First Images from the VLT Interferometer

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The ESO Very Large Telescope Interferometer has recently produced its first images, achieving a spatial resolution of a few milliarcseconds. The published images reveal the precise astrometry of close massive binaries (θ^1 Ori C and HD87643), the presence of material close to the surface of an old, variable star (T Lep), and the dusty environment of an active galactic nucleus (NGC 1068). However, this is only a first step and additional results and numerous improvements are expected in the forthcoming years.

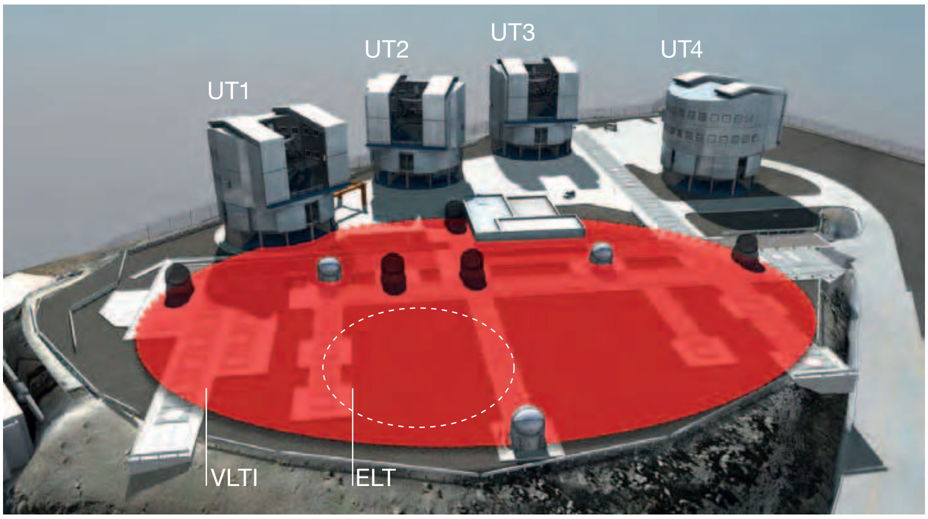


Figure 1. Overview of the Paranal Observatory platform, showing the four Unit Telescopes (UTs) and the three relocatable Auxiliary Telescopes (ATs). The three ATs are the small white telescopes arranged in an equilateral triangle. Combining them together and moving them to different positions (black shadows) emulates the resolving power of a virtual giant telescope, represented here as the red area. It is important to note that the interferometric technique only reproduces the resolving power of the virtual giant telescope, not its sensitivity. The size of the ELT is represented for comparison.

The stars with the largest apparent size in the sky are of the order of ten milliarcseconds. This is much smaller than the resolving power of the largest world-class telescopes, such as the Unit Telescopes (UTs) of the ESO Very Large Telescope (VLT). In the coming decades, the Extremely Large Telescopes (ELTs) will deliver better resolving powers thanks to their larger apertures and the use of new generation adaptive optics (AO). However, even the ELTs will only be able to image a few of the largest stars of the sky, such as Betelgeuse (α Orionis), whose diameter is about 30 milliarcseconds. To resolve solar-like stars, interacting binaries, or the inner part of planet-forming discs requires a telescope of at least 150 m in diameter. At optical wavelengths, building and co-phasing such a telescope will remain out of reach of our technical and financial capabilities for decades yet.

Interferometric aperture synthesis is the only currently available solution. This technique mixes the light collected by several small, independent telescopes separated from each other by tens or even hundreds of metres, and so recovers the resolving power of a virtual telescope of equivalent size (see Figure 1).

Optical long-baseline interferometry has been used by a steadily growing community, as shown by the publications graph in Figure 2. Since 2003, the rate of increase has been higher due to the introduction of "user-friendly" interferometers such as the Keck Interferometer (Keck-I), the ESO Very Large Telescope Interferometer (VLTI) and CHARA. Even so, for the general astronomer, optical interferometry still appears as a technical engineering playground, instead of an attractive high-angular-resolution observing method. This can be explained by the fact that general users have little intuition about how interferometric observables, called visibilities, behave as a function of the object shape. In order to bridge the gap for general users, optical interferometry has to step into an "imaging era", as was done for radio interferometry decades ago.

We present the first images from the ESO VLTI (Haguenauer et al., 2008), showing that we are just entering the long-waited "imaging era" of this facility. The instruments are now working better than ever, and the requisite image reconstruction

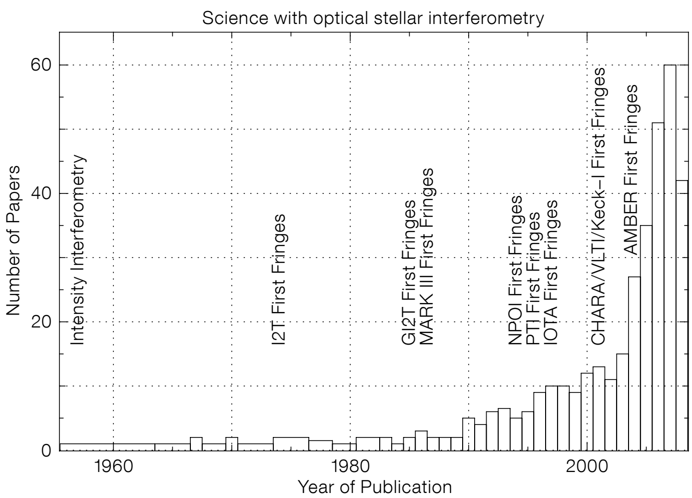


Figure 2. Publications made with optical interferometers, only including scientific results (source OLBIN[1]). We see a steadily increasing number of publications.

software exists. However, this is only a first step, as numerous aspects still need polishing. We will therefore also describe improvements expected to take place in the near future.

Image reconstruction

When light beams coming from two distant telescopes are overlapped they form an interference pattern; and by measuring the contrast and position of this pattern, information about the morphology of the observed astronomical source can be determined. Mathematically, the fringe contrast and position (amplitude and phase) define a complex number, V, linked to the Fourier Transform of the observed brightness distribution (Image) at the spatial frequency B/λ, given by:

$$V(B) = FT\{Image\}\ (B/\lambda)$$

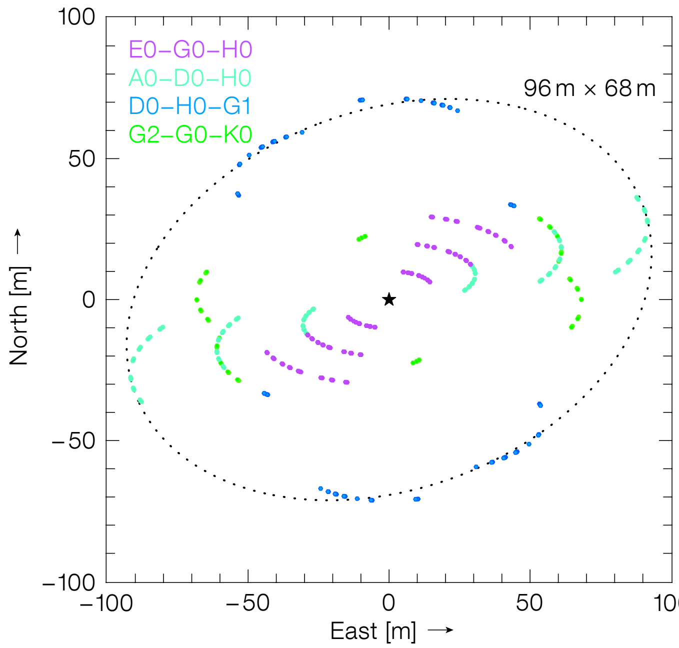
In this equation, B is the geometrical vector joining the telescopes of the interferometer projected into the plane of the sky, generally called the projected baseline. λ is the wavelength of the observation, typically between 1 and 10 microns for the VLTI. FT denotes the Fourier Transform operator, normalised to 1 when B = 0. An interferometer measures some discrete values of the Fourier Transform of the observed image and not a continuous image.

When only a few pairs of telescopes are available, model fitting must be used to convert these observables, the visibilities V(B), into astrophysical quantities. In particular, only the spatial extent — the size — and the level of asymmetry can be constrained, but at a precision unachievable with classical single telescopes. Until recently, this was the method used for the major discoveries made by the VLTI. Among them, we recall the precise radius and limb-darkening measurements of different kinds of stars (see ESO PR 14/03 and ESO PR 25/04), the characterisation of discs surrounding young stars (ESO PR 29/05) and hot Be stars (ESO PR 35/06), the astrometry of close spectroscopic binaries, the study of mass-loss events around evolved stars or novae (ESO PR 22/08), the direct size determinations of small asteroids (ESO PR 04/09), and the unique probe inside the dusty environments of a few nearby active galactic nuclei (AGN).

When large numbers of observations of the visibilities, V(B), of a given target are available, it becomes possible to invert the Fourier Transform of the visibilities (*viz.* $FT^{-1}\{V(B)\}$) to produce an Image of the source. Performing such a computation is called "image reconstruction" because it has to deal with several difficulties. Firstly the spatial sampling of the points V(B) is anything but regular or homogeneous, as shown by the example in Figure 3. Secondly each observation is corrupted by random noise, whose amplification should be avoided during the inversion process. Finally, the phase information cannot be estimated independently for each point V(B), but only along closing triangles of observations (called closure phase). The use of the incomplete phase-closures, instead of the exact phases, makes the inversion problem non-convex (meaning hard to solve).

Several algorithms are now available to reconstruct an image from sparse and noisy V(B) datasets: MIRA, BSMEM, WISARD, BBM and MACIM. These algorithms were the challengers in the series of Optical/IR Interferometric Imaging Beauty Contests, which have quantitatively compared the results of various image synthesis methods every two years since 2004. See Cotton et al. (2008) for the latest results and winners. All the reconstruction methods attempt somehow to adjust an image to the data according to some additional knowledge about the shape of the object. At the least, this additional *a priori* information is that the reconstructed image is positive everywhere. But the reconstruction is strongly aided, and the result more accurate, if additional information can be supplied. Is the image composed of unresolved components (such as a multiple system)? Does the image contain some background level? Is all the flux concentrated inside an area of some known size? All these pieces of information can, and should, be injected into the (choice of the) reconstruction algorithm.

Figure 3. Coverage of the uv-plane obtained after observing with nine different pairs of telescopes made with four configurations of three ATs. Each telescope pair creates an arc since the projected baseline B changes with the Earth's rotation during the night. An estimation of the complex fringe contrast has been obtained for each point. The poor and irregular sampling of the spatial frequencies represents a real challenge for the reconstruction algorithms. The dotted ellipse is the shape of the virtual telescope emulated by these observations.



Recent VLTI images

Imaging multiple stars

The first reconstructed image produced by the VLTI is of the binary θ^1 Ori C (see the article in the last *Messenger* issue, Kraus et al., 2009b; and Kraus et al., 2009a), located in the well-known dense Orion Trapezium Cluster. To create an image of this object, the investigators had to observe the system for several nights, using the movable 1.8-metre Auxiliary Telescopes (ATs) and the AMBER instrument (Petrov et al., 2007). The ATs were combined in different groups of three, and were also moved to different positions, creating more new interferometric configurations. Taken together the configuration emulates a virtual telescope approximately 130 m across. AMBER's continuous spectral coverage across the *H*- and the *K*-bands at a spectral resolution of R = 35 allowed better filling of the so-called uv-plane, thanks to the $1/\lambda$ term in the spatial frequency term in the equation. However, because observations were not simultaneous enough, the authors had to artificially rotate the uv-plane between each configuration to account for the binary rotation. The authors employed the Building Block Mapping software (BBM). Starting from an initial single δ-function, this algorithm iteratively adds unresolved components to the image, which is convolved finally with a clean beam that reflects the elongation of the sampled uv-plane.

θ^1 Ori C is one of the youngest and closest high-mass (O5–O7) stars and is also a binary. The resulting interferometric image separates the two components of the system. The observations themselves have a spatial resolution of about 2 milliarcseconds. Figure 4 compares the images of θ^1 Ori C obtained with the VLTI and with the 6-metre Russian Big Telescope. The evident increase of resolving power in the VLTI image directly translates into a much better astrometric accuracy. From these, and several other speckle and interferometric observations, the authors could precisely derive the orbital parameter of this binary system (Kraus et al., 2009a). They concluded that the total mass of the two stars is 47 $M_\odot$ and their distance from us is 415 parsec (pc).

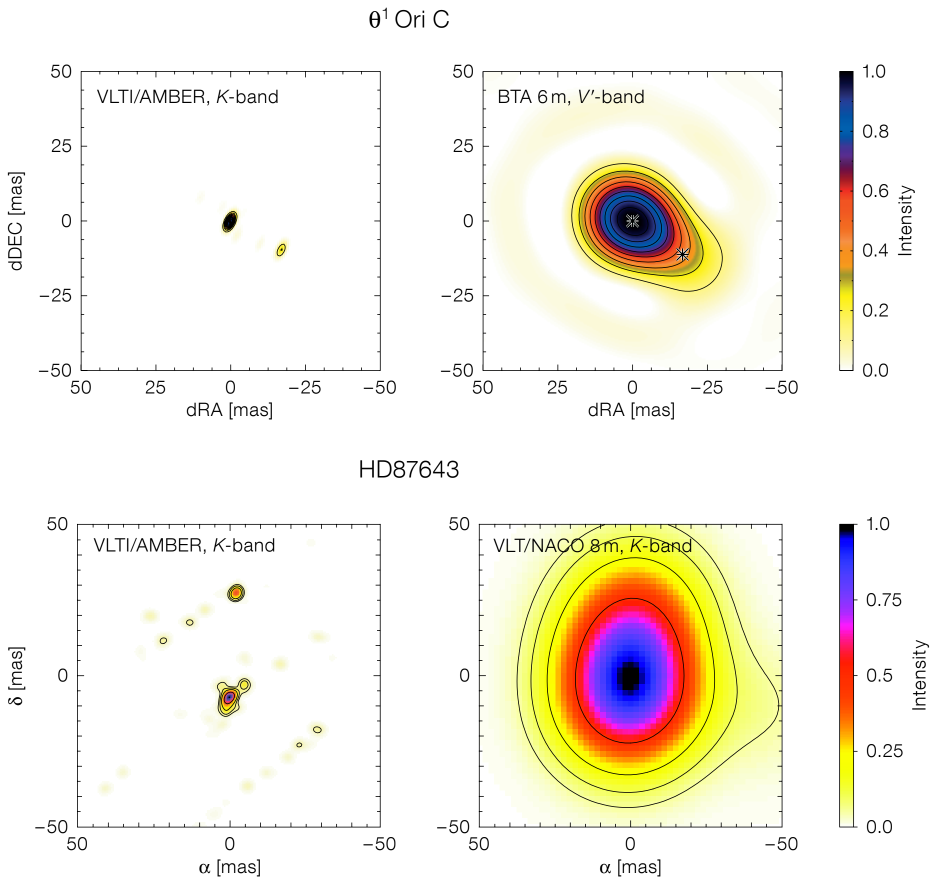


Figure 4. Top: Images of the θ^1 Ori C binary from Kraus et al. (2009). Shown at left is the interferometric image reconstructed with VLTI/AMBER emulating a telescope of around 130 m in diameter. Shown right is the de-convolved image obtained at the 6-metre Russian Big Telescope. For each image, 10 % intensity level contours are shown and the fitted component positions are marked with an asterisk. Bottom: Images of HD87643 from Millour et al. (2009). Shown left is the AMBER interferometric image of the system, with roughly the same spatial resolution as for θ^1 Ori C, and right is a de-convolved image obtained with the AO-assisted NACO instrument at UT4.

The same instrument and method was used by Millour et al. (2009) to reconstruct the image of the binary star HD87643. This star is an extreme example of the B-type stars that show the B[e] phenomenon (*viz.* a B-type star with emission lines). These stars exhibit a spectrum of emission from light element recombination and metallic forbidden line transitions, as well as infrared excess associated with dust emission. Figure 4 shows the images of HD87643 obtained by Millour et al. (2009) with the VLTI and with the NACO camera on UT4. The interferometric image has been built with the MIRA software, employing the "smoothness" and "positivity" constraints only. We have compared the resulting image with that produced by other existing software packages (BBM and BSMEM), which gave substantially the same results.

Interestingly, very little was understood about this B[e] star before our interferometric observations. The evident increase in resolving power in the VLTI image, compared to the NACO image, permitted a clear detection of the binary nature of this system. In addition, the image allowed us to resolve the circum-primary dust shell, which was unattainable at the resolution of single telescope observations. Therefore our new view of HD87643 is: 1) a B[e] star, enshrouded by its dusty circumstellar disc, and whose inner dust-sublimation rim can be seen in the images; 2) a very compact and

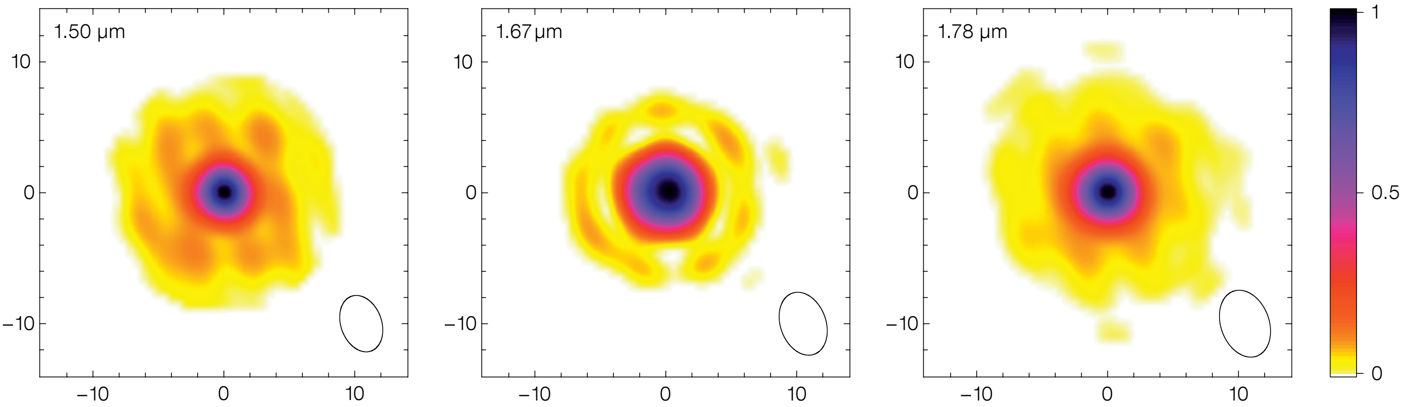


Figure 5. Images of the Mira star T Lep obtained with VLTI/AMBER emulating a telescope of around 100 m in diameter (Le Bouquin et al., 2009). These images in three narrow bands have been extracted from a position-wavelength datacube of around 30 images. Spatial scale is in milliarcseconds. As a comparison, the full image displayed here would fit inside a single pixel of VLT NACO.

dust-enshrouded companion star; 3) the binary system itself immersed in a cocoon of warm silicate dust.

Imaging the surfaces of stars

Mira stars are favourite targets of amateur variable star observers because of their huge variability in the visible wavelength range. These are giant stars that have almost extinguished their nuclear fuel and are losing mass at a high rate before entering the cooling track as white dwarfs. They pulsate with periods of several hundred days and molecules and dust are formed in the layers of the atmosphere immediately surrounding the central star. The Sun will become a Mira star in a few billion years, engulfing the Earth in the dust and gas. Although Mira stars are among the biggest factories of molecules and dust in the Universe, the exact shape, density and composition of the expelled material is still debated.

The classical Mira star T Leporis, in the constellation of Lepus (the Hare), is located at 170 pc and pulsates with a period of 380 days. Although it is a giant star, it is so far away that only facilities like the VLTI can obtain a resolved image of it. We achieved this recently by using the data from four configurations of three ATs (Le Bouquin et al., 2009; ESO PR 06/09). Instead of combining all spectral channels together, as in the case of θ^1 Ori C or HD87643, we were able to build an independent image at each wavelength bin, as shown in Figure 5. We employed the MIRA software (Thiebaut, 2008) with a specific two-step strategy. The first step consisted of building a radially symmetric image from the data. This supposition was supported by a previous analysis of the data, showing no obvious difference in apparent size along different directions. The main interest is that we could make use of relatively simple *a priori* constraints (smoothness) for this first guess image. As a matter of fact, the reconstructed ring-like structure is highly trustworthy. On the other hand the smoothness of the central star is not necessarily a correct assumption and the star could have normal, sharper edges. The second step uses these initial brightness distributions as support for a quadratic regularisation of the 2D images, allowing the software finally to map the asymmetries.

Although only a few pixels across, the reconstructed images shows an extreme close-up of a star about one hundred times larger than the Sun, corresponding roughly to the distance between the Earth and the Sun. The star appears encircled by a sphere of material, which is about three times as large again. Such images unambiguously demonstrate that an envelope of dust and gas, whose aspect ratio and opacity is changing with the wavelength, surrounds a Mira star.

Imaging the innermost part of AGNs

Raban et al. (2009) recently presented interferometric observations of the nucleus of NGC 1068, using the VLTI MIDI instrument. They obtained extensive uv-plane coverage with 16 baselines with a maximal resolution of 120 m (corresponding to 7 milliarcseconds at 10 microns). In common with other AGNs, NGC 1068 is so faint that it could not be observed with the relocatable ATs, but only with the 8-metre UTs. As a consequence, the distribution of the tracks is concentrated in the second/fourth quarter of the uv-plane, with only one observation on a perpendicular baseline, reflecting the fixed physical placement of the UTs. On account of the near-zero declination of NGC 1068, the tracks are parallel to the u-axis.

The authors were able to reconstruct an image of the nucleus using maximum entropy (ME) methods by combining all the 16 observations. The ME methods guarantee that the resulting image will be the most statistically probable reconstruction given the information in the data and considering positivity as the unique constraint (together with the implicit smoothness criterion of ME). One of the main advantages of the ME method is that few prior assumptions about the source are needed to obtain good results from the algorithm. According to Raban et al. (2009), the reconstructed image confirms the basic properties of the source in a completely model-independent way, but it does not provide a more detailed picture than previously known.

Feedback from first images

About six months after obtaining the first images, we can already draw some

general conclusions concerning image reconstruction at the VLTI:
1) The published results demonstrate nicely the capability of this ESO facility to deliver images at a spatial resolution of a few milliarcseconds, although on bright targets only. We recall that such a spatial resolution is unattainable by classical single telescopes, even when considering the ELT era.
2) Up to now, only rather simple objects have been imaged: binaries, simple circumstellar environments, or images with a small field-of-view (perhaps 5 by 5 pixels in size, at maximum).
3) The main results have been obtained in Visitor Mode, with at least three different telescope configurations, so typically over three observing (half-)nights.
4) While it has often been said that the VLTI is too slow, a sampling speed of approximately 25 minutes per calibrated point sounds sufficient.
5) The poor quality of the calibrated visibilities is an important limitation.
6) Finally all existing datasets suffer from a poorly populated uv-plane, especially in the North–South direction.

The two last points cover the majority of the VLTI user complaints, and should receive careful attention from the Science Operations team in the future.

Several other imaging projects are in progress concerning B[e] stars, young stellar objects and supergiants. The investigators generally conclude that the reconstructed images validate the basic properties of the targets in an independent manner for the first time. However, for the moment, the images do not provide a more detailed picture than parametric models. This hurdle could only be overcome by increasing the number and the quality of the visibility measurements, as previously mentioned. However models will always be needed to provide quantitative constraints and to test consistently the physics underlying the images.

Positioning the VLTI in the current international context is rather easy. The VLTI does not yet provide the best imaging capabilities: the MIRC instrument at the CHARA array already combines four telescopes and is being upgraded to six (see, for instance, the image of the surface of Altair by Monnier et al., 2008). The VLTI does not yet provide the best dynamic range: the FLUOR instrument at CHARA, although combining only two telescopes, provides precision below 1%. In terms of limiting magnitude, Keck-I and the VLTI with the UTs have similar performance. However, the VLTI and its instruments do provide a unique spectral coverage, from 1 to 10 microns and a unique spectral resolution up to R = 12 000. It does provide the unique capability of relocatable telescopes (the ATs) that allows both compact (~ 16 m) and large (~ 130 m) interferometric arrays to be built within a few days. Finally, it is the only interferometer with real Service Mode scheduling and a high level of user support, resulting in a large number of refereed publications (more than 200 to date).

Prospects

In the forthcoming years, we believe that improvements in the imaging capability of the VLTI will mainly lie in an enhancement of the data quality, as well as an increase in the number of offered interferometric baselines. Background work by the Science Operations team at the Paranal Observatory is ongoing on these two points. For instance, it is planned to increase the number of offered AT triplets from four (current period) to more than ten (goal for Period 86). Opening and offering new triplets and new telescope stations however requires an intensive effort both from the Engineering and Science Operation teams.

In 2012, the VLTI is expected to receive the second generation instruments MATISSE (Lopez et al., 2008) and GRAVITY (Eisenhauer et al., 2008). These instruments will make use of four telescopes. Combining four telescopes simultaneously, instead of three, simply doubles the number of possible simultaneous visibility measurements (six instead of three): with only one additional telescope, the interferometer is twice as fast at collecting enough points to build up an image. We believe it will be possible to reconstruct a simple image within about two observing nights instead of about four as of now. At that time, getting six ATs could be a decisive step towards allowing routine imaging within the ESO Service Mode framework. Regarding the UTs, the main challenge is to reduce their mechanical vibrations to an acceptable level for interferometry; if achieved, important gains in interferometric efficiency can be expected. The VLTI should then be able to reconstruct simple images of 11th magnitude objects when combining the four UTs together.

In 2015, the VSI instrument (Malbet et al., 2008) is planned to allow six telescopes (15 visibility points) and eventually even eight telescopes (28 visibility points) to be combined simultaneously. Associated with real-time data processing, eminently feasible within the standard ESO observation framework, it would provide a realistic snapshot imaging capability. Ideally a visiting astronomer to the VLTI will see the image of the observed object being reconstructed in real-time at the console.

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Links

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