

High-Resolution with Large Ground-Based Optical/IR Telescopes

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Abstract. The Keck Interferometer on Mauna Kea and ESO's Very Large Telescope Interferometer (VLTI) on Cerro Paranal (2635 m) in Northern Chile both saw first fringes in 2001. In the meantime, MIDI, the mid-infrared science instrument of the VLTI, also had first fringes. Using the VLTI test siderostats and the VLTI near-infrared commissioning instrument VINCI, 300 hours of shared-risk science programs were executed. A few years from now, the Large Binocular Telescope (LBT) in Arizona will be the third large telescope interferometer, providing a large field of view by using a Fizeau beam combination. Here, we compare the general concepts of these three interferometers, and describe the VLTI in detail discussing the layout of the interferometer, its current status, and the general philosophy as a facility observatory.

1. Introduction

High-resolution studies directly revealing the morphology of astrophysical objects are essential for our understanding of all areas of astrophysics, and have often been the key to milestone achievements. Whereas studies with angular resolutions of up to 1 mas have already routinely been achieved in radio astronomy by employing interferometric techniques with facilities like the Very Large Baseline Array (VLBA), large-aperture optical and infrared interferometers with long baselines are currently in the process of construction and commissioning. Several optical and infrared interferometers with relatively small collecting areas have been operated, starting with the pioneering works of Fizeau and Michelson. The first construction of large interferometric facilities with 8–10 m class telescopes and baselines of up to the order of 100 m is currently in progress. These facilities include the Keck, VLT (Very Large Telescope), and LBT (Large Binocular Telescope) interferometers. Further interferometric beam combinations including 8–10 m apertures have been discussed, as for instance those between neighboring Mauna Kea telescopes (e.g. Nishikawa et al. 1998; Perrin et al. 2000). These facilities with their large collecting areas have become the first instruments that allow us to study galactic centers with high spatial resolutions of up to the order of 1 mas (Swain et al. 2003; ESO Press Release 17/2003). Using for instance a VLTI baseline B of 120 m, the resolution λ/B at $\lambda = 1.2 \mu\text{m}$ is 2 mas, i.e. about the same as currently achieved at radio wavelengths with VLBI.

2. Interferometry with large ground-based optical/IR telescopes

Until extremely large optical telescopes with diameters of the order of 100 m become available (see the concept of the Overwhelmingly Large Telescope OWL, e.g. Dierickx et al. 2003), optical and infrared studies with spatial resolution up to the order of 1 mas require the use of interferometers. The Keck interferometer is located on Mauna Kea, Hawaii, the VLTI on Cerro Paranal, Chile, and the LBT on Mt. Graham, Arizona. The Keck and VLT interferometers are "Michelson" style (see above) facilities and provide relatively large maximum baselines of 85 m and 130 m, respectively. As a result, the available uv -coverage is not complete, and the field of view is limited to about 1-2 arcsec. First VLTI instruments include the mid-infrared instrument MIDI (Leinert et al. 2003) and the near-infrared instrument AMBER (Petrov et al. 2003), followed by the dual feed facility PRIMA (see the recent reviews by Glindemann et al. 2003a,b; Schöller & Glindemann 2003). AMBER will allow the combination of three beams, and thus will provide imaging capabilities. Using PRIMA to stabilize the fringes on a bright ($K \sim 12$) reference star, AMBER will have a limiting K magnitude of about 20, and MIDI a limiting N magnitude of about 9. PRIMA can also be used for phase referenced imaging (see above), allowing imaging with both MIDI and AMBER, for fainter objects than with closure phase techniques. The LBT interferometer is a "Fizeau" style facility with two 8.4 m telescopes on one mount. This facility will provide a fairly complete uv -coverage and a relatively large field of view of 1 arcmin, on the cost of a more limited spatial resolution corresponding to a maximum baseline of 23 m. Interferometric beam combiners at mid- and near-infrared wavelengths are planned as first generation instruments (Hinz et al. 2003, Herbst et al. 2003).

3. The status of the VLTI

On October 30, 2001 at about 1am, the two 8-m Unit Telescopes Antu and Melipal of the Paranal Observatory with a baseline of 102 m were combined for the first time as a stellar interferometer observing fringes on the star Achernar (see Fig. 1), only six months and twelve days after the VLTI produced the first fringes with two siderostats. In the first year of commissioning, more than one hundred different objects were observed to verify the performance and the scientific potential of the VLTI. We found that all specifications were met or exceeded (Schöller et al. 2003; Koehler et al. 2003).

Recently, on September 15/16 and 16/17, 2002, the combination in pairs of all four Unit Telescopes was completed using a total of five different baselines (see Fig. 2). Only the combination Melipal - Yepun could not be provided due to the current configuration of delay lines in the interferometric tunnel.

The mid-infrared instrument MIDI was delivered to Paranal in October 2002 and first fringes using MIDI and the 8 m UTs Antu and Melipal were recorded on December 15, 2002 (see Fig. 3). MIDI has undergone further commissioning and "paranalization" runs during the year 2003, and is offered in standard VLT mode to the scientific community in ESO period 73, for observations between April and September 2004.

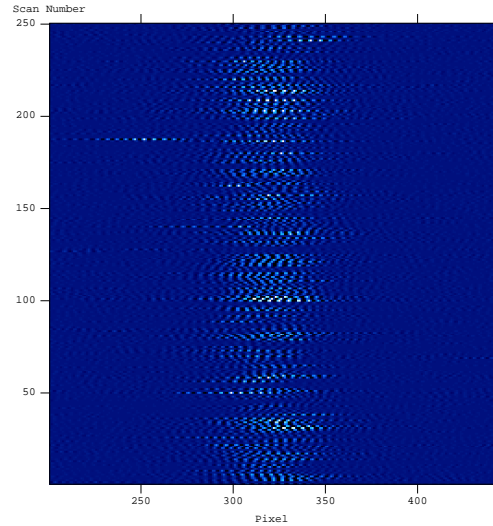


Figure 1. First fringes of Achernar with VINCI and the two 8 m Unit Telescopes Antu and Melipal on October 30, 2001. Each horizontal line represents the interferometric fringes in the K-band registered during a single scan with scan numbers increasing from bottom to top. Due to atmospheric turbulence, the fringes are slightly shifted sideways between individual scans. The shift is typically less than one fringe ($2.2 \mu\text{m}$), illustrating the stability of the VLTI.

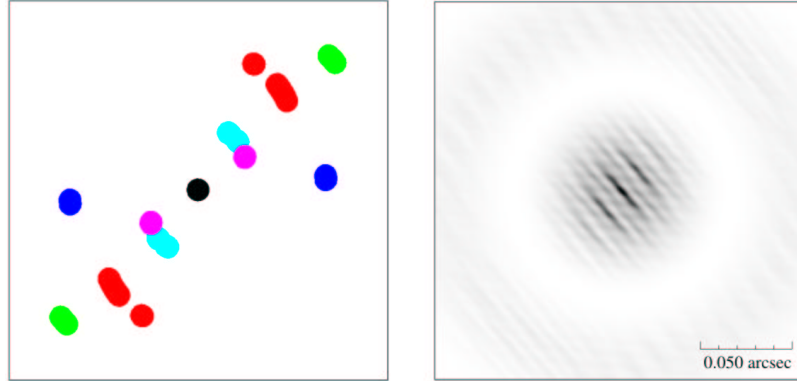


Figure 2. The result of observing Achernar in the K -band with all four Unit Telescopes on September 15 and 16, 2002. The uv coverage is shown on the left, and the point spread function (PSF) on the right. The width of the central fringe, i.e. the angular resolution limit, is about $3 \times 15 \text{ mas}$ due to the distribution of baselines used during the observations. On the largest scale, the image is enveloped by the Airy disk of a single 8 m Unit Telescope. Its first minimum at 57 mas off the center can be clearly seen.

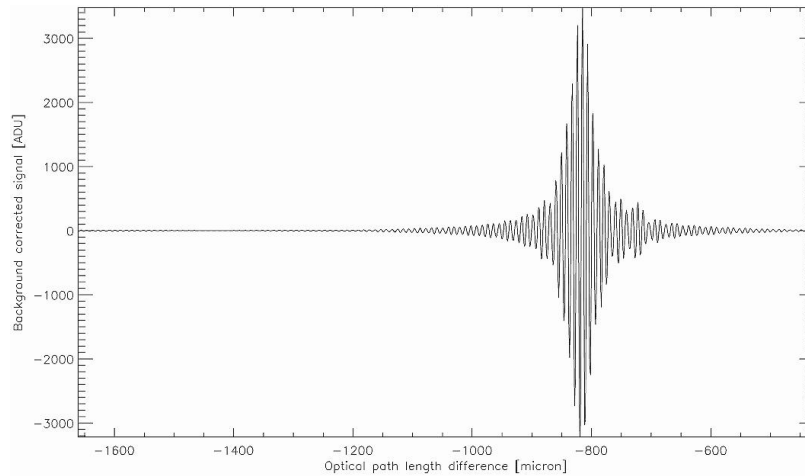


Figure 3. First fringes of ϵ Car with MIDI and the two 8 m Unit Telescopes Antu and Melipal at a mid-infrared wavelength of $8.7 \mu\text{m}$ obtained on Dec. 15, 2002.

In the course of 2003, the fringe sensor unit FINITO arrived on Paranal and two UTs were successfully equipped with the adaptive optics system MACAO. The near-infrared instrument AMBER will arrive at the end of 2003, and four 1.8-m Auxiliary Telescopes (AT) will be integrated during 2003–2004 (see Fig 4). Three more Delay Lines for a total of six will complete the first phase of the VLTI.

In 2005, the dual feed facility PRIMA will extend the capabilities of the VLTI to faint objects ($K = 16\text{--}20$) and it will allow for high-precision astrometry. Last but not least, a joint ESO/ESA project for GENIE, the DARWIN ground demonstrator planned for 2006, will open the door for planet hunts with the VLTI.

The final goal of the VLTI is to produce images with a few milli arcseconds resolution. Fig. 5 shows a simulated point spread function when observing for eight hours with all four UTs. The result shows an impressive albeit elongated PSF with full width at half maximum (FWHM) of about $4 \times 8 \text{ mas}$ for a wavelength of $2.2 \mu\text{m}$.

4. VLTI operations

VLTI operations in service mode and visitor mode will follow the same procedure as established for the instruments at the single UTs. The procedure for preparation of VLT observations involves a Phase I and Phase II proposal preparation. In Phase I, proposals are submitted electronically to ESO and evaluated by the Observing Program Committee (OPC). After the OPC selection has taken place, Phase II preparation is based on the creation of Observing Blocks. Each Observing Block specifies an individual observation sequence which can be scheduled and executed completely without any interruption. Observing Blocks are created by specifying instrument modes and parameters, target information,



Figure 4. The first Auxiliary Telescope (AT) during final integration at AMOS in Belgium. The 1.8 m telescope with Alt-Az mount like the Unit Telescopes provides a collimated beam 1.2 m underground that is sent towards the Delay Line Tunnel through insulated light ducts. The ATs are relocatable on 30 stations using special transporters moving on rails.

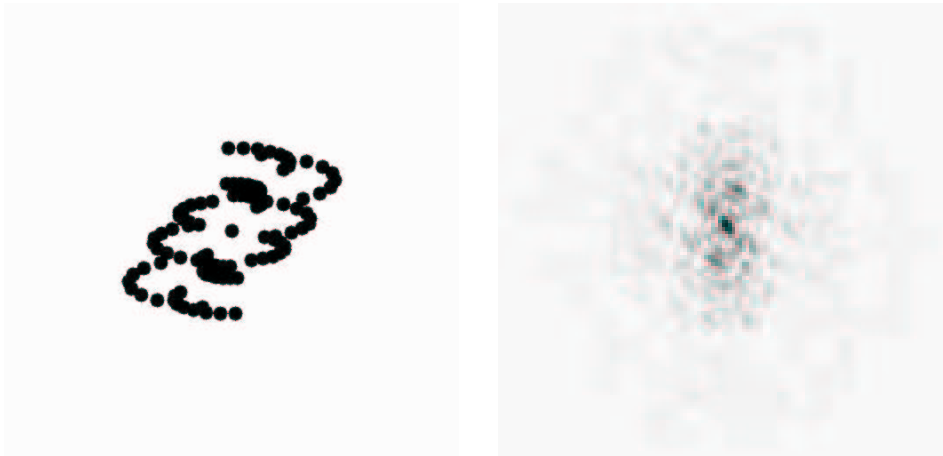


Figure 5. The uv coverage on the left and the point spread function (PSF) on the right with a full width at half maximum of 4 mas resp. 8 mas in the narrow resp. wide direction of the PSF at $2.2 \mu\text{m}$. The uv coverage and the PSF are calculated for -15° declination and 8 hours of observing with phase referenced imaging (PRIMA) when combining all four UTs. Producing images with this quality at a magnitude of $K \sim 20$ is the ultimate goal for the VLTI.

and user-defined scheduling constraints. The user is assisted during these phases by the User Support Group and by observation preparation tools. Observation preparation tools for the VLTI will include a visibility calculator (VisCalc), a calibration star selection tool (CalVin), and an exposure time calculator (ETC). For a more detailed description of this process and the preparation tools, see Ballester et al. (2001,2002). The operation of the VLTI includes additional observing constraints, namely the array configuration (specification of the used UTs or AT stations), and the constraint of the hour angle in order to specify the projected baseline length and azimuth. The ATs will be fully dedicated to the VLTI, and will allow VLTI operations throughout the year, independently of the UT observations.

These general VLTI operations are now offered for the first time in ESO period 73, for observations between April and October 2004, with the MIDI instrument and two different UT baselines.

The commissioning instrument VINCI and the test siderostats were made available to the community during the VLTI commissioning period for 150 hours shared risk science operations in each of the periods 70 (October 2002 to March 2003) and 71 (April to October 2003). A number of 39 proposals were received for P70, and 25 for P71. All data taken in the course of this shared risk program, as well as all scientifically interesting commissioning data, are publicly available through the ESO archive. First scientific results based on these data include for instance diameter measurements of dwarf stars and comparison to stellar models (e.g., Segransan et al. 2003; Kervella et al. 2003a,b; Pijpers et al. 2003), an observation of the elliptical shape of a rapidly rotating Be star (Domiciano de Souza et al. 2003), the measurement of the limb-darkened intensity profile of a M giant and comparison to stellar model atmospheres (Wittkowski et al. 2003b), and preliminary results on Mira stars (e.g. Richichi & Wittkowski 2003, Wittkowski & Boboltz 2003). A recent review on first scientific results from the VLTI can be found in Paresce (2003).

5. The Overwhelmingly Large Array - La OLA

With extremely large telescopes like OWL lurking above the horizon, future interferometry only makes sense if it delivers an angular resolution that is at least a factor of 10 higher. This means baselines of a few kilometers. Then, the optical delays that have to be compensated are of the order of kilometers, too. However, rather than building Delay Line tunnels that are kilometers long one should combine moving cat's eyes like in the VLTI with static Delay Lines. Again, the technical progress in integrated optics would be extremely helpful when delivering fast optical switches. One could then continuously observe fringes while the static Delay Lines are being switched on with optical switches. The static Delay Lines and the beam transport could be built with bulk optics or with fibers. First experiments with a laboratory fiber interferometer were successful (Delage et al. 2000).

The possible designs for such a next generation interferometer range from a large number of 4m telescopes to a modest number of 8 m telescopes. The boldest and most ambitious approach, however, is clearly to copy the VLTI concept by

combining several OWL telescopes surrounded by an array of movable auxiliary telescopes with a diameter of e.g. 8 m.

A characteristic K -band size of the circumnuclear structure of one of the brightest and closest Seyfert galaxies, NGC 1068, was measured by speckle interferometry to be $\sim 2\text{-}4\text{ pc}$ (Wittkowski et al. 1998). An interferometer consisting of telescopes with diameters of the order of 100 m and baselines of the order of 5 km would allow us to measure such a characteristic structure of $\sim 2\text{ pc}$, emitted in the near-infrared and observed in the mid-infrared, out to a redshift of $z = 1$ (Wittkowski et al. 2003a). Hence, an interferometer consisting of OWL-like telescopes would not only allow us to observe nearby extragalactic objects, but even to study the young universe on scales of the order of a few parsec.

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