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 after 2010. 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 observing capabilities and 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, high angular resolution, high dynamics imaging, coronagraphy, prospective.

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 2010 and after, and to compare them in terms of observing capabilities and 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 (see also Table 1):

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 dynamics 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

The instruments are compared in Table 1 and described hereafter.

3.1. The extremely large filled-aperture telescope

This 20 to $100m$ telescope has a single giant mosaic mirror. The primary mirror segments are 0.5 to $8m$ in diameter. Typically the entrance pupil is filled (filling factor c=1), but slightly diluted pupils with a collecting area filling factor above c=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. To quantify and compare the contrast that should be reached in practice with the different designs, it is necessary to carefully take into account the exact entrance pupil shape (size of the secondary and spider, gap between segments) and residual wavefront errors (narrow turned edges on segments for example, quasi static spatial spectrum of segment polishing residual errors, polishing quality and residual roughness, dust on the primary, tip-tilt residuals, higher order AO residuals, etc.). Partial analysis have be done up to now.[1]

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 c=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.

The hypertelescope is an interferometer that provides a direct image of the object at its focus. To provide these snapshot images, the light beams from the sub-pupils are combined in the 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 $100mas$ and contain $\approx 1.8 \times N$ resels for a redundant pupil. The field-of-view resolution ratio is adressed in a paper by Koechlin and Perez.[7] The small field can nevertheless be extended by:

i) image processing depending on object complexity or field crowding. For broad objects, a diluted aperture array reaches the imaging performance of a filled aperture only when the object fits in a field smaller or equal to the ZOF. No other source should be present in the larger PSF of the individual apertures (the High Order Field HOF). In the case of a bright background such as in planet imaging or nebulae, a hypertelescope would yield an image with a reduced contrast, by a factor = ZOF/HOF.

ii) 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.

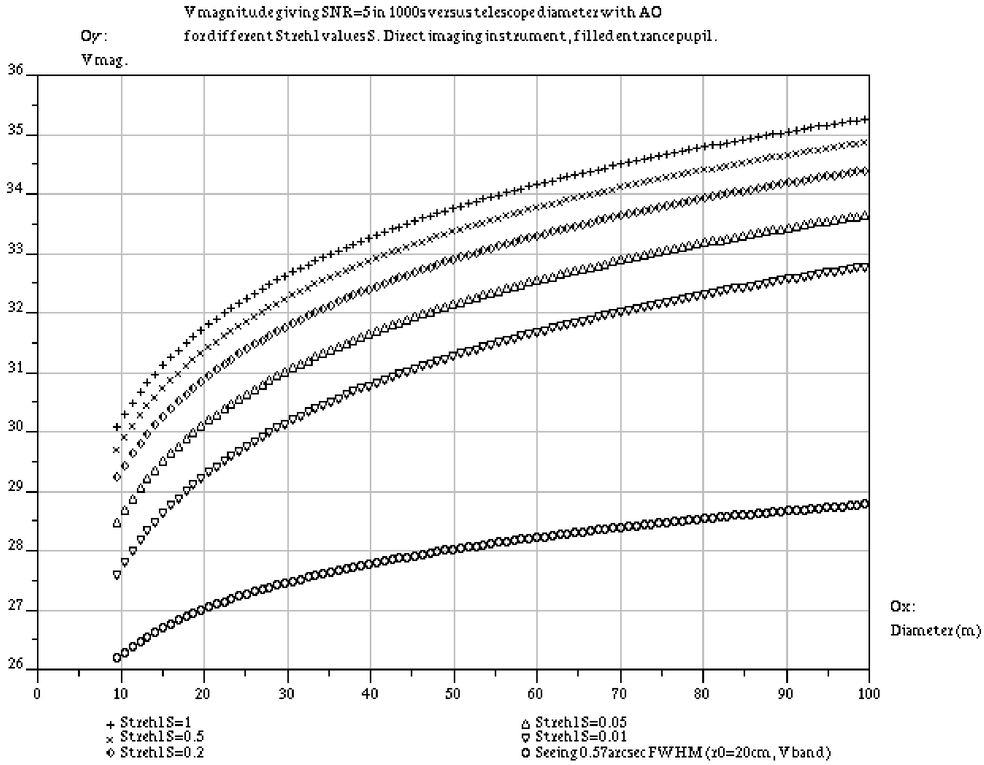

Figure 1. V magnitude giving a $S/N = 5$ for $1000s$ exposure time versus telescope diameter and different values of the Strehl ratio. A filled pupil instrument is considered here.

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] The figure 2 show the PSF in log scale for OWL and Carlina, a 2500 sub-pupils hypertelescope.[8] The figures 3 and 4 represent cuts in the figure 2, in the brightest and darkest radial directions. The hypertelescope PSF reaches $\approx 10^{-5}$ at $\approx 3\lambda/B$ and is potentially darker than OWL PSF in some regions. This is mainly due to the central obscuration, which is very small or zero for a hypertelescope but reaches 0.3 for an ELT.

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.5). This kind of instrument may be more easily upgradable (baseline, collecting area, N) than an giant monolithic telescope.

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^{-5}. Here we consider $N = 6$ to 156 sub-pupils spread over 100 to $1000m$ baselines (or more in space), with sub-pupils diameter ranging between 0.6 and $8m$ (for the record, an array of 156 $8m$ telescopes would provide the same collecting area as a $100m$ ELT, and 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.[9] 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.

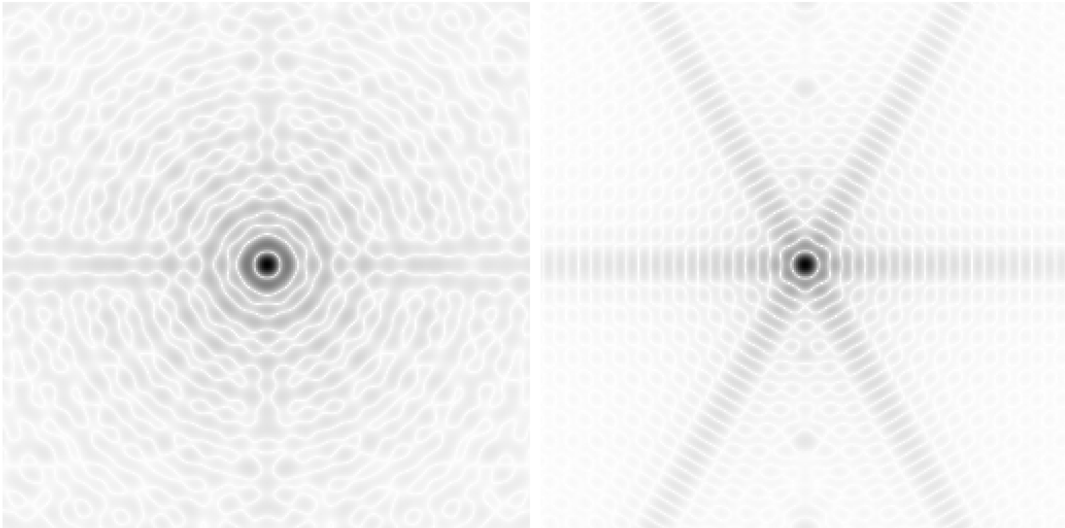

Figure 2. PSF for ELT OWL[2] (left) and a hypertelescope with 2500 segments, Carlina[8] (right). Intensity is represented with the same log scale on both figures. The log scale intensifies the speckles around the central core. The exact pupil shapes are taken into account (including the 4mm gap between OWL segments).

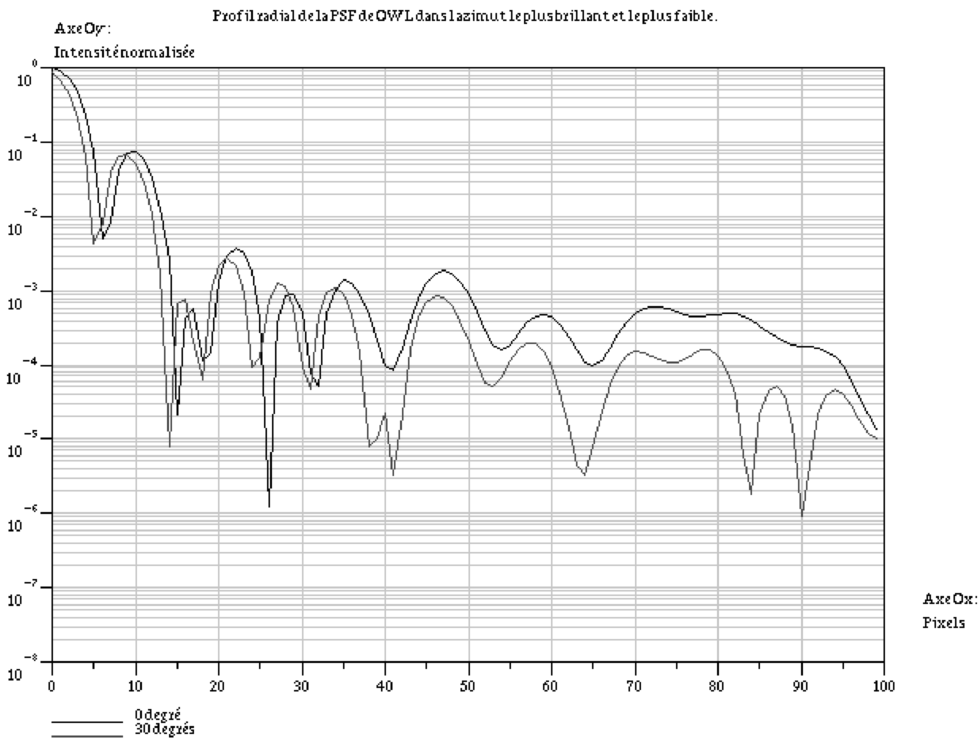

Figure 3. Cuts in the OWL PSF in the brightest (above) and darkest (below) radial directions. Each bump (upper curve for example) is $\approx \lambda/B$ wide.

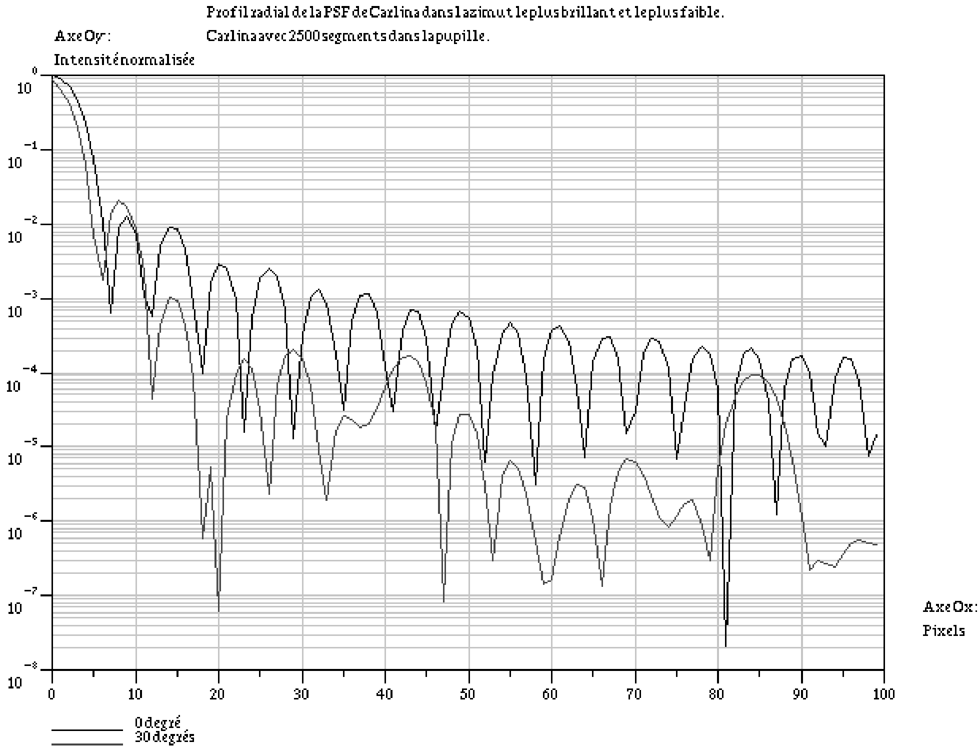

Figure 4. Cuts in the Carlina PSF in the brightest (above) and darkest (below) radial directions. Each bump (upper curve for example) is $\approx \lambda/B$ wide.

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 such 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 for the VIDA proposal[10] for the VLTI.

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[11, 12] show its feasibility, MCAO producing high Strehl at visible wavelength on a $100m$ telescope is probably not foreseen before 2020.

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[13] are a possible 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

Table 1. Performances computed for the three different concepts. The limit magnitude in V band (0.55μm, 90nm FWHM) and K band (2.2μm, 600nm FWHM) have been computed with a background magnitude of 21.5/arcsec^2 in V and 11.2/arcsec^2 in K. Extinction in V is 0.12mag/airmass and 0.09 in K. The airmass is set to 1.15. Typical Visible and IR performances for the detector (RON, thermal noise, QE, etc.) are considered. The instrument transmission is 0.5 with the imaging camera, 0.3 with the spectrograph (and 0.0035 with the combiner for the aperture synthesis interferometer).

Instruments $\rightarrow$ Design param. and perf. $\downarrow$	Direct imaging filled pupil telescope (ELT)	Direct imaging interferometer (hypertelescope)	Aperture synthesis interferometer
Diameter (or baseline B)	30 to 100m	100 to 1000m ($\geq$1000m in space)	100 to 1000m ($\geq$1000m in space)
Wavelength	V to N	V to N (UV in space)	V to N (UV in space)
Resel size (in V)	3 to 1mas	1 to 0.1mas (smaller in UV in space)	1 to 0.1mas (smaller in UV in space)
Instrument parameters: Pupil filling factor (c) Collecting area Segment (sub-pupil) diam. (d) Number of segments (N)	 c=0.5 to 1 350 to 7800m^2 0.5 to 8m 7 to 2000	 c=0.1 to c=5×10^{-4} 220 to 7800m^2 0.6 to 2m 450 to 30000	 c=0.1 to 10^{-5} 10 to 7800m^2 0.6 to 8m 6 to 156
Imaging	direct	direct	image synthesis with $\leq N(N-1)/2$ parameters
Time resolution	snapshot	snapshot	depends on N (+ supersynthesis possibilities)
PSF profile: lowest intensity at $\approx 3\lambda/B$	 4×10^{-4} (Fig.3)	 1×10^{-5} (Fig.4)	 -
Field of view diameter	3 to 60 arcmin	1 to 100 mas (ZOF), 1 to $\gg 1''$ with multi densifiers, mosaicing or HOF reconstruction	0.1 to 10 mas (more with supersynthesis)
Number of resels (N_r)	$\approx 10^8$	200 to 50000	15 to 12000
Zenith distance (in deg.)	1 to 60	0 to 45 (up to 60?)	0 to 45 (up to 60?)
Sky coverage: in V, with MCAO and S=0.4 in K, with MCAO and S=0.8	 10 to 70% 10 to 100% (see ref[11, 12])	 idem idem	 idem idem

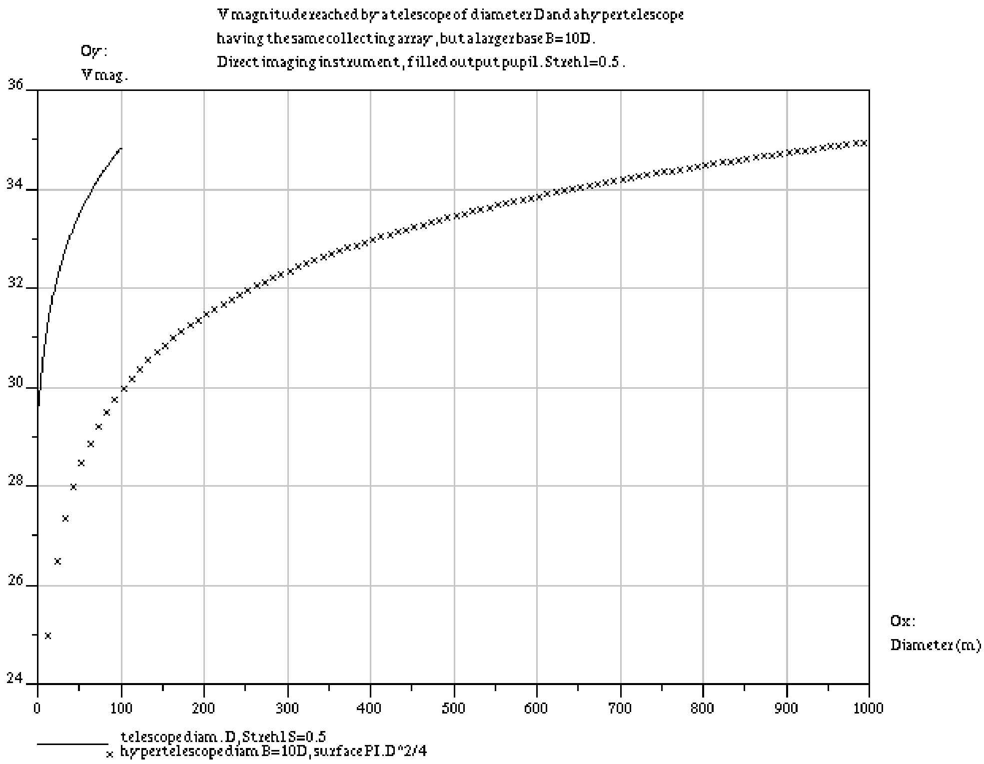

Figure 5. V magnitude ($S/N = 5$ in $1000s$, Strehl=50%) reached by a telescope of diameter D (solid curve at left) and a hypertelescope (curve at right) having the *same collecting area*, but a *larger baseline* $B = 10 \times D$. For example, the $50m$ ELT and the $500m$ baseline hypertelescope will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

Table 1. continued Instruments → Design param. and perf. ↓	Direct imaging filled pupil telescope (ELT)	Direct imaging interferometer (hypertelescope)	Aperture synthesis interferometer
Sensitivity (magnitude): (S/N=5 in 1000s expos.) in V, with AO and S=0.5 in K, with AO and S=1	 31 to 35 (Fig.1) 24 to 28	 31 to 35 24 to 28	 26 (8m sub-pupils) 21
Photometric range (magnitude) in K, S=0.8	 8 (see ref[18])	 10 (see ref[18, 19])	 ≤ 5 (see ref[36])
Focal instrument, sensitivity in spectroscopy (magnitude): (Res=5000, S/N=20, 1h expos.) in V, with AO and S=0.5 in K, with AO and S=1	 23 to 27 19 to 23	 23 to 27 19 to 23	 18 (8m sub-pupils) 15

out that in the case of an interferometric array of $8m$ telescopes or smaller, AO technology is available today for the infrared. It should be available in the visible for $8m$ sub-pupils obviously sooner than for an ELT.

Laser guide stars, various wavefront sensing methods (interferometric, Hartman-Shack, curvature, pyramid, LIDAR technics,[14] 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.[15–19] All have been tested in the lab or even on the sky.[20] Recent developments can be read in the *Astronomy with High Contrast Imaging* May 2002 proceedings.[21] These coronagraphs need today to be carefully compared to choose the best concept for HDI future applications, such as the VLT Planet Finder. It has been recently suggested to significantly improve the extinction around the central star with multi-stage coronagraphy.[22]

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[23] and need to be tested, particularly for hypertelescopes.[24]

Fast delay lines, on rails or possibly able to move in 2-D on the ground,[25] with sensitive fringe trackers, have to be develop for ground-based $1km$ baseline interferometry.

4.4. Combiners

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 combiners can be considered.[25]

4.5. Material and optical technology

Mirror substrates (Zerodur, SiC) and optics fiber materials for beam transport in long baseline interferometry (OHANA[26] for Hawaii or ALMIRA[27,28]on the ALMA site), related polishing and thin layers 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.[29,30]

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, in preparation, also Koechlin 2002, in preparation) and need to be developed further to show how the information in the ZOF can be used to reconstruct the image over the HOF, 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 positioning 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[31–33] may be of interest for fringe trackers with a spectral resolution around 100. But only some tens of pixels are available today. Moreover, STJ require 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.[34]

Dry salars can be perfectly flat areas to install interferometers with mobile sub-pupils,[25] but they have not been tested. Another promising alternative is the Antarctic Dome C site.[35]

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 (DARWIN/TPF).

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.[8, 22] In this case, a stabilized balloon-born combiner 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.

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