High Angular Resolution in 2010-2020: A comparison between possible post-VLT/VLTI instruments

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ABSTRACT

The 8-m class telescopes are now in full operation, while 100-m baseline interferometers (VLTI, KeckI) are starting routine operation too. A working group from the French high angular resolution community tried to identify what could be our post-VLT/VLTI instruments for the period 2010 to 2020. Possible future instruments, ground or space-based, can be split into three main categories: Extremely large filled aperture telescopes, diluted interferometric arrays for direct imaging, and diluted interferometric arrays for aperture synthesis imaging. These concepts are compared in terms of scientific performances (spatial resolution, field of view, imaging capability, sensitivity, photometric dynamical range, etc.), technological issues (adaptive optics, phasing, instrument mount, etc.) and R&D priorities.

Keywords: Extremely large telescope, ELT, interferometric array, hypertelescope, science performance, technological issue

1. INTRODUCTION

The aim of this article, based on a more complete work by the French high-angular resolution prospective working group,[1] is to identify the different categories of possible post-VLT/VLTI instruments that will be available in 10 or 20 years, and to compare them in terms of scientific performances (spatial resolution, field of view, imaging capabilities, sensitivity, photometric dynamic range, etc.) and in terms of technological issues (adaptive optics, phasing, instrument mount, etc.). This work was motivated by the different studies started for extremely large telescopes (ELT)[2, 3] or interferometers.[4, 5] We give the list of scientific criteria (Sect.2) that have been used to compare the main categories of future instruments (Sect.3). In Sect.4, we discuss the R&D priorities that we have identified.

2. SCIENTIFIC PERFORMANCE CRITERIA

We consider that all instruments will be equipped with adaptive optics (AO). The ten following criteria have been considered:

i) spatial resolution (*i.e.* wavelength/diameter ratio),

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ii) imaging capability, direct imaging versus aperture synthesis, number of resolution elements (resel) in the final image, PSF profile,

iii) field of view, direct or reconstructible,

iv) sky coverage in AO with natural guide stars (GS) or laser GS, maximum zenith angle,

v) sensitivity, limit magnitude versus diameter and Strehl ratio,

vi) photometric range for high-dynamic imaging (HDI), coronagraphy,

vii) spectral bandpass (V to N), down to UV in space,

viii) spatial, spectral resolution and sensitivity of the focal instrument,

ix) instrument modularity, upgrading potential (baseline, collecting area, focal instrument),

x) instrument versatility.

3. THREE CATEGORIES OF INSTRUMENTS

3.1. The extremely large filled-aperture telescope

This 20 to $100m$ telescope has a single giant mosaic mirror. Typically the entrance pupil is filled, but slightly diluted pupils with a filling factor above 0.5 enter this category, providing a Fizeau recombination of light is done at instrument focus (*i.e.* the exit pupil is a homothetic transform of the entrance pupil). The field of view is 3 to $60arcmin$ in diameter, with resel sizes ranging from 1 to $5mas$ (milliarcsec) at $\lambda = 500nm$. Even with a slightly diluted pupil, the diffraction pattern remains compact and suitable for coronagraphy and other HDI technics.

Generally speaking, such kind of giant telescopes might be versatile, but only upgrading of its focal instrument seems possible. Sentitivity reaches $V = 35$ with an exposure time of $1000s$ for a $100m$ instrument with a signal to noise ratio (S/N) of 5 and a Strehl ratio of 50%, but only $V = 28.5$ without AO (Fig.1).

3.2. The diluted interferometric array for direct imaging

The entrance pupil can be extremely diluted, with a filling factor from 0.1 to 10^{-4}. The number of sub-pupils ranges from $N = 450$ to 28000, spread over 100 to $1000m$ baseline, possibly much more in space. The angular resolution is at least one order of magnitude better than for the previous category of instrument. To provide snapshot images at the instrument focus, the light beams from sub-pupils are combined in the hypertelescope mode, also called densified pupil mode,[6] a particular case of Michelson interferometry where two homothetic transforms are used to transport the light from the entrance to the exit pupil. The direct field of view (called zero-order field or ZOF) is very small, typically smaller than $100mas$ containing $\approx 1.8 \times N$ resels for a redundant pupil. This field can nevertheless be extended by i) image processing depending on object complexity or field crowding or ii) by multiplying by N_d the number of recombining optics, allowing mosaicing by simultaneous observations of N_d different fields. The field would reach $1arcsec$, with thousands ($\approx N \times N_d$) resels in the final image. The PSF is compact and thus bright too, and HDI is possible.

Therefore a hypertelescope is much more efficient for imaging than a very diluted Fizeau interferometer where the PSF energy is split between numerous secondary lobes and a consequently weak central core.[1, 6]

An important point to note is that, for a given collecting area, a hypertelescope reaches the same limit magnitude that a single pupil telescope (Fig.2). This kind of instrument may be more easily upgradable (baseline, collecting area, N) than an giant monolithic telescope.

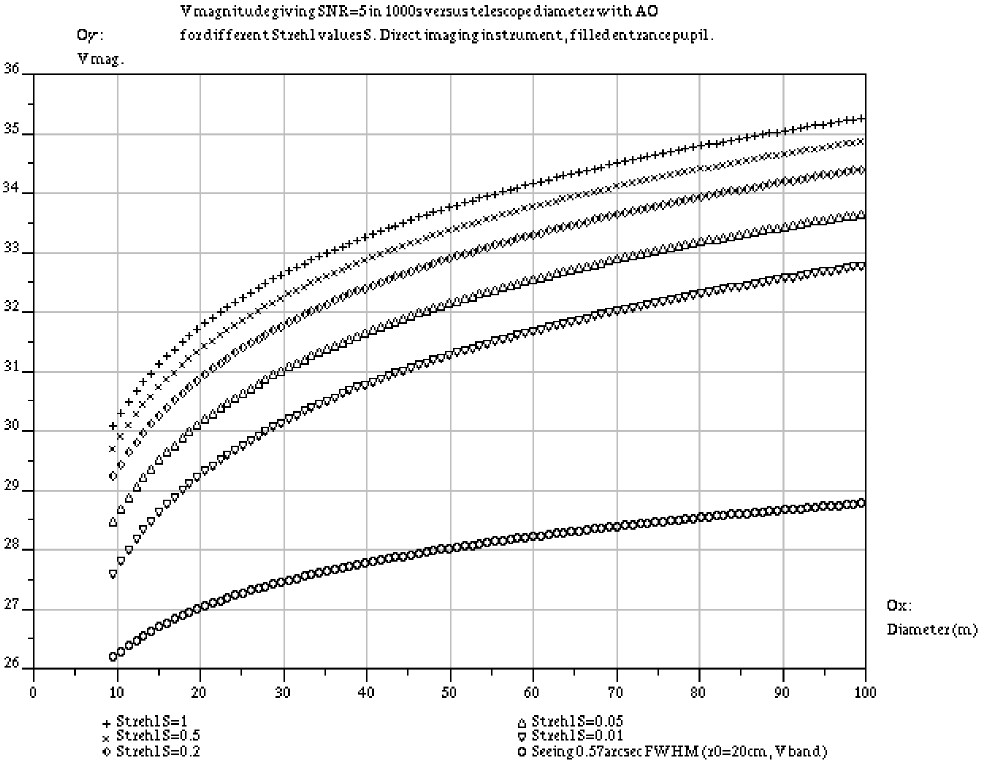

Figure 1. V magnitude giving a $S/N = 5$ for $1000s$ exposure time versus telescope diameter and different values of the Strehl ratio. A filled pupil instrument is considered here.

3.3. The diluted interferometric array for aperture synthesis imaging

As the previous instrument, it has a very diluted entrance pupil, with a filling factor from 0.1 down to 10^{-4} and with $N = 6$ to 150 sub-pupils spread over 100 to $1000m$ baselines (or more in space). Sub-pupils diameter ranges between 2 and $8m$. It is interesting to note that an array of 150 $8m$ telescopes would provide the same collecting area as a $100m$ ELT (or 37 $8m$ would gather the light of a $50m$ ELT).

The aperture synthesis interferometers do not provide directly an image of the object, since the relation between the entrance and the exit pupils is not one (or a pair of) homothetic transform(s). But each pair of sub-apertures allows the measurement of one object visibility (fringes contrast and phase) and all visibilities allow the image reconstruction. The number of resels in the final image varies from $\approx N$ to $\approx N^2$, depending the pupil pattern is redundant or not, respectively.

Based on the collecting array of a pair of $8m$, one finds a sensitivity of $V = 26$, but this value may vary depending of the fringe tracker sensitivity.

These ground-based instruments would need long and fast delay lines, but on the other hand, AO for $8m$ apertures is already available today (at least with high Strehl in the K band). One should also note that interferometric arrays seem quite easily upgradable. Moreover, it is possible to have a focal instrument, among others, that can densify the exit pupil, thus transforming the array into a direct imager (a hypertelescope) as suggested for VIDA[7] on the VLTI.

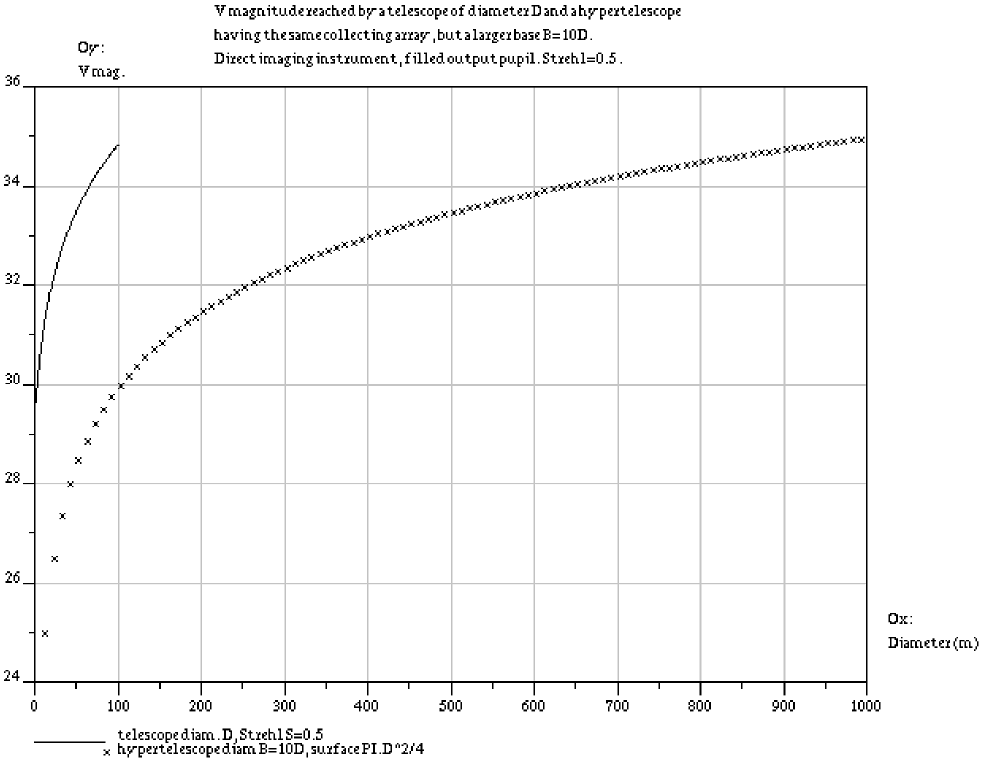

Figure 2. V magnitude ($S/N = 5$ in $1000s$, Strehl=50%) reached by a telescope of diameter D (solid curve at left) and a hypertelescope (curve at right) having the *same collecting area*, but a *larger baseline* $B = 10 \times D$. For example, the $50m$ ELT and the $500m$ baseline hypertelescope will reach the same limit magnitude ($V \approx 33.5$), providing both have the same collecting area.

4. R&D PRIORITIES

4.1. Adaptive optics AO

AO, moreover Multi Conjugate AO (MCAO) and atmospheric tomographic technics, are major difficulties to overcome for ELTs. Although several works[8, 9] show its feasibility, MCAO producing high Strehl in the visible range on a $100m$ telescope is not reasonably foreseen before 2020 (G. Monnet, atelier d'optique, Grenoble, 5th March 2001).

MCAO allows in principle to correct over a large field (of the order of $1 arcmin$). This requires several deformable mirrors and wavefront sensors, with up to 10^5 degrees of freedom for a $100m$ in the visible. MOEMS[10] is a solution to integrate a high number of actuators on a reasonable surface.

Future ground based AO/MCAO extreme complexity is in favor of space mission, where AO, even if it may be necessary (controlling large segments shape and piston - instrument jitter may require high frequency bandpass), should be relaxed in terms of degrees of freedom if we consider projects before 2020. We must point out that in the case of an interferometric array of $8m$ telescopes or smaller , AO technology is available today for the infrared, and it may obviously be available sooner in the visible for $8m$ sub-pupils than for an ELT.

Laser guide stars, various wavefront sensing methods (interferometric, Hartman-Shack, curvature, pyramid, LIDAR technics,[11] etc.), the use of photorefractive material as a 3-D turbulence corrector, should be investigated further.

4.2. Coronagraphy and HDI technics

Several new concepts of coronagraph have been proposed since 1997.[12–16] All have been tested in the lab or even on the sky.[17] These coronagraphs need today to be carefully compared to choose the best concept for HDI future applications, such as the VLT Planet Finder. It as been recently suggested to significantly improve the extinction around the central star with multi-stage coronagraphy.[18]

Obviously, these technics require a high Strehl ratio and consequently an excellent AO system.

4.3. Metrology, phasing and fringe tracking

A least $\lambda/100$ is required to achieve good coronagraphic extinction and this required phasing in the nm range in the visible. Astrometry also requires very high internal metrology.

Several piston recovering technics in diluted arrays are under studies[19] and need to be tested, particularly for the hypertelescopes.[20]

Fast delay lines, on rails or possibly able to move in 2-D on the ground,[21] with sensitive fringe trackers, have to be develop for ground-based $1km$ baseline interferometry.

4.4. Recombiners

They need particular R&D depending on the concept of the interferometer. They have to integrate several functionalities: pupil stabilization, field rotation compensation, star tracking, residual piston correction (delay line 2nd-stage), calibration source, internal alignment and metrology tools.

Depending on the interferometer design, multi-stage recombiners can be considered.[21]

4.5. Material and optical technology

Mirror substrates (Zerodur, SiC) and optics fiber materials for long baseline interferometry (OHANA[22] for Hawaii or ALIRA[23]on the ALMA site), related polishing and thin layer deposition technologies have been identified as another pole to develop. Membrane mirrors must also be considered as an alternative for future very large collectors in space.[24, 25]

This section also should include structural materials studies for large telescope mounts or space-based instruments, possibly integrating active or adaptive structures (so-called smart structures).

4.6. Data / image processing

Field crowding can be a limitation in high-angular resolution imaging. Simulations are currently done for hypertelescopes (Labeyrie 2002, not published) and need to be developed further to show how the information in the ZOF can be used to reconstruct the image over the High Order Field, which in practice may be typically 10 times larger in diameter.

Progresses in image reconstruction from visibilities measurements should ideally reach the level reached in radio astronomy, where images are directly computed from data.

4.7. Focal instrumentation, detector

The large field of view of ELTs will require high parallelization of their focal instrument. Today on the VLT, the VIMOS spectrograph, made of 4 parallel spectrographs, can be considered as an example of parallelized instrument. Second generation VLT instruments may reach up to 24 parallelized spectrographs (MUSE proposal to ESO). Fibers positioner systems, already highly parallelized, also require developments in robotics (mechanics, optics and software). New image slicers are also of interest.

Detectors and related cryogeny are continuously developed. 3-D detectors (xyλ) like STJ[26–28] may be of interest for fringe trackers with spectral resolution around 100. But only 6x6 pixels arrays are available today. Moreover, it requires liquid Helium cryogeny.

3-D detectors also include xy-time detectors.

4.8. Site selection

Earthquake for ELTs is an issue and a non-seismic region must be chosen. A plateau, if it fulfills the atmospheric requirements, would be a good solution if a large array has to be constructed near or around an ELT. The large structure of the ELT itself and AO/MCAO requirements have also to be taken into account in the site selection.[29]

Dry salars can be perfectly flat areas to install interferometer[21] but they have not been tested. Another promising alternative is the Antarctic Dome C site.[30]

4.9. Instruments in space

Two types of interferometers can be foreseen for space: an array on a large (probably smart) structure, or an array of free-flyers. Free flyers will allow to reach much larger baselines. Missions like ESA SMART-2 or NASA ST3 StarLight, which will test formation flying interferometry, are obvious cornerstones for space interferometry.

Although a $10km$ diameter hypertelescope with $30km$ focal length is only foreseen in space, smaller ground-based ones (hundreds meters diameter with a shorter f/2 focal ratio) have been proposed.[18, 31] In this case, a stabilized balloon-born recombiner is required. Several studies and tests are under way.

5. CONCLUSION

These future instruments, ground or space-based, clearly will be extremely complex, and require strong R&D programmes. The performances of these instruments are often different, pointing out their potential scientific complementarity. Technological critical points are different too, suggesting that a single versatile instrument would be more difficult to built. Probably building one or two slightly specialized instruments would significantly relax the difficulties and the cost.

Two ground-based specialized instruments would provide scientific complementarity, as it is today the case for the VLT and the VLTI, or the Keck telescopes and the KeckI. It may also be the case in the future with an ELT and a long baseline diluted array with a significant collecting surface, possibly both installed on the same site to benefit from the observatory facility, but also to benefit from possible further interferometric coupling from the array itself with the ELT.

REFERENCES

1. L. Arnold, *et al.*, *Prospective pour l'instrumentation HRA* (http://wwwrc.obs-azur.fr/fresnel/ashra/), 2001.
2. R. Gilmozzi, *et al.*, *Proc. SPIE* **3352**, p.778, 1998.
3. D. Burgarella, *et al.*, *The Large Petal Telescope, NG-CFHT replacement study, final report, May 2001* (http://wwwrc.obs-azur.fr/fresnel/ashra/), 2001.
4. S. Ridgway, F. Roddier, *Proc. SPIE* **4006**, p.940, 2000.
5. A. Labeyrie, *et al.*, *Proc. SF2A - Scientific Highlights 2001*, EDP Sciences, Combes *et al.*, ed., p.505, 2001.
6. A. Labeyrie, *A&AS* **118**, p.517, 1996.
7. O. Lardière, *et al.*, *Proc. SPIE* **4838**, this volume, 2002 (http://www.obs-hp.fr/ lardiere/).
8. M. Le Louarn, *et al.*, *MNRAS* **317**, p.535, 2000.
9. R. Dekany, *et al.*, *Proc. SPIE* **4003**, p.212, 2000.
10. F. Zamkotsian, *et al.*, *Proc. SPIE* **4007**, 2000.
11. C. Townes, *Astrophys. J.*, **565**, 2, p.1376-1380, 2002.
12. J. Gay, *et al.*, Infrared Space Interferometry : Astrophysics & the Study of Earth-Like Planets. C. Eiroa et al. ed., Dordrecht, Kluwer Academic, p.187, 1997.
13. F. Roddier, *CRAS* **t.325**, Srie Iib, p.35, 1997.
14. L. Abe *et al.*, *A&A* **374**, p.1161-1168, 2001.
15. D. Rouan *et al.*, *PASP* **112**, p.1479-1486, 2000.
16. P. Riaud *et al.*, *PASP* **113**, p.1145-1154, 2001.
17. P. Baudoz *et al.*, *Proc. SPIE* **3353**, p.455, 1998

18. A. Labeyrie, *ESLAB 36 Conference*, ESA ESTEC, Noordwijk, June 2002, in press.
19. K. Dohlen, F. Fresneau , *Proc. of Backaskog Workshop on Extremely Large Telescope*, T. Andersen et al. eds., Sweden, 1-2 June 1999, p.162-167, 1999.
20. V. Borkowski *et al.*, *ESLAB 36 Conference*, ESA ESTEC, Noordwijk, June 2002, in press.
21. O. Lardière, PhD thesis, Université de Provence, 2000.
22. G. Perrin *et al.*, *Proc. Semaine de l'astrophysique SF2A*, ed. EDP Sciences & SF2A, Paris, June 2002, in press.
23. V. Coudé du Foresto *et al.*, *Proc. 36th Liège International Astrophysical Colloquium*, 2001, in press.
24. A. Labeyrie, *A&A* **77**, p.L1, 1979.
25. R. Angel, *et al.*, *Proc. Ultra Lightweight Space Optics Challenge NASA Workshop* mars 1999, Napa, California, 1999.
26. T. Peacock *et al.*, *A&AS*, **123**, p.581-587, 1997.
27. M.A.C. Perryman *et al.*, *A&A*, **346**, p.L30-L32, 1999.
28. R.W. Romani *et al.*, *Astrophys. J.*, **521**, p.L153-L156, August 20, 1999.
29. M. Sarazin, *Proc. Semaine de l'astrophysique SF2A*, ed. EDP Sciences & SF2A, Paris, June 2002, in press.
30. E. Fossat, *Proc. Semaine de l'astrophysique SF2A*, ed. EDP Sciences & SF2A, Paris, June 2002, in press.
31. A. Labeyrie, *Proc. "Beyond Conventional Adaptive Optics"*, Venice, May 7-10, 2001, Eds. Roberto Ragazzoni, Norbert Hubin and Simone Esposito, to be published by European Southern Observatory.