 mas. We used $\lambda = 2.2\ \mu$m for the simulation.

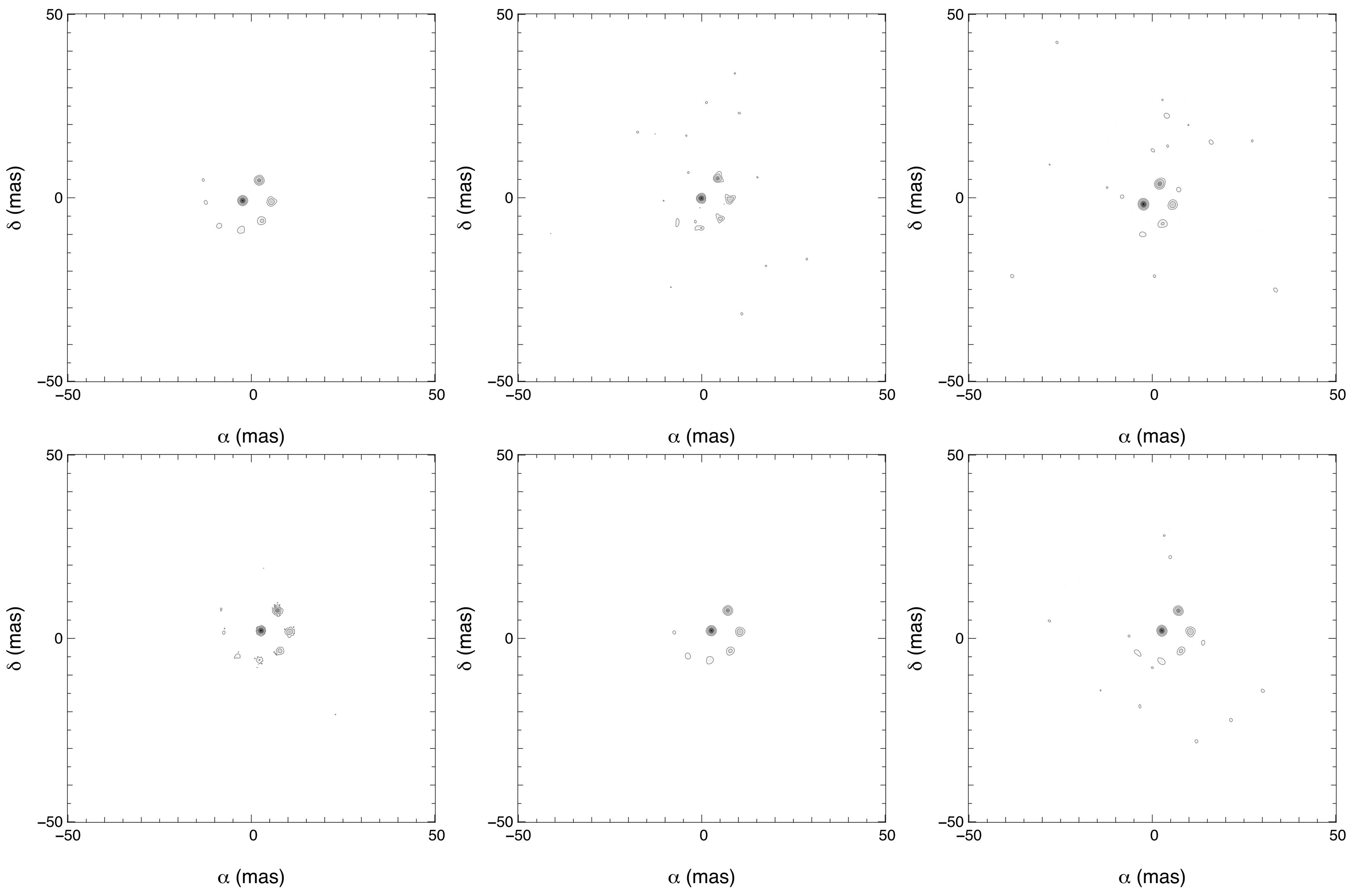

Figure 2: Contour plots of the reconstructed images. *Top row:* AMBER case; *Bottom row:* PRIMA+AMBER case. *Left:* $N \sim 10^7$; *Middle:* $N \sim 10^5$; *Right:* $N \sim 10^3$. The contour levels are at 1, 10, 40 and 90%.

Results

Star No.	Reference Distance (mas)	Distance (mas)
2	7.11	7.16 ± 0.05
3	7.81	7.86 ± 0.06
4	7.57	7.48 ± 0.09
5	8.0	8.7 ± 0.8

Star No.	Reference Distance (mas)	Distance (mas)
2	7.11	7.13 ± 0.02
3	7.8057	7.8063 ± 0.0006
4	7.57	7.60 ± 0.03
5	8.0	8.3 ± 0.3
6	9.34	9.33 ± 0.02

Tables 2 and 3: Astrometry of the reference and third set ($N \sim 10^3$) of reconstructed images, using (*left*) closure phase and (*right*) visibility phase information. The "*Reference*" column refer to the synthetic image. The distances are in respect to the brightest star.

Star No.	Reference Flux (relative)	Flux (relative)	Reference Flux Ratio	Flux Ratio
1	0.501	$(5.04 \pm 0.03) \times 10^{-1}$	–	–
2	0.250	$(2.58 \pm 0.07) \times 10^{-1}$	0.50000	$(5.0336 \pm 0.0003) \times 10^{-1}$
3	0.13	$(1.1 \pm 0.2) \times 10^{-1}$	0.249989	$(2.50713 \pm 0.00007) \times 10^{-1}$
4	0.06	$(4 \pm 2) \times 10^{-2}$	0.12502	$(1.1570 \pm 0.0009) \times 10^{-1}$
5	0.03	$(1 \pm 2) \times 10^{-2}$	0.06249	$(5.661 \pm 0.006) \times 10^{-2}$

Star No.	Reference Flux (relative)	Flux (relative)	Reference Flux Ratio	Flux Ratio
1	0.501	$(4.92 \pm 0.09) \times 10^{-1}$	–	–
2	0.250	$(2.54 \pm 0.04) \times 10^{-1}$	0.5000	$(5.170 \pm 0.002) \times 10^{-1}$
3	0.125	$(1.16 \pm 0.09) \times 10^{-1}$	0.2500	$(2.354 \pm 0.002) \times 10^{-1}$
4	0.063	$(5.6 \pm 0.6) \times 10^{-2}$	0.1250	$(1.142 \pm 0.001) \times 10^{-1}$
5	0.03	$(2 \pm 1) \times 10^{-2}$	0.0625	$(4.18 \pm 0.02) \times 10^{-2}$
6	0.016	$(1.3 \pm 0.3) \times 10^{-2}$	0.03125	$(2.604 \pm 0.005) \times 10^{-2}$

Tables 4 and 5: Photometry of the reference and third set ($N \sim 10^3$) of reconstructed images, using (*top*) closure phase and (*bottom*) visibility phase information. The "*Reference*" column refer to the synthetic image. The flux ratios are in respect to the brightest star.

Conclusions

One of the biggest problems of image reconstruction is the calibration of the visibilities. In our work, we considered stochastic errors but it is possible that calibration errors, which change between observation nights, might dominate the uncertainties. In that perspective, this simulation is not realistic. Under the imposed conditions, MiRA was able to fairly reconstruct the first five stars. Relative positions are correct, shapes are well reproduced and most of the flux is restored. The flux ratio between these stars is equivalent to $\Delta m = 3$. In the phase referencing case, at least six stars were restored, which corresponds to $\Delta m \simeq 4$. Only for the faintest stars, with fluxes less than 4% of the brightest star, reconstructions are of inferior quality: in the lower SNR scenarios, their positions and fluxes are not well determined and, sometimes, they are not even restored at all. The results seem to indicate that when using FFTs in MiRA, phase referencing case gives better results than closure phase case in a low SNR scenario.

References

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