Image reconstruction with MATISSE at the VLTI*

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ABSTRACT

MATISSE (Multi-AperTure mid-Infrared SpectroScopic Experiment) is a mid-infrared spectro-interferometer project combining up to four UTs/ATs beams of the VLTI. It will measure closure phase relations, thus offering the capability for image reconstruction. The VLTI offers the possibility to position the Auxiliary Telescopes at several different stations, which gives much better *uv*-coverage than fixed telescopes. We carried out simulated observations with MATISSE, in order to find out the requirements for efficient image reconstruction. In particular, we study how many different telescope configurations are necessary to obtain sufficient coverage of the *uv*-plane. We analyse which stations are the most important for an optimal *uv*-coverage. We also examine which measurement precision is necessary to reconstruct images suitable for the science goals of MATISSE.

Keywords: Astronomical software, aperture synthesis, imaging, interferometry, mid-infrared, Instruments: MATISSE

1. INTRODUCTION

The European Southern Observatory (ESO) operates the Very Large Telescope Interferometer (VLTI) on Cerro Paranal, Chile. The first generation of instruments at the VLTI combines the light of only two or three telescopes. It is therefore very time-consuming to collect data at different points on the *uv*-plane. Because of this, scientific projects at the VLTI have mostly relied on fitting models to visibilities.

The next generation of instruments at the VLTI will have the capability to combine the light from 4 telescopes at the same time, which provides simultaneous observations on 6 baselines. The VLTI has the (up to now unique) capability of moving the Auxiliary Telescopes (ATs) to a number of different stations, which provides a multitude of baselines with lengths between 16 and 202 m. By observing with different telescope configurations, and taking advantage of the change in baselines due to Earth's rotation, it will be possible to collect enough data points in the *uv*-plane to reconstruct images of the astrophysical objects.

MATISSE, the "Multi AperTure mid-Infrared SpectroScopic Experiment",[1,2] will be installed at the VLTI in 2016. It operates in the L-, M-, and N-band at 3.2 to 13 μm (with gaps in the wavelength coverage due to the lack of atmospheric transmission). This wavelength range is ideal for the study of circumstellar disks around pre-main-sequence stars, which are therefore one of the main science cases of MATISSE. With the six baselines measured simultaneously by MATISSE, observations over a few nights will deliver enough data to reconstruct images of the disks.

However, observing time with the VLTI is precious. Even with simultaneous observations on 6 baselines, the number of *uv*-points that can be obtained in a reasonable time is limited. Furthermore, changes of the telescope locations have to be carried out during the day and typically require a few hours of night time for the alignment of the telescope. It is therefore desirable to keep the number of telescope relocations small.

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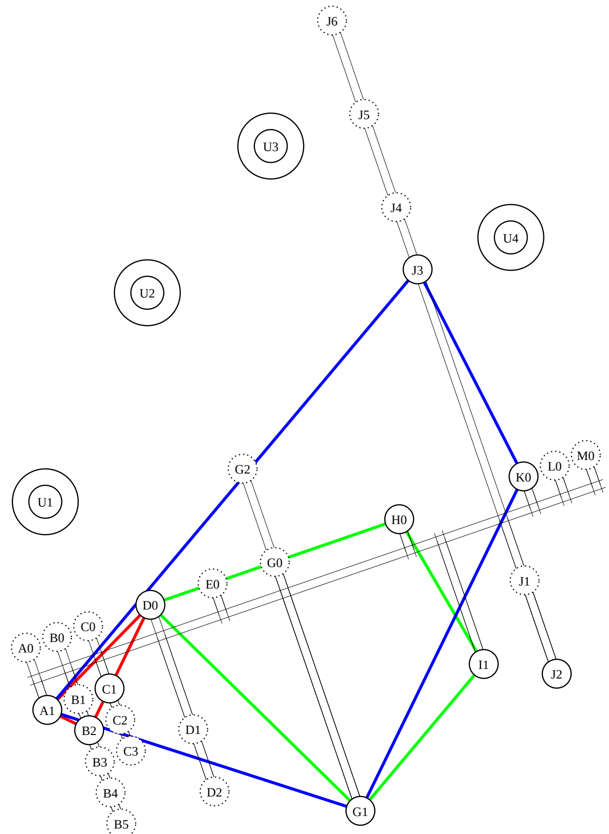

Figure 1. Layout of the telescope stations of the VLTI. The circles labeled U1 to U4 show the positions of the UTs, while the circles labeled A0 to M0 indicate stations where ATs can be located. The stations drawn with dotted lines have not been commissioned yet (with the exception of G2, which has been commissioned, but is only used for engineering work, not for science operations). The three quadruplets currently offered ("small", "intermediate", and "large") are indicated by the red, green, and blue tetragon.

In this project, we aim to find out which telescope configurations are well suited for image reconstruction of circumstellar disks. We also aim to find out whether one telescope configuration is enough, or whether observations with more configurations are required, which implies a telescope relocation between the observations. To assess the agreement of the reconstructed images with the true image, it is necessary to know the true image. Therefore, we work with simulated images and observations.

2. LAYOUT OF THE VLTI STATIONS

The VLTI can operate with the four 8 m Unit Telescopes (UTs) of the VLT, and/or with four 1.8 m Auxiliary Telescopes (ATs). The UTs are fixed, while the ATs can move on railway tracks to a number of different stations. This way, operations on several different baselines can be carried out.

Figure 1 shows the layout of the VLTI and the telescope stations. Thirty AT stations have been built, but only 11 of them have been commissioned for use in interferometric observations. Still, this makes baselines possible with lengths between 11.3 m and 140 m.

For observations with 4 telescopes, ESO currently offers three different quadruplets:

- "small", consisting of stations A1–B2–C1–D0, baseline lengths 11.3 to 35.8 m,
- "intermediate", consisting of stations D0–H0–G1–I1, baseline lengths 40.8 to 71.6 m,

- and “large” with stations A1–G1–K0–J3 and baseline lengths between 56.6 and 140 m.

Figure 1 shows that more configurations would be possible, including some with longer baselines (up to 202 m). However, the required telescope stations have not been commissioned yet, and the baselines are currently not offered for technical reasons.

3. SIMULATIONS

As input for our simulated MATISSE observations, we use a simulated image of a T Tauri star with a circumstellar disk (see the top panel of Fig. 4). These are determined via Monte Carlo radiative transfer calculations of hydrodynamic disk simulations. The star has a mass of $0.95\,\mathrm{M}_\odot$ and a temperature of 4000 K. The disk has a mass of $10^{-6}\,\mathrm{M}_\odot$ and extends from 1 AU to 25 AU from the center. We see it at an angle of 10° (almost face-on). At a radius of 5 AU, we put a planet with a mass of $10\,\mathrm{M}_{\mathrm{Jupiter}}$ and an age of 1 Myr. Based on the evolutionary models of young giant planets by Baraffe et al.,[3] this corresponds to a luminosity of $0.032\,\mathrm{L}_\odot$ and a temperature of 2250 K. The disk is perturbed by the planet, which leads to the opening of a characteristic gap and a region around the planet with higher density and temperature. This circumplanetary disk is efficiently heated by the planetary radiation. We expect that this bright spot in the disk can be detected by MATISSE, not the planet itself.

The image was created for an observing wavelength of $10\,\mu$m, assuming a distance to the system of 140 pc, which results in a total flux of the star and the disk of 0.46 Jy. Since this is too faint for the expected performance of MATISSE, we created images of brighter targets by artificially scaling the flux in the image by factors of 10 and 100. The images were “observed” with the MATISSE simulator, using different telescope configurations. For each of the reconstructed images, the object was observed with one telescope configuration, i.e. we did not combine data from different configurations. The declination of the object was set to $-70°$. We assumed that the observations were repeated over the course of one night, with 11 observations distributed uniformly between hour angles of $-75°$ and $+75°$. These are somewhat idealized conditions, but serve well as starting point to find configurations that are not suitable for the science case.

To simulate MATISSE observations we use a custom software. It is primarily intended as a research tool to allow prospective MATISSE observers to test whether their projects are feasible, and to optimize the observing parameters. The simulator has two major components:

- A sky image simulator. This represents the brightness distribution on the sky either as a series of images in FITS files (used here for the science target) or in analytic form (used here to simulate a star with a known diameter that served as visibility calibrator).
- A MATISSE instrument simulator. This takes the output of the previous component, computes perfect photometric and interferometric fluxes, and then runs these through a digital version of MATISSE to produce simulated MATISSE outputs (files in oifits format).

For the image reconstruction, we use the MIRA software (Multi-aperture Image Reconstruction Algorithm[4]). It creates images based on the visibilities computed by the MATISSE simulator. Because of the sparse *uv*-coverage, the reconstruction of images from optical or infrared interferometric data is mathematically an ill-posed inverse problem.[5] To turn it into a problem that has a unique and stable solution, it is necessary to introduce additional constraints. In general, one finds the solution by minimizing a penalty function f, with

$$f = f_{\mathrm{data}} + \mu f_{\mathrm{prior}}.$$

Here, f_{data} measures the discrepancy between the model and the measurement data, while the so-called regularization term f_{prior} measures the discrepancy with the *prior* information. The so-called hyperparameter μ controls the relative weight of the measurement data and the prior. For f_{prior}, many different mathematical descriptions are possible, e.g. to enforce a smooth image, a compact object in the image plane, or based on maximum entropy methods. See Renard et al.[6] for an overview of regularisation terms.

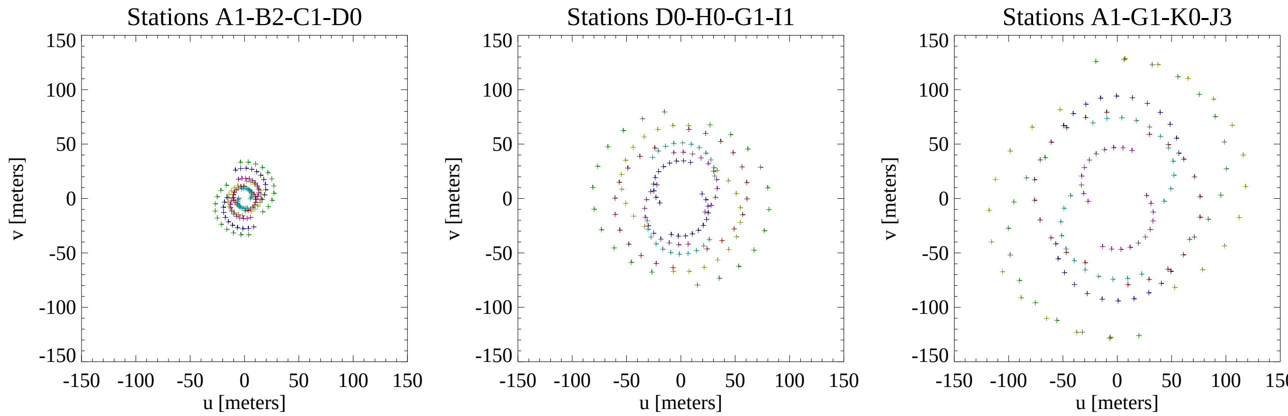

Figure 2. uv-coverage of the simulated observations with the small (left), intermediate (middle) and large telescope configuration (right).

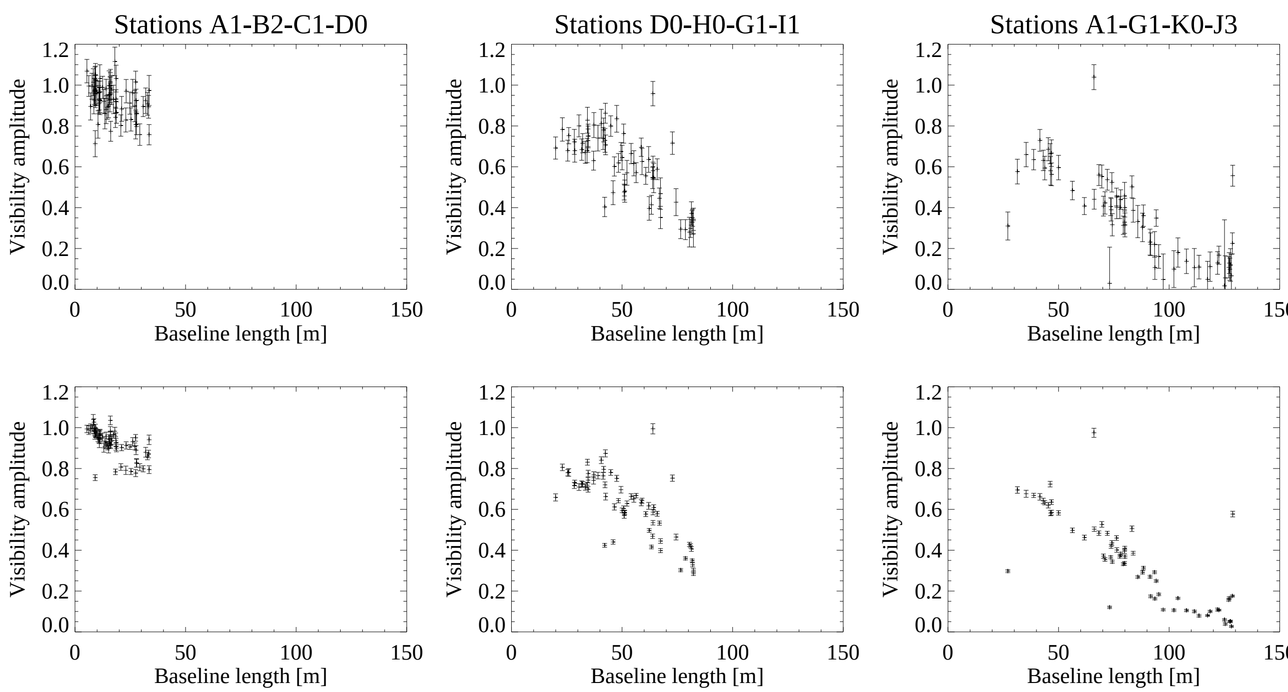

Figure 3. The visibility amplitudes for the simulated observations with the small (left), intermediate (middle) and large telescope configuration (right). For the top row, the flux in the input image has been scaled by a factor of 10, while a scaling factor of 100 was used for the bottom row.

In this work, we used the "total variation" regularization, because it usually results in the best reconstructed images.[6] Total variation minimizes the total gradient of the image, resulting in uniform areas with steep but localized changes. In general, this is well-suited for images of circumstellar disks, although it can lead to some artifacts in the reconstructed images (see section 4).

To reconstruct an image, we run MIRA three times with decreasing values of μ. The initial image consists of a delta peak in the center, while subsequent runs start with the reconstructed image of the previous run. We use $\mu = 10^5$, 10^4, 10^3 for the three iterations, following the recommendation of Renard et al.[6]

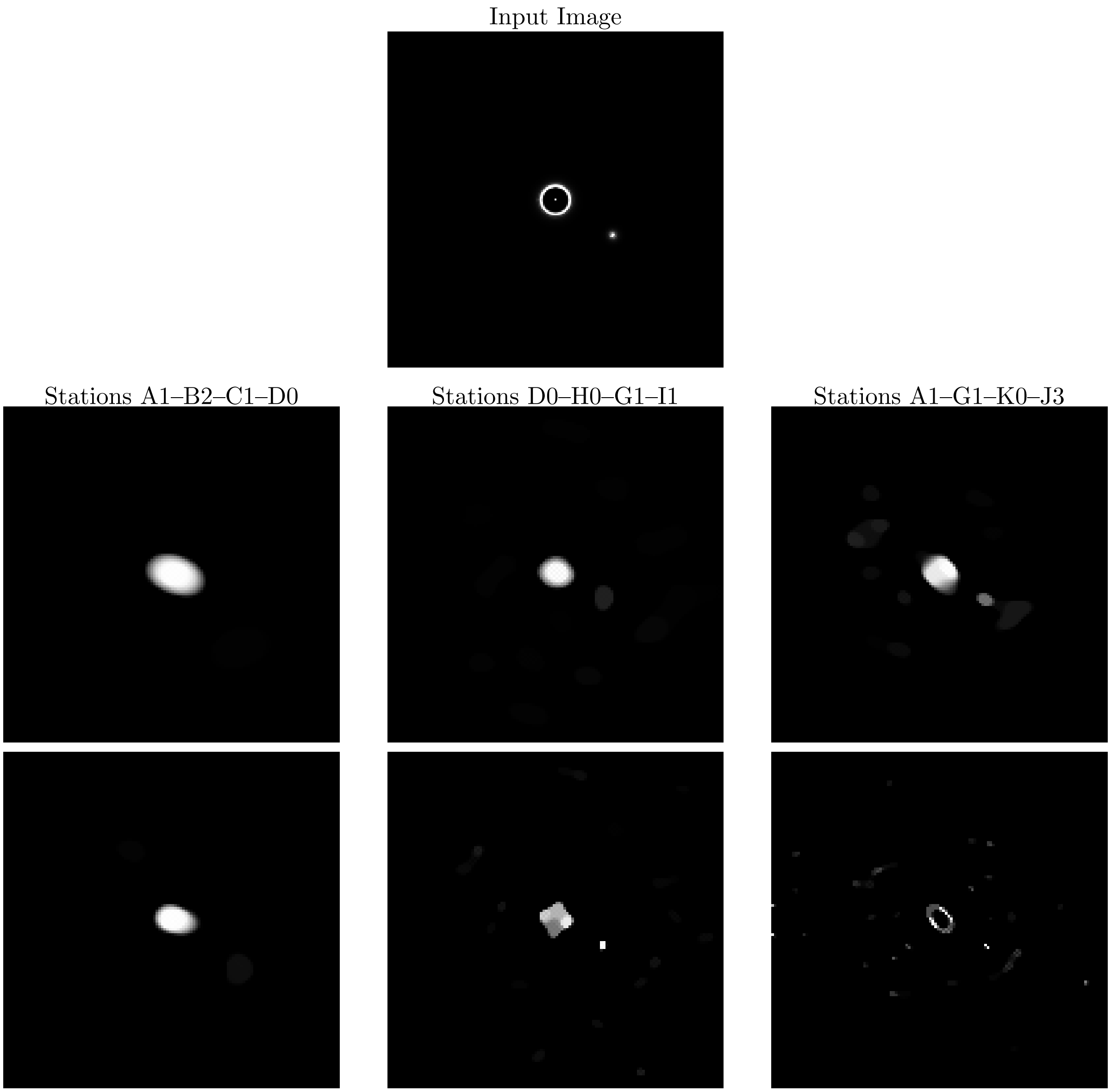

Figure 4. Images reconstructed from simulated observations. The input image is shown at the top, while the other images are the results of our reconstruction experiments. To analyze the influence of the source brightness, the flux in the input image has been scaled by a factor of 10 for the reconstructed images in the second row and by 100 for those in the bottom row. The columns show the effect of observations with different baselines, with the small configuration on the left, the intermediate configuration in the middle, and the large configuration on the right.

4. RESULTS

4.1 Observations with Auxiliary Telescopes

Figures 2 and 3 show the uv-coverage and the resulting visibility amplitudes for the three telescope configurations. The visibilities measured with the small configuration (stations A1–B2–C1–D0) are all close to one, which means that there is not much information about the structure of the image at the spatial frequencies covered by this configuration. Therefore, we can not expect that an image reconstruction based on data collected with the small configuration will show the structures we are interested in.

Figure 4 shows the results of the simulated observations and image reconstructions as function of source brightness and the telescope configuration used. A number of conclusions are obvious: As expected, the small VLTI configuration (stations A1–B2–C1–D0) does not have the resolution required to resolve either the inner rim of the disk or the bright spot caused by the planet. There is faint emission to the lower right of the central source, but it is not at the same position as the planet.

With the medium-sized telescope configuration (stations D0–H0–G1–I1), it is possible to detect the bright spot around the planet. However, the inner rim of the disk is unresolved. The disk appears as an extended structure, with only a hint of a central hole in the case of the brightest input image. With the large telescope configuration (stations A1–G1–K0–J3), the bright spot around the planet is always detected. There are a number of artificial sources in the image, but the real spot is brighter than all the artifacts. If the flux of the target is high enough, even the inner rim of the disk appears as a ring in the reconstructed image.

It is worth noting that it is possible to reconstruct a reasonable image of the target from only one night of observations, at least for bright sources. However, one should keep in mind the peculiarities of the regularisation used: total variation favors regions of constant brightness with sharp jumps at the edges. This tends to produce artificially flat regions in the reconstructed images, surrounded by edges of exaggerated sharpness. This is clearly visible in the images reconstructed with the intermediate telescope configuration. It is probably also the reason for the brightness variations of the disk rim in images reconstructed with the large telescope configuration. Consequently, one should be careful with the interpretation of such brightness variations, since they might not represent real features of the astrophysical object.

4.2 Observations with Unit Telescopes

The results of simulated observations with the Unit Telescopes are shown in Fig. 5. Since the UTs can not be moved, there is only one configuration with four telescopes. Its longest baseline is comparable to the longest baseline of the large AT configuration. However, there are two UT-baselines with length $\sim 50\,\mathrm{m}$, which results in a *uv*-coverage that is more concentrated to low spatial frequencies. The UTs are larger and collect more light than the ATs. Therefore, we simulated observations of the unscaled version of our test image (i.e. with the flux predicted by the model), and for comparison with an image that was scaled by a factor 10.

With the unscaled image, the inner rim of the disk is not resolved. The reconstructed image contains faint emission at the position of the planet, but it is smeared out to about the same size as the disk.

If the flux is 10 times higher, then the inner disk rim is resolved and the bright spot around the planet is clearly detected. The rim of the disk has brightness variations that were not present in the input image. The variations are even more severe than with the large configuration of the AT telescopes. However, as long as one is aware of this kind of artifacts, it is possible to reconstruct useful images based on one night of UT observations, despite the limited *uv*-coverage of the fixed telescopes.

5. CONCLUSIONS AND OUTLOOK

Our simulated observations and image reconstructions show that it is possible to resolve structures in circumstellar disks with only one night of observations with the VLTI and MATISSE. To resolve the central hole of our model disk, the large configuration of the ATs is required. In the case of a more extended disk (either closer to Earth or intrinsically larger), the intermediate or even the small configuration might be better suited for the observations. If the size of the disk cannot be estimated before the observations, then data should be collected with at least two configurations in order to determine the characteristic length scale of the object.

The flux predicted by the astrophysical model used in our simulations is not sufficient to reconstruct an image at the full resolution of the VLTI. With the 8-m Unit Telescopes, we can tentatively detect the spot caused by a planet in the disk, but to resolve the inner rim of the disk, at least 10 times more flux is required. For observations with the 1.8-m Auxiliary Telescopes, the flux has to be even higher. Our method of scaling the flux of the model image can only serve to estimate the flux limits. To assess which kind of astrophysical objects can be observed successfully with MATISSE, simulations have to be based on actual models of brighter stars and disks (e.g. HAeBe stars).

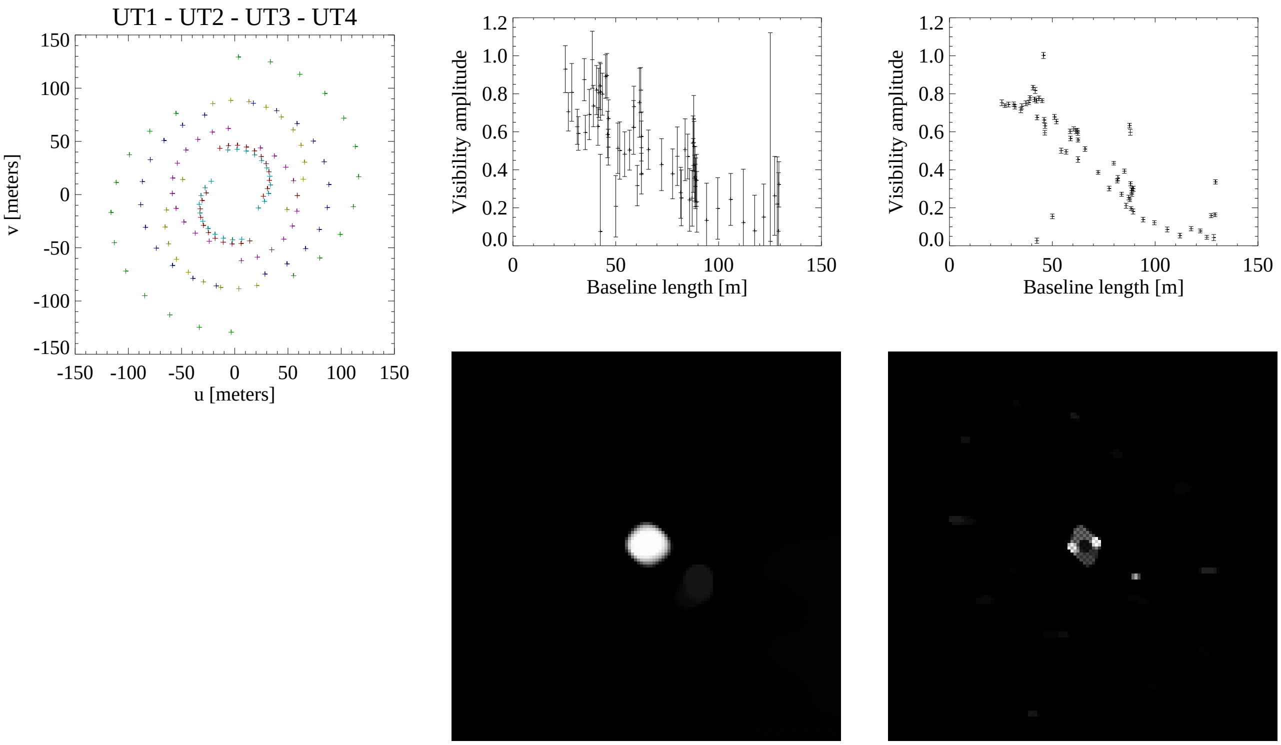

Figure 5. Simulated observations with the Unit Telescopes. The *uv*-coverage is shown to the left, the visibility amplitudes in the top row, and the reconstructed images in the bottom row. The visibilities and image on the left were computed with the original input image, while the flux was multiplied by 10 for those on the right.

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