

Wavefront sensing with Hypertelescope Laser-Guide-Stars

P. D. Nuñez^{1,2} & A. Labeyrie¹

¹*Collège de France*

²*Laboratoire Lagrange, Observatoire de la Côte d’Azur*

Abstract. A Hypertelescope with a spherical architecture is an attractive solution to simultaneously use tens to hundreds of mirrors in a ~ 100 m interferometric array. Provided that phasing is possible, such an instrument will allow us to obtain direct images as well as to push the limiting magnitude in optical interferometry. In order to achieve this a modified laser guide star technique has been proposed. We summarize the status of recent simulation studies of wavefront-sensing with hypertelescopes equipped with laser-guide-stars.

1. Introduction

There are proposals to increase the number of apertures in optical interferometry to improve imaging capabilities. The *Carlina* architecture is an optical diluted version of the Arecibo concept, consisting of many small mirrors sparsely arranged on a sphere and having light combined at their common focus. The main advantage of the Carlina architecture is that it will allow the combination of many apertures without the need for optical delay lines. The *Hypertelescope* is a type of interferometer that makes use of pupil densification (Labeyrie 1996), a wavefront manipulation that reduces the size of the diffraction envelope that would be obtained in a direct “Fizeau” combination, concentrating light on a reduced number of fringes. There have been tests of Hypertelescopes with Carlina architectures at the Observatoire de Haute Provence (Dejonghe et al. 2014, Le Coroller et al. 2004) and recently at “Ubaye” in the French southern Alps (Labeyrie et al. 2012).

Hypertelescopes are expected to initially operate in speckle interferometry mode, but will have to be eventually equipped with adaptive optics in order to obtain phased images over long exposures. Several wavefront sensing methods with natural-guide-stars have been proposed (Labeyrie et al. 2002, Mourard et al. 2012) which are essentially extensions of the dispersed fringes method pioneered by Michelson. In the absence of a natural-guide-star, we propose to use a modified Laser-Guide-Star (hereafter LGS) technique that is suitable for diluted apertures as described by Labeyrie (2013) and in more detail by Nuñez et al. (2014).

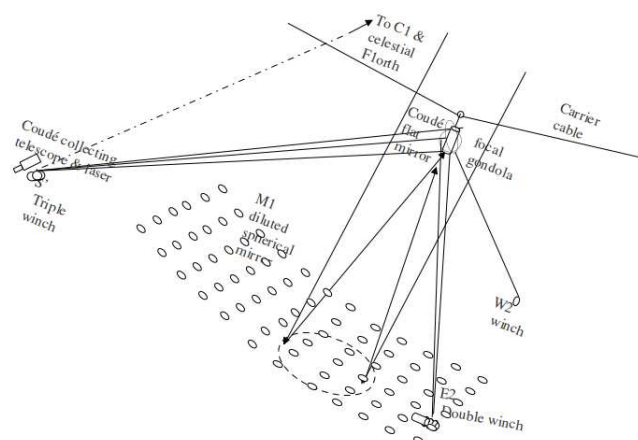


Figure 1.: *The Ubye Hypertelescope schematic plan: Ground mirrors focus light on a suspended gondola. A coude beam is sent to the southern slope of the valley.*

2. The Ubye Hypertelescope

Tests are being performed in an east-west oriented valley at “la Moutière”. Two ~ 15 cm mirrors are used to make a north-south baseline, and a focal gondola is suspended at 101 m from the ground by attaching a ~ 800 m cable from both sides of the valley (see Figure 1). Star tracking is achieved by moving the gondola in the west-east direction with the help of auxiliary cables and winches. The gondola has a pupil densifier and a coude-mirror which relays the optical beam to an 8 inch telescope on the southern slope where actual fringes will be acquired. So far, coude-beam acquisition tests have been performed and fringes are expected in the summer of 2014.

3. Laser-Guide-Stars for Hypertelescopes

Conventional wavefront sensing schemes used in monolithic apertures cannot be used with large interferometers, e.g. Hypertelescopes, mainly due to the modest sodium layer altitude. This results in the well-known “cone-effect” problem (Tallon & Foy 1990), in which laser light does not sample the same atmosphere as the light from the science target. There is also the fact that “small” (~ 10 m) interferometric baselines already resolve typical artificial laser guide stars. Since a conventional LGS would be resolved, Fourier analysis of direct images cannot be done as in the methods proposed with natural guide stars (e.g. Labeyrie et al. 2002, Mourard et al. 2012).

Therefore, the solution described by Labeyrie (2013) and Nuñez et al. (2014) consists of using sub-sets of apertures to create an array of spots in the sodium layer and collecting back-scattered light with the same apertures. The cone effect is reduced by using close sub-apertures as the laser emitting optics, and the fringe contrast is retained if exposure times are greater than ~ 0.3 ns (the Brownian motion time-scale).

As described in Nuñez et al. (2014), we have considered the case of using quadruplet apertures as the laser emitting optics. We have only studied the case

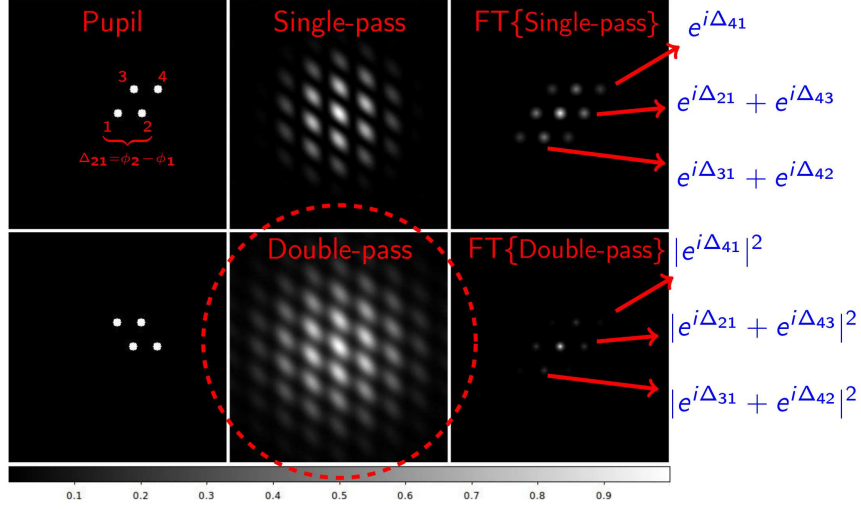


Figure 2.: Numerical simulations of a Hypertelescope Laser-Guide-Star. A subset of apertures as shown in the top-left corner will form the “single-pass” image in the sodium layer. The “double-pass” image is obtained when the single-pass image is re-imaged with the same pupil. The Fourier transform of the “double-pass” image contains peaks that retain relative piston information (Δ_{ij} between apertures i and j) when there are redundant baselines.

of small ~ 15 cm mirrors, over which the wavefront is approximately uniform, so that only piston errors play an important role.

In Figure 2, we show a simulation of the interference pattern that can be formed in the sodium layer by using a quadruplet aperture with redundant baselines. The image formed in the sodium layer (or “single-pass” image) is re-imaged with the same set of sub-apertures to obtain the “double-pass” image in the focal plane of the hypertelescope. The Fourier transform of each image contains peaks corresponding to different baselines as shown in Figure 2. The brightest secondary peaks are the most useful for piston sensing since they retain phase information when there are redundant baselines. Other pupil configurations can be used as long as there are redundant baselines, but the quadruplet configuration seems to be optimal in order to reduce the cone effect (Nuñez et al. 2014).

In order to sense pistons across a large array consisting of many overlapping quadruplets, one must use one laser-guide-star for each quadruplet. Each laser-guide-star allows measuring relative pistons within adjacent apertures, and the absolute piston at each aperture can be found by adding the relative pistons across the array. See Nuñez et al. 2014 for details.

4. Simulations

Numerical and laboratory (bench-top) simulations have verified the wavefront sensing technique, estimated its sensitivity and laser power requirements (Nuñez

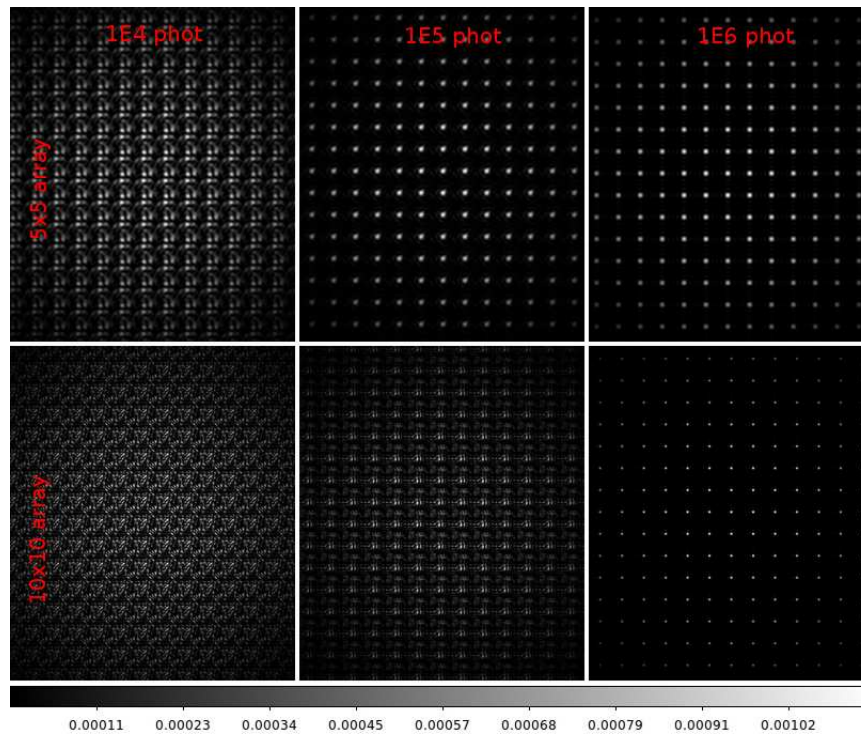


Figure 3.: The top row corresponds to the corrected PSF of an array of 5×5 telescopes and different number of detected photons per aperture quadruplet, i.e. the number of detected return photons per LGS. The bottom row corresponds to an array of 10×10 apertures.

et al. 2014). In Figure 3, we show example numerical simulations of the corrected Point-Spread-Function (PSF) of periodic arrays of 5×5 apertures and 10 apertures. Note that as the number of photons decreases, the PSF starts to resemble a speckle pattern. Note as well that smaller arrays require less return photons per quadruplet since piston sensing errors are additive across the array.

Laboratory simulations were also performed with a single quadruplet aperture and verify that one can use double-pass images to sense piston errors (see Nuñez et al. 2014 for details). Both laboratory and numerical simulations indicate that $\sim 10^6$ return photons per quadruplet are necessary to perform wavefront sensing for imaging applications (more or less depending on the number of apertures in the array).

5. Discussion and Hard points

There are several important challenges that must be overcome in order to build a Hypertelescope equipped with a Laser-Guide-Star. The first is that a laser is needed for each quadruplet, and the laser power required is of the order of ~ 10 kW (Nuñez et al. 2014). There is also a phase unwrapping problem: A polychromatic LGS can conceivably be used for this, but numerical simulations have shown that 2π errors in the measured phase are a common occurrence (Nuñez et al. 2014). The main reason for requiring a large number of return photons when compared to other wavefront sensing methods is that the Hypertelescope-LGS method relies on a fringe contrast measurement rather than a centroid measurement as in the Shack-Hartmann technique.

The issues mentioned above indicate that the subject of Laser-Guide-Stars for optical interferometry still needs significant work, even at the conceptual stage. However, the idea of using the same sub-apertures as laser emitting optics and wavefront sensors, i.e. the “double-pass” scheme, deserves further development. More general pupil configurations should be explored other than the redundant quadruplet case. The pupil redundancy can be somewhat relaxed, requiring only local redundancy, by applying “pin-cushion” distortions of less than the aperture size which also enhance the imaging capabilities of an array. It may also be possible to perform pupil-remapping for the returning image to retain phase information of double-pass images of non-redundant configurations, although this possibility has not yet been investigated. It should also be noted that this wavefront sensing scheme may be applicable to segmented telescopes in general, and a study of higher-order wavefront errors (e.g. tip-tilt) across individual sub-apertures should be performed.

6. Conclusions

Using subsets of apertures to form fringes in the sodium layer is a possible way to perform wavefront sensing with diluted apertures and has been studied via simulations. While numerical and laboratory studies have validated the method, initial results suggest that the required photon return rate is too high for an implementation of the method in the near future. More realistic numerical simulations should be performed as well as experiments on the sky, for example, by creating fringes with a masked large telescope such as the European Very Large Telescope.

References

- Labeyrie, A. 1996, *A&A*, 118, 517
- Labeyrie, A., Allouche, F., Mourard, D., et al. 2012, *Proc. SPIE*, 8445
- Labeyrie, A., 2013, *EAS Publication series*, 59, 5
- Labeyrie, A., Borkowski, V., Martinache, F., et al. 2002, *European Southern Observatory Conference and Workshop Proceedings*, 58, 109
- Mourard, D., Meilland, A., Dali-Ali, W., et al. 2012, *Proc. SPIE*, 8445,
- Le Coroller, H., Dejonghe, J., Arpesella, C., Vernet, D., & Labeyrie, A. 2004, *A&A*, 426, 721
- Dejonghe, J., et al. 2014, this conference
- Nuñez, P.D., Labeyrie, A., Riaud, P., 2014. *MNRAS*, in press
- Tallon, M., & Foy, R. 1990, *A&A*, 235, 549