Bulletin de la Société Royale des Sciences de Liège, Vol. 74, 5-6, 2005

Hypertelescopes without delay lines.

V. Borkowski [1], O. Lardière [1],
J. Dejonghe [1] and H. Le Coroller [2]

[1]LISE-Collège de France,Observatory of Haute Provence, France
[2] Keck Observatory, Kamuela, Hawaii 96743 USA

Abstract: One of the major costs in interferometry comes from the delay lines (Mourard D. et al. 2003) serving to combine the beams. This paper deals with two concepts of hypertelescope which do not use delay lines : Carlina and OVLA in order to propose prototypes having a low-cost and a large size.

1 Introduction

Many interferometers are working around the world and the beam-combination is still a problem. We discuss two concepts which do not use delay lines so that their cost decreases significantly compared to other ambitious interferometers. These concepts, called Carlina and OVLA (**O**ptical **V**ery **L**arge **A**rray; Lardière et al., *these proceedings*), take advantage of the hypertelescope concept which will be briefly recalled in the second section.
We describe also VIDA (**V**LTI **I**maging with a **D**ensified **A**rray), a project already proposed by Olivier Lardière (Lardière and Schneider, *these proceedings*). The third section will be focused on Carlina with a description of the project and the last developments. The fourth section will be dedicated to OVLA. The last one will present space hypertelescope versions.

2 Hypertelescopes

2.1 The concept

The principle of the hypertelescope (Labeyrie A. 1996) consists of densifiying the entrance aperture in order to concentrate the light spread in secondary peaks of the diffraction pattern in the central peak. Thanks to the energy conservation principle, it can be done by shrinking the size of the envelope produced by one sub-aperture. This can provide a welcome image intensification if the size of the sub-apertures is large compared to their spacing. Antoine Labeyrie proposed an optical method using inverted Galilean telescopes to enlarge the beams and obtain an output pupil with contiguous sub-pupils (see *fig. 1*).

The image properties of the remapped pupil are not destroyed because the pattern of sub-aperture centers is preserved. A pupil densification allows to improve the gain by 10 in the PSF

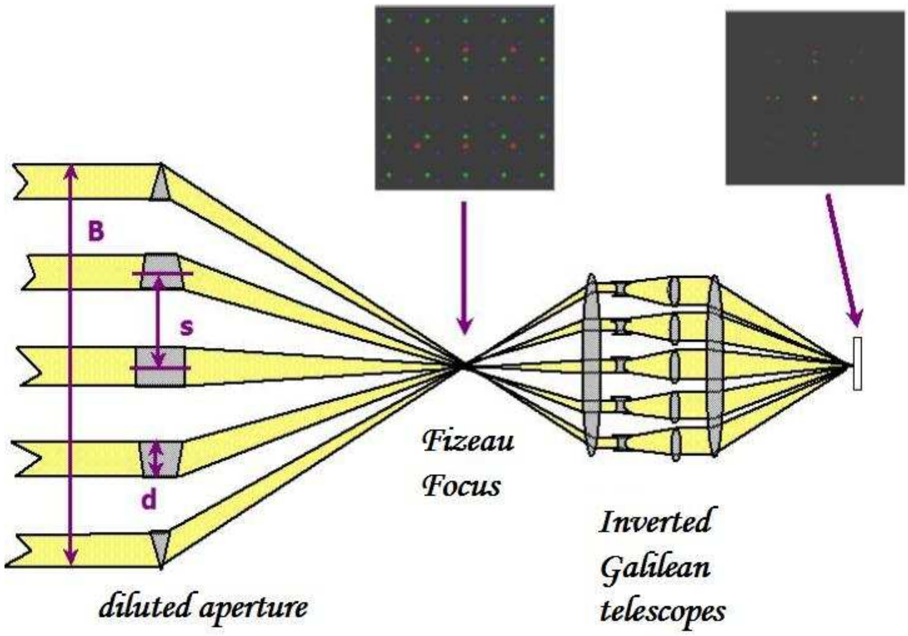

Figure 1: *Principle of hypertelescopes. From left to right : the diluted interferometer; at the Fizeau focus, the image consists of a central peak amidst dispersed secondary peaks; the 2^{nd} lens collimates the beams; the series of diverging lenses and converging lenses form inverted galilean telescopes which enlarge the beams. The last lens focuses all the beams. The resulting image consists of a very intense peak with weaker secondary peaks (see upper right image).*

(Point Spread Function) for a diluted array having a baseline ten times larger compared to the same compact Fizeau array. For an array such as the one sketched in *fig.2*, the densification factor could not exceed 4 because the sub-pupils are then joined. The maximum gain of the PSF is about 16. This densification factor γ is equal to :

$$\gamma = \frac{(B/d)_i}{(B/d)_o} \tag{1}$$

where B_i and B_o are respectively the maximum baseline of the entrance and the exit pupil; d_i and d_o are respectively the diameter of one sub-aperture of the entrance and the exit pupil.

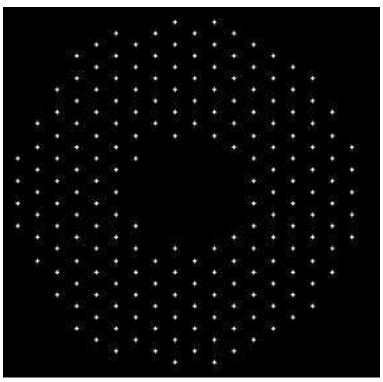

Figure 2: *Example of an entrance pupil. The maximum densification factor can reach 4.*

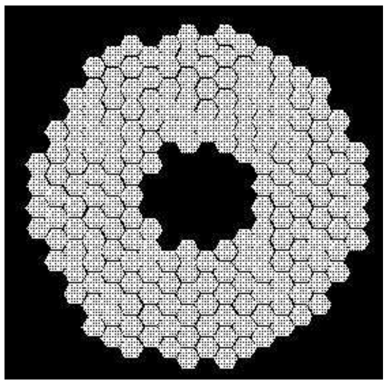

Figure 3: *Exit pupil. The maximum gain of the PSF is equal to 16 compared to the PSF of the entrance pupil.*

As it was previously mentioned, it has been demonstrated that there is no loss of field (Martinache F. and Lardière O., these proceedings), it depends on what "field" means. The **DIF** (**D**irect **I**mage **F**ield) is defined by :

$$DIF = \frac{\lambda}{(\gamma - 1)d_i} \tag{2}$$

Inside the DIF, the direct imaging is theoretically possible because the image has a sharply peaked pseudo-spread-function. Adjusting the densification factor allows to avoid loosing flux which is concentrated in the central peak of the PSF.

2.2 Validation on sky

The hypertelescope concept was first tested in laboratory and then validated on the sky by Ettore Pedretti (Pedretti et al. 2000) and by Sophie Gillet. The prototype built by Pedretti was formed by 64×1mm sub-apertures for a maximum baseline equal to 10 cm. It allowed to measure the parameters of the binary α Gem (see *fig.4*), which were about 4.1 ± 0.4" and 67 ± 3 degrees respectively for the angular separation and the position angle. This is in good agreement with values calculated, respectively 3.97 " and 64.7 degrees.
S. Gillet built another prototype with 78× 1mm sub-apertures for a maximum baseline equal to 10 cm (Gillet S. et al, 2003). The angular separation measured between the two components of the binary Castor is 3.8 arcsec (see *fig.5*).

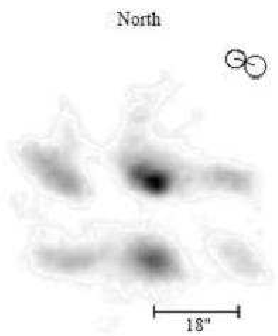

Figure 4: *Image of the Binary α Gem obtained with a 64×1mm sub-apertures hypertelescope with a 10 cm baseline (Pedretti et al, 2000). The angular separation is about* 4.1 ± 0.4" *and the position angle about* 67 ± 3 *degrees*

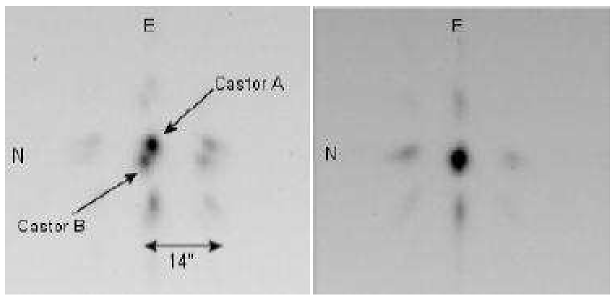

Figure 5: *Image of Castor on the left and Pollux on the right obtained with a 74×1mm sub-apertures hypertelescope with a 10 cm baseline (Gillet et al, 2003).*

As the tests with small prototypes gave encouraging results, the next step should be to validate the pupil densification at a larger scale on a current large interferometer, before building more ambitious prototypes.

2.3 VIDA

This instrument is intended to exploit the telescopes of the VLTI to do direct imaging in the near-IR using a hypertelescope mode (Lardière et al. a, *these proceedings*; Lardière et al. 2005).

2.3.1 The concept

VIDA consists of combining the 4 UTs and the 4 ATs with a densified mode. It will use the delay lines of the VLTI. In addition, it proposes an optional coronagraph mode and focal instrumentation such as a spectro-imager.
It will be possible to search and study extra solar planets by direct imaging but the accuracy of the beam cophasing should be about $\lambda/100$. One of the approaches to reach such a precision is the dispersed speckles fringe sensor unit.

2.3.2 The dispersed speckles method

The dispersed speckles FSU (DS-FSU) will allow to cophase telescopes of diluted interferometers using three dimensional Fourier transform (Borkowski et al., A&A 2005; Borkowski et al 2005). It is used to measure piston errors between pairs of telescopes.
By stacking recorded images from an interferometer at several wavelength free from dispersion effects, an *input cube* can be built. It is important to notice that the third dimension of this cube is in wave number units. A three dimensional Fourier transform of this cube will provide an *output cube* for which its third dimension gives a direct measure of the piston between pairs of telescopes.

Simulations of the VIDA instrument have shown that in the visible, for a coronagraphic precision ($\lambda/100$), magnitude 4 can be reached. So it is expected to reach 8 magnitude stars with a precision of $\lambda/10$ on the piston with an exposure time T of 5 ms, an optical transmission τ of 2.2% and a quantum efficiency q_{eff} of 0.6. In J and in K band a magnitude respectively of 6.3 and 6 can be reached for a coronagraphic precision.

The DS-FSU can also be implemented for cophasing the mirrors of hypertelescopes with longer baselines such as Carlina and OVLA.

The next step is to build more ambitious prototypes **without delay lines**. Two different concepts were proposed:

- OVLA : with movable telescopes on a flat ground
- CARLINA : with fixed mirrors put on a spherical shape

For both there are many mirrors, simultaneous recombination without delay lines and a densified mode. Direct imaging is thus possible. OVLA is more interesting for kilometric baselines.

3 Carlina

The concept of Carlina was first described by Antoine Labeyrie (Labeyrie A. et al. 2002) and by Hervé Le Coroller (Le Coroller et al. 2004). It is a diluted interferometer having fixed mirrors placed on a spherical natural surface such as a crater.

3.1 The concept

Carlina is a project of hypertelescope which does not use delay lines so that its cost and technical complexity decrease significantly compared to other ambitious interferometers. Carlina is a diluted version of the Arecibo radio-telescope with a balloon carrying the focal optics. Its densified pupil allows to do direct imaging. The helium balloon carries a gondola where the focal optics are : a corrector of spherical aberration called Mertz corrector, a pupil densifier and a detector (see *fig. 6*).

The role of the balloon is to carry the focal optics and to keep the cable tripod tightened so as to ensure the stability of the gondola. The gondola is little affected by the balloon movements in the wind, because these oscillations produce pure translations of the recorded image without losing the fringes and the vertical movements of the gondola produce defocus. The winches are used to pull three pairs of cable in order to move the gondola along the focal sphere to track the image of the star. The focal sphere is at 35 meters from ground which corresponds to half of the curvature radius of the diluted primary mirror.

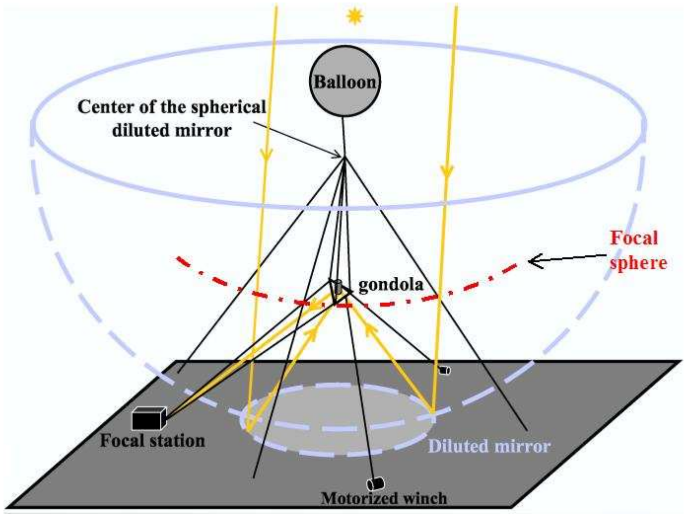

Figure 6: *Optical design of Carlina. The light coming from the star is reflected by the primary mirrors on the gondola at 35 m from ground. The shape of the primary mirrors avoids the use of delay lines because all optical paths are coarsely equalized by the spherical mirror, and finely equalized by the Mertz corrector. The gondola moves along the focal sphere, thanks to the winches, in order to track the star.*

The light coming from the star is reflected by the primary mirrors and goes through the Mertz corrector and the densifier in order to enlarge the beams and increase the sub-pupils diameter. The last lens focuses the beams on the camera (see *fig.7*).

There are three advantages with this concept :

1. *no delay lines* : their absence is explained by the spherical shape of the diluted primary mirror which, together with the Mertz corrector of spherical aberration, keeps optical paths equal. So increasing the number of mirrors can easily be done.
2. *ground stability* : the primary mirrors are fixed on the ground and initially adjusted in tip-tilt and piston. These adjustments are performed within tens of microns and do not need to be repeated frequently.
3. *internal metrology* : in order to cophase the mirrors, a polychromatic laser and a CCD are installed near the curvature center. If the mirrors are cophased, all the laser images reflected by them are stacked on the CCD and feature contrasted white fringes.

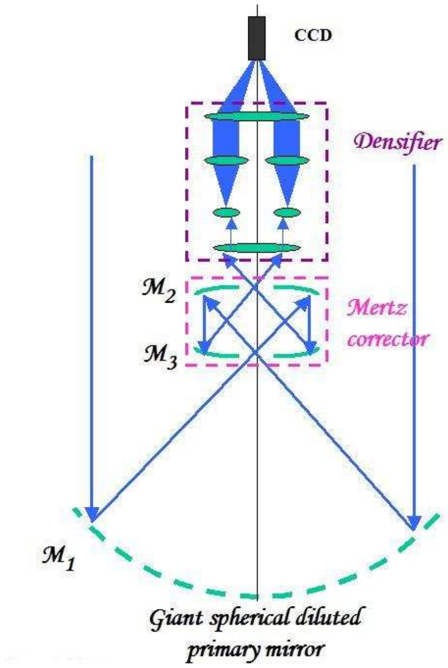

Figure 7: *Optical setup of Carlina*

Figure 8: *Photo of the balloon*

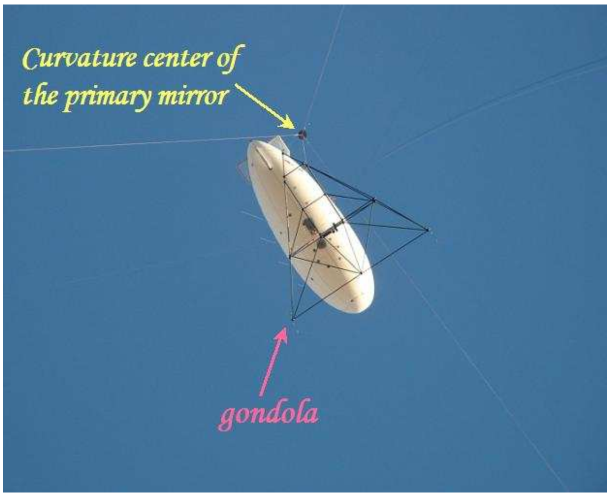

Figure 9: *Above view of the balloon*

First fringes were obtained in 2004 in the Fizeau mode with a simplified prototype. The wind speed was less than 10 km/h and the oscillations of the gondola were stabilized within 3mm. This allowed to track the fringes during one hour.

The next step was to test the corrector of spherical aberrations.

3.2 The Mertz corrector

This corrector is needed to compensate for the spherical shape of the diluted primary mirror. As sketched on *fig.10*, the light passes through a hole in mirror M_3 and is reflected by M_2 first, and by M_3. It passes through the hole in M_2 corrected from spherical aberration and goes to the densifier.

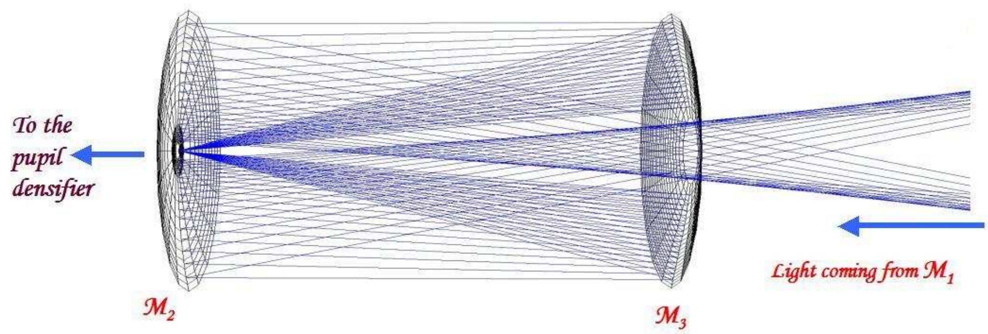

Figure 10: *Beams propagation into the spherical corrector of aberrations drawn with Zeemax (J. Dejonghe).*

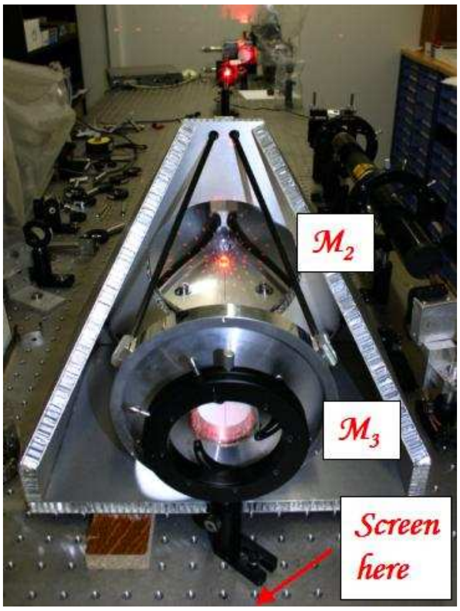

Figure 11: *Hartmann testing of the Mertz corrector in the laboratory. The corrector is back-illuminated by a laser, through a micro-lens array. The spherical aberration, evidenced by the distorted grid pattern of the spots on the mirror M_2, is correctly corrected if non-distorted in the plane of M1.*

Figure 12: *The spherical aberration is removed by the Mertz corrector, as indicated by the regular dot pattern in the relayed plane of mirror M_1 at top.*

On *fig.11*, the grid pattern of laser dots on M_2 (corresponding to M_3 on *fig.10*) shows spherical aberration. At the output of the Mertz corrector (under back propagation, see *fig.12*), the dots are regularly arrayed on the screen, which demonstrates the efficiency of the corrector.

3.3 Results and perspectives

Tests have shown that it is possible to track a star with a camera carried by a balloon in spite of a wind speed about 10 km/h, because the gondola can be stabilized within a few millimeters.

The first fringes were obtained with two mirrors. It is now attempted to co-spherize three mirrors within 1 mm with baselines of 5, 9.3 and 10.5 meters.
Tests with the Mertz corrector and the densifier are still left to be done. The next step will be the construction of a second prototype, called *Carlina II*, which will be installed at Calern Observatory, within one of the "doline" sink holes. With the 40-60m baselines expected, it should be possible to reach angular resolution better than 2 mas in the visible without adaptive optics, using speckle interferometry. A subsequent step will be to implement adaptive optics, particularly for stellar coronagraphy. Larger baselines will also be developped.

With moderate baselines, a few hundred meters, it seems that a prototype located in a deep canyon, with cables carrying the focal optics and without balloon could provide simplified solutions. But for larger baselines, the use of a crater and a balloon would remain the best solution.

Since a spherical natural crater is needed, this is a strong limitation for hypertelescopes with kilometric baselines. This is why OVLA remains a good alternative to Carlina.

4 OVLA

This concept consists in movable telescopes located on a flat ground along an ellipse. The mobility of each telescope during the observation allows to track stars without delay lines (Lardière et al. b, *these proceedings*). The telescopes have to move during the observations (see *fig.14*).

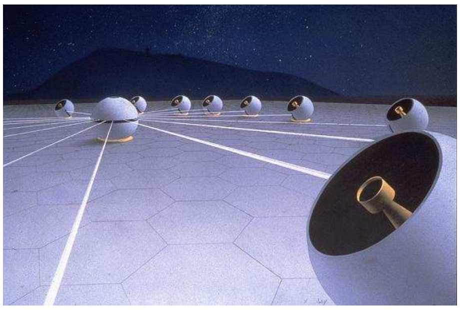

Figure 13: *Artist view of the OVLA project.*

A hypertelescope mode can be implemented (OVLA-HT) to obtain a filled output pupil which improves the dynamic range of imaging. The more important advantage is that the telescope positions can be optimized :

- non-redundant configurations to reach a better u-v plane coverage in order to image complex extended sources
- redundant configurations to reach a high dynamic range so as to imaging faint compact sources or to do coronagraphy.

The OVLA remains the best solution for kilometric baselines needed for imaging stellar surfaces.

5 Space versions

A hypertelescope in space will be the best instrument because there is no atmospheric turbulence, no Earth rotation and no limitation for the baseline length. A space hypertelescope could

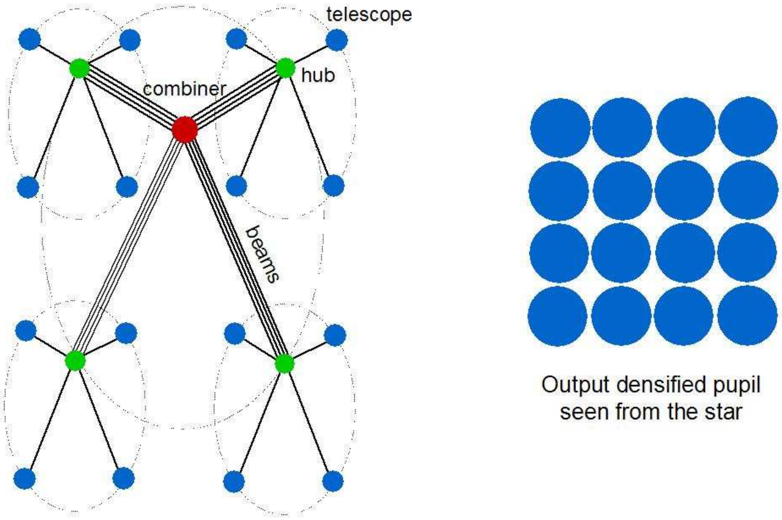

Figure 14: *Schematic picture of an OVLA hypertelescope involving 4 rings of 4 telescopes each, observing a star out of zenith. Collimated beams coming from the telescopes of a given ring are collected by a hub which sends the beams towards the focal combiner. To avoid delay lines, each hub is located on a focus of its telescope ellipse, and the combiner is located on a focus of the hub ellipse. Moreover, the pupil seen from the star is not distorded, and can be fully densified during all the observing time (right).*

consist in a flotilla of numerous small mirrors in a formation flight. Such a hypertelescope could in principle reach the 150 km or even 100000 km required to map an Exo-Earth or a neutron star respectively (Labeyrie et al. 2003).

The main problem is to be able to stabilize the relative position of each telescope in order to ensure the mirror pointing and cophasing. Solar sails offer an elegant solution to provide very faint accelerations and torques required for positioning each mirror at a nanometric level (Lardiere and Labeyrie 2002).

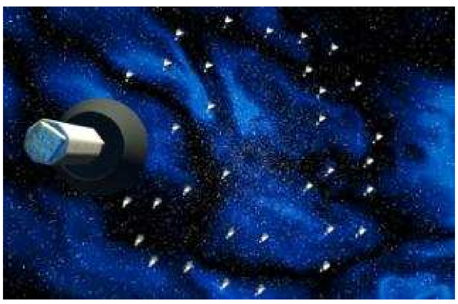

Figure 15: *Artist view of a space hypertelescope. (NASA-Boeing)*

6 Conclusions

The hypertelescope principle proved its efficiency. Both concepts Carlina and OVLA promise interesting science such as imaging stellar surfaces. The high dynamic range should permit easy detection of extra solar planets and relax constraints on coronagraphy precision.

VIDA can be an interesting first step before more ambitious projects such as Carlina and OVLA-HT. Imaging stars with magnitude about 20.5 in K band will become possible with 4 UT (Unit telescope) thanks to high dynamic range reachable.

Carlina with its many fixed mirrors, baseline spanning a few hundred meters and redundant or non-redundant array will be more efficient for the direct imaging of compact faint sources. With a 40 meter baseline, an angular resolution better than 2 mas in visible can be reached. With a baseline longer than 50 meters, studies of Mira stars and post-AGB atmosphere will be possible.

OVLA-HT will provide the largest field of view with non-redundant arrays and the best dynamic range with redundant arrays thanks to its movable telescopes. There are R&D studies in progress to check if the motion of telescopes during observation can degrade the fringe contrast.

Stepwise, beginning from the less complicated project to the more ambitious, VIDA, then Carlina, OVLA and finally space hypertelescopes can be expected to achieve new scientific results through direct imaging.

Acknowledgements

The authors are grateful to Antoine Labeyrie for the critical reading of this paper.

References

Borkowski et al, 2005, A&A, 429, 747.
Borkowski et al, 2005, Proc ESO EII Workshop 4-8 april, in press.
Fossé D., Ciel et Espace, october 2005, n^r 426.
Gillet S. et al. 2003, A&A, v.400, p. 393-396.
Labeyrie et al. 2003, Proc. SPIE, 4852, 236.
Labeyrie A. et al. 2002, *Beyond conventional adaptive optics.* Proceedings of the Topical Meeting held in May 7-10, 2001, Venice, Italy. vol. 58, p. 109.
Lardiere O. and Labeyrie A. 2002, Proc. ESA ESLAB, 514, 51.
Labeyrie A, 1996,A&A Supp. Series,v.118, p.517-524.
Lardière O. et al. a, "VIDA", these proceedings.
Lardière O. et al. b, these proceedings.
Lardière O. et al, 2005, Proc ESO EII Workshop 4-8 april, in press.
Le Coroller H. et al. 2004, A&A 426, 721.
Martinache F. and Lardière O., these proceedings.
Mourard D. et al. 2003, Interferometry for Optical Astronomy II, Wesley Traub ed., Proc. SPIE 4838, 9.
Pedretti et al. 2000, A&A Suppl. Series, v. 147, p.285-290.