VIDA (Vlti Imaging with a Densified Array), a densified pupil combiner proposed for snapshot imaging with the VLTI.

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ABSTRACT

Only in the recent years did it become realized that multi-aperture interferometric arrays could provide direct snapshot images and coronagraphic images in a non-Fizeau mode. Whereas homothetic mapping of entrance pupil to exit pupil is useless when the aperture is higly diluted, a "densified-pupil" or "hypertelescope" imaging mode can concentrate most light into a high-resolution Airy peak. In addition to the luminosity gain, there is a contrast gain particularly valuable for stellar coronagraphy and exoplanets finding. The current VLTI is able to combine light from two telescopes coherently. In subsequent phases, a combiner is planned for applying closure phase with up to eight telescopes (UT and AT). The small number of apertures currently considered at the VLTI, does not take full advantage of hypertelescope imaging, but still performs significantly better than other observing modes (+3.8mag gain in comparison with Fizeau mode). We propose some possible optical scheme for a densified-pupil combiner for the VLTI. Beyond its science value, the proposed instrument can serve as a precursor for many-element post-VLTI hypertelescopes.

Keywords: Interferometry imaging, densified pupil, hypertelescope, extrasolar planets.

1. INTRODUCTION

Only in the recent years did it become realized that multi-aperture interferometric arrays can provide direct snapshot images and coronagraphic images[1] in a non-Fizeau mode. Whereas basic Fizeau arrangements are useless when the aperture is highly diluted, this "densified-pupil" or "hypertelescope" imaging mode[2] can concentrate most light into a high-resolution Airy peak.

A 37-elements hypertelescope was proposed to NASA for TPF[3]. A 100 to 500m ground-based version is also proposed as a diluted optical "Arecibo-like" telescope containing hundreds of small elements[4]. Another possible design for larger hypertelescopes on Earth uses an array of numerous mobile telescopes moving on a flat ground[5] (dry salt lakes…) to stabilize the optical paths and the entrance pupil shape[6]. The mobility of the telescopes during observations avoids the use of delay lines which limit the base length and the number of telescopes.

The aim of this article is to estimate how some existing interferometers, the VLTI in particular, having few apertures, can be used in a hypertelescope mode. We also evaluate their imaging performances for searching extrasolar planets, and their suitability as test benches to prepare future large hypertelescope projects.

2. THE DENSIFIED PUPIL IMAGING MODE

2.1 Hypertelescope principle[7]

Highly diluted multi-element apertures can produce direct images according to the classical Fizeau scheme, but the image becomes difficult to exploit efficiently at high aperture dilution since the central interference peak contains only a very small fraction of the energy. Most of it is dispersed in a large diffractive halo. With additional optics producing a densified exit pupil (fig.1), where the pattern of centres is preserved, a full-luminosity image is directly obtainable, although in a small field of view (FOV).

The pupil densification consists in enlarging each sub-aperture by the same factor, their center's pattern being kept invariant. This densification factor is defined as $g_d=(d_o/D_o)/(d_i/D_i)$, where d_i and d_o are the diameter of each aperture element before and after the pupil densification respectively. D_i and D_o are the array size before and after the pupil densification respectively.

After pupil densification, the central interference peak of the focal image is intensified by a factor γ_d^2, whereas the FOV diameter is divided by γ_d. Indeed, the usable field of the hypertelescope, called "Zero Order Field" (ZOF), has an angular radius of $\lambda/((\gamma_d - 1).d_i)$ on the sky, where λ is the wavelength.

The optimal amount of pupil densification is thus a trade-off between the image intensity and the FOV. Both a wide FOV and full luminosity are achievable with a large number N of small sub-apertures periodically arranged as a grid, with square or hexagonal pitch. In this case, the exit pupil can be completely densified if $\gamma_d=s/d_i$ (s is the sub-aperture spacing). With this full densification, the ZOF size is λ/s and its edge is exactly at the first-order side-peaks. The central peak is then fully intensified, and the remaining field is not contaminated by secondary peaks. For such redundant arrays, the ZOF contains of the order of N resolution elements (resels). So, for a given collecting area and array size, the field/resolution[8] ratio is larger if sub-apertures are smaller but more numerous and closer.

These properties of hypertelescopes have been successfully verified with simulations[9] and small-scale testing in the laboratory and on the sky[10,11]. Studies are under way to reconstruct the image over the Higher Order Field (HOF), a wider field corresponding to the sub-aperture airy disk (λ/d_i), from information contained inside the ZOF. Indeed, a source located outside the ZOF but inside the HOF shows dispersed orders in the ZOF, and these are also intensified by the pupil densification.

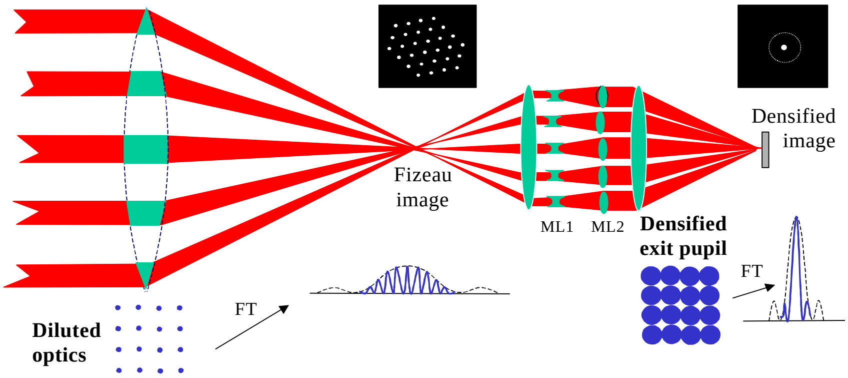


Figure 1 : *Hypertelescope principle. The Fizeau image at the prime focus of a phased optical array (left, sketched as a segmented lens) has numerous sidelobes if the aperture is highly diluted. With a pupil densifier (right), having an array of micro-Galilean telescopes, light is concentrated in the central interference peak. Off-axis stars provide a displaced peak, up to a limit which defines the Zero Order Field (ZOF).*

2.2 Densified-pupil imaging mode with a small number of apertures

Hypertelescopes can use a redundant pupil to optimize the imaging dynamic range. The poor u-v coverage due to the strong pupil redundancy is compensated by the large number N of sub-apertures considered. Current and forthcoming ground-based interferometers have fewer apertures than hypertelescopes proposed for the future. The FOV of these interferometers used in a densified-pupil imaging mode can thus become extremely narrow or even un-exploitable if the array is too redundant or the pupil densification too high. An extreme example is 4 apertures on a large square, where a complete pupil densification reduces the FOV to only one resel ($\lambda/s=\lambda/D_i$)!

If the interferometer array can be reconfigured, a non-redundant array is highly recommended for increasing the FOV to N(N-1) resels. The redundancy of the VLT Interferometer Mean Array (VIMA), consisting of the four 8.2m Unit Telescopes (UTs), cannot be changed. Although VIMA was not planned for snapshot imaging, we will see later that it gives a relatively wide FOV; if the pupil is densified, considering the small number of apertures. Concerning the VLT Interferometer Sub-Array (VISA) involving 1.8m Auxiliary Telescopes (ATs), the redundancy will be fully configurable due to the large number of possible stations, provided that more than 3 ATs will be available.

For a highly non-redundant array, the maximum pupil densification easily reachable is the one making the two closest sub-pupils in contact. In principle, an even higher densification further intensifies the central peak, but is, in practice, uncommon and inefficient because it involves more complex and less transmissive optical schemes (beam splitters). For these reasons, we consider in the following, the maximum allowed pupil densification factor equal to $\gamma_{d0}=s_{min}/d_i$, where s_{min} is the spacing between the two closest telescopes. The corresponding intensification of the central interference peak is $I_0=\gamma_{d0}^2$, and the corresponding ZOF is noted ZOF_0.

A lower pupil densification will offer a lower on-axis intensification but a wider FOV. Figure 3 shows the best luminosity amplification and the corresponding γ_d for an off-axis source, with UTs or ATs as sub-apertures. For VIMA, the maximum allowed pupil densification is γ_{d0}=5.68, giving a gain of 3.8 mag. (in comparaison with the Fizeau mode) over a 12mas FOV in K band. With VISA, γ_{d0} is about 40, giving a gain of 8.0 mag. over a 8mas FOV in K band. Lastly, we can verify again that, at a given γ_{d0}, the intensification is optimal only for sources located within the central half of the ZOF_0. In the same way, for a source located at the extreme border of the minimum field (off-axis = ZOF_0), the flux intensification will be maximum for half the densification i.e. $\gamma_{d0}/2$.

If the required field reaches the HOF, the densified pupil does not offer any intensification in comparison to the Fizeau mode, but we propose in sec. 4.2 some possible optical schemes to exploit a wider field with the densified-pupil mode.

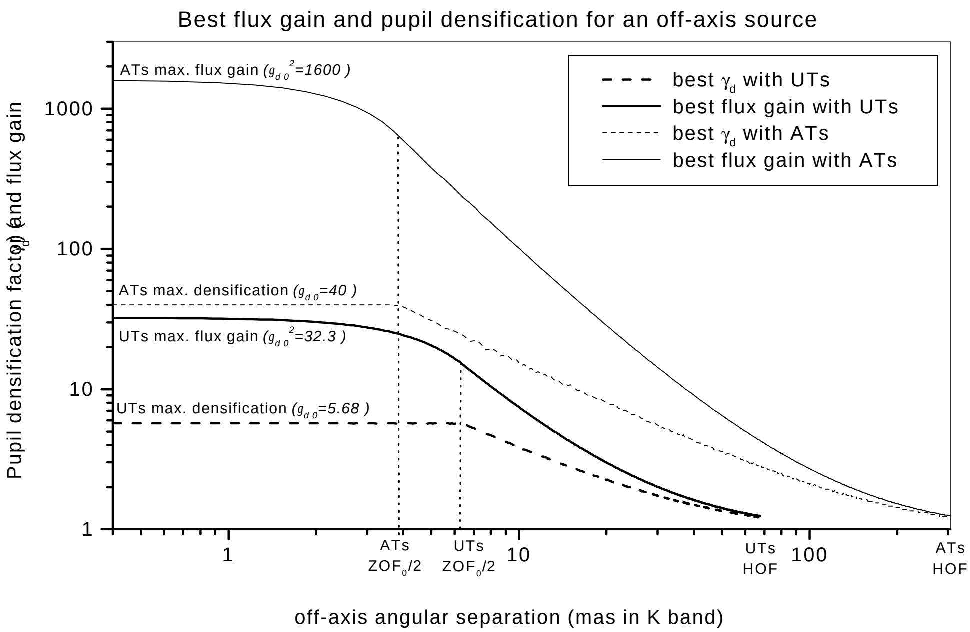


Figure 2: Best image intensification and corresponding pupil densification factor vs. the desired field, in the case of using VLTI UTs or ATs as sub-abertures.

3. DENSIFIED-PUPIL IMAGING WITH THE VLTI

3.1 Densified-pupil imaging mode with the VIMA

The following imaging simulations consider a star transiting at the zenith. Figure 3 shows the evolution of the entrance pupil pattern projected on the sky, at three hour angles: H=-4 h, H=0 (zenith), H=4 h. The pupil shape (and thus the PSF) and the maximum allowed densification factor (γ_d) are time dependant. As telescopes are pointed to the star, the sub-pupils remain circular. This figure shows also the maximum allowed γ_d with the 4UTs for different star declinations and hour angles. The pupil deformation does not much restrict the pupil densification factor, which can remain larger than 5 during 7 hours for a large enough sky coverage (0° < δ < –55°).

Figure 4 compares the snapshot imaging capabilities of the VIMA using the classical Fizeau mode and the densified-pupil mode. These simulations show the image of a point source and a binary star (sep.=1resel, Δm=0.4), assuming perfect sub-pupil wavefronts and no optical path difference (OPD). We can verify again the hypertelescope mode properties in comparison to the Fizeau mode. The VIMA allows snapshot high-resolution images (resel=3.96mas in K band) with 32.3 times more luminosity than the Fizeau mode. However, the FOV is then very narrow due to the small number of apertures: the amplified field diameter contains only 3.6 resels (i.e. 14.2mas in K band).

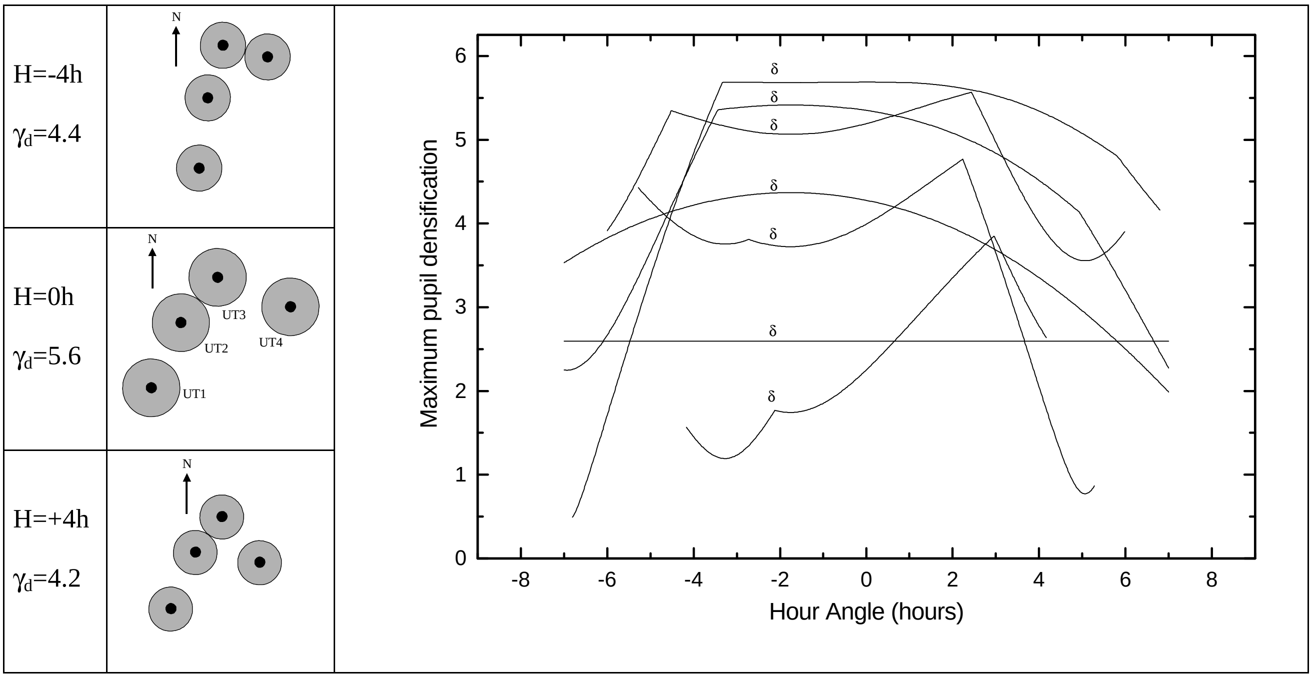


Figure 3:Left: entrance pupil of the VIMA projected on the sky for a star located at d=-24.6° (latitude of Cerro Paranal), for 3 hour angles: H=-4h, H=0h (zenith), H=+4h. Black and gray disks represent the UT pupils before and after densification respectively (pupil patterns are to scale, celestrial north is up).Right: maximum allowed pupil densification factor (g_d) of the 4UTs for different star declinations and hour angles.

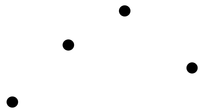
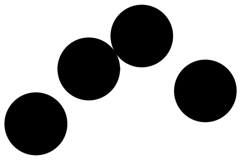
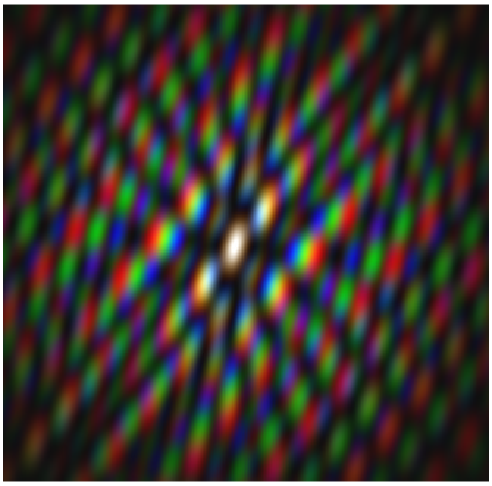
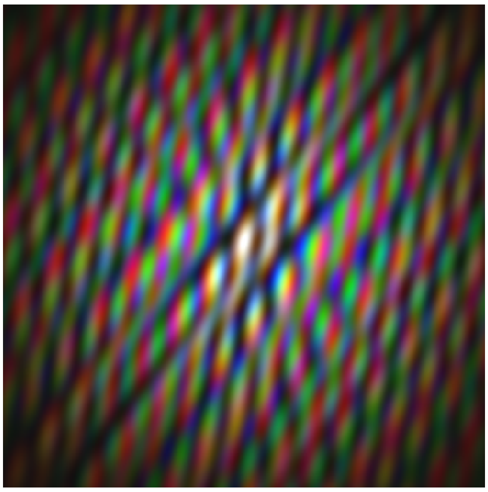
	Fizeau mode	Densified pupil mode
Exit pupil		
Image of a point source		
Image of a binary star *(sep.=1resel, Dm=0.4)*		
Pupil densification factor (γ_d)	1	5.68
Central peak intensification	x1	x32.3 (+3.8mag.)
Field diameter	infinite	3.6 resels

Figure 4: High-resolution snapshot imaging simulations of an on-axis point source and a binary star, using the VLTI 4 UTs array in the classical Fizeau mode and in the densified pupil mode. The latter mode gives a 3.8mag. luminosity gain in a reduced field containing 3.6 resels wide (1 resel = 3.96mas in K band).

3.2 Densified-pupil imaging mode with the VISA

To significantly improve the direct imaging performance of 4 UTs, it takes many ATs, 20 or more. This simply results from the much larger aperture of the UTs. However, it is of interest to use the VISA alone because of the numerous possible stations for the ATs (fig. 5), and also because ATs will certainly be more readily available than UTs for interferometry. The pupil densification with ATs is higher than with UTs, and the image intensification can reach 8.0mag (fig 2).

The imaging performances of ATs using the densified-pupil mode are presented in figure 6. As for the VIMA, these simulations show the image of a binary star for different possible arrays involving from 3 to 8 ATs (8 delay lines are planned by ESO in subsequent phases[12]). We have not yet looked for the best possible configurations, optimizing both the intensification and the FOV. The aim of these preliminary simulations is only to show the various results obtainable and the impact of the number of telescopes and of the array redundancy on the FOV size. For example, we can see that 4 ATs located on a redundant array (A1, G1,G2 and J1 stations) give the same FOV as 3 ATs, but provide a large luminosity gain (+7.9mag). No more than 4 ATs may ever become built, but 8 of them would largely improve the imaging performances and would make the whole VLTI infrastructure profitable even without the highly demanded UTs.

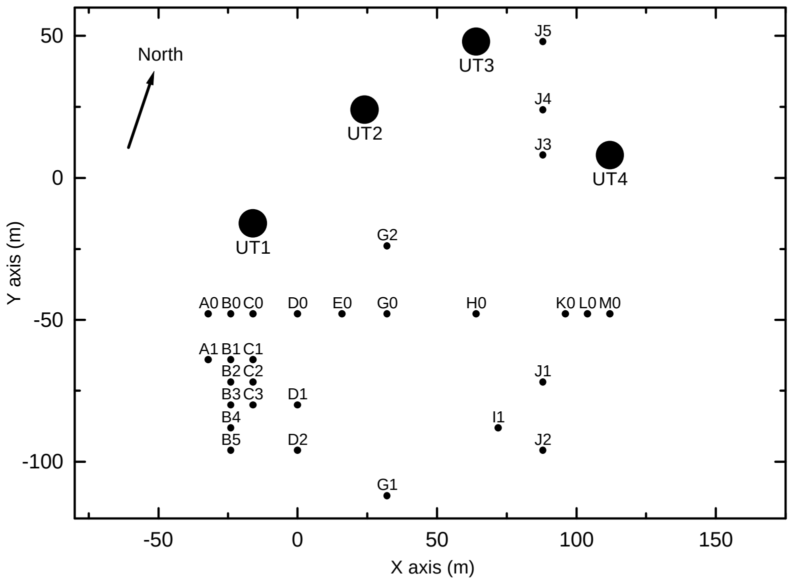


Figure 5: The complete VLTI array (VIMA+VISA)

3.3 Densified-pupil imaging mode with other interferometers

The densified-pupil imaging mode is usable with other multi-telescope interferometers (KeckI, CHARA, NPOI…). For comparison, figure 7 shows images obtainable on the Navy Prototype Optical Interferometer (NPOI), in Arizona, equipped with its forthcoming 6-beams simultaneous combiner plus a possible pupil densifier. The first array planned for Fizeau imaging will use the 4 fixed astrometric stations and the East 2 and West 7 stations. This array is highly non-redundant, nevertheless it allows a significant luminosity gain (+6.6mag), due to the small aperture size (0.35m) and the long base lengths. To push the gain to +9.0mag, we propose to use the East 7 station instead of East 2.

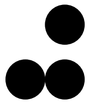
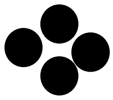
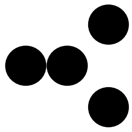
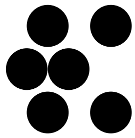
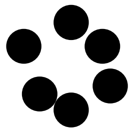
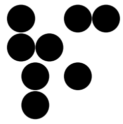
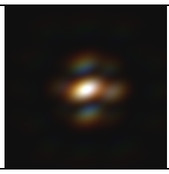
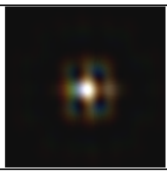
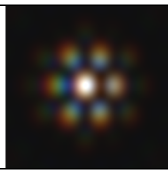
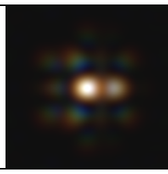
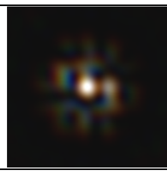
	3 ATs	4 ATs		6 ATs		8 ATs
Stations	B3+D0+D1	A1+G1+G2+J1	A1+C1+D0+D1	A1+B0+B3 +C1+D0+D1	C0+D2+G1 +G2+H0+I1	A0+A1+B3+ B5+C1 +D0+D1+E0
Densified pupil						
Image of binary star *(sep.=1resel, Dm=0.4)*						
Max. baseline (m)	41.8	122	37.6	41.8	98.5	64.3
Resolution at 1 µm (mas)	6.0	2.1	6.7	6.0	2.6	3.9
γ_d	13.3	38.2	8.9	8.9	19.9	8.9
Intensification	178 (+5.6mag)	1462 (+7.9mag)	79 (+4.7mag)	79 (+4.7mag)	395 (+6.5mag)	79 (+4.7mag)
Field diameter (resels)	1.85	1.82	2.64	2.94	2.9	4.52

Figure 6: Snapshot imaging simulations of a binary star with the VLTI ATs in different possible arrays using the densified pupil imaging mode.

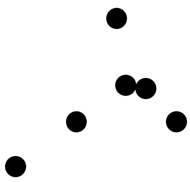
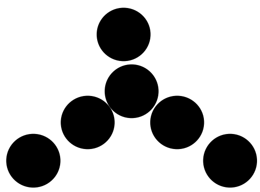
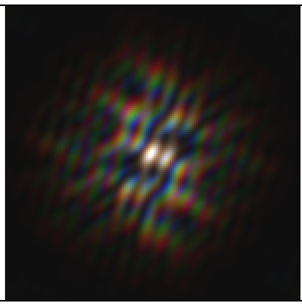
	NPOI-E2-W7	NPOI-E7-W7
Exit pupil		
Image		
Res. at 1µm (mas)	3.9	3.1
Densification γ_d	21.4	63.3
Flux gain	458 (+6.6mag)	4014 (+9.0mag)
Field diameter (resels)	9	3.7

Figure 7: Snapshot imaging simulations of a binary star with the NPOI in two different 6 telescope arrays using the densified pupil imaging mode.

4. POSSIBLE OPTICAL SCHEMES FOR VIDA

We see that the small number of apertures currently considered at the VLTI, although not optimal for hypertelescope imaging, still performs significantly better than other observing modes. For this reason, we propose to study a densified pupil beam-combiner for the next generation VLTI instruments, assuming that adaptive optics (AO) on each telescope and a real-time piston error correction will be implemented. This new combiner, which could be named Vlti Imaging with a Densified Array (VIDA), would be a fully scientific instrument as well as a precursor for post-VLTI large imaging arrays and hypertelescopes.

4.1 Possible combiners

Fundamentally, the densified pupil imaging mode requires exactly the same optical scheme from telescopes to the coherent focus as the Fizeau mode. One only has to add a pupil densifier behind the Fizeau focus, which can use two arrays of micro-lenses as shown on figure 1, or a set of periscopes involving a pair of flat mirrors (better for IR wavelengths).

The combiner planned for homothetic pupil mapping (Fizeau mode) by the NEVEC group[13] consists of a cylindrical hole under the VLTI Beam Compressors with a parabolic mirror at the bottom. In front of this mirror, movable small pupil mirrors re-image the telescope array according to pointing direction. This design requires a complex dynamic translation of the pupil mirrors with a micrometric accuracy.

A star-pointed combiner can also reproduce automatically the entrance telescope pupil seen from the observed star without dynamic adjustments of pupil mirrors (fig.8). Moreover, this optical set-up compensates also the field rotation.

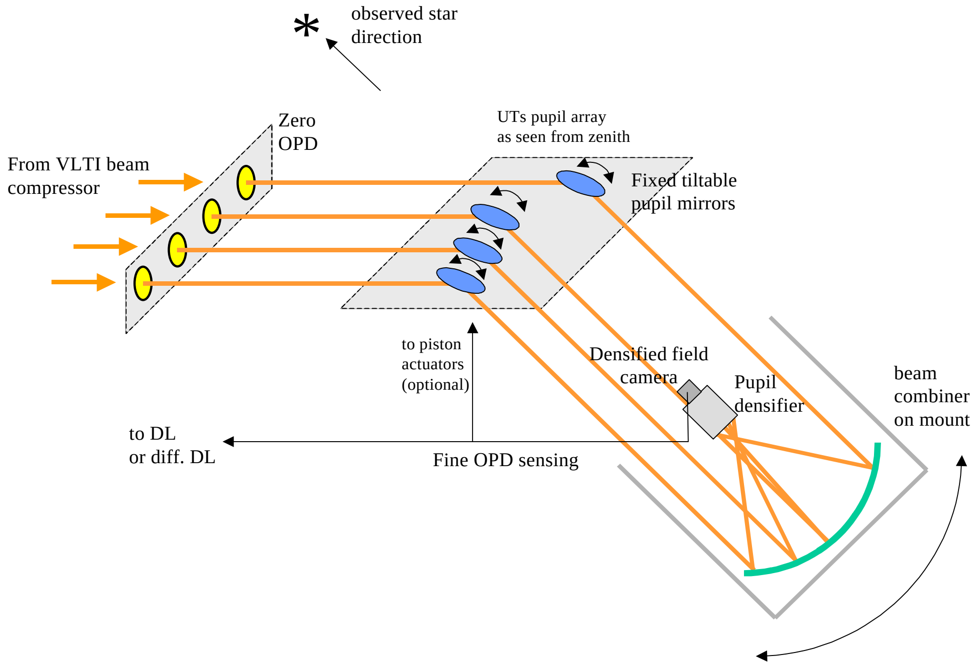


Figure 8: Star-pointed densified-pupil combiner proposed for VLTI. Spacing between beams coming from telescopes have to be adjusted in order to re-image, in a horizontal plane, the telescope pupil array as seen from zenith at a reduced scale. Tiltable small pupil mirrors are fixed (no mirror translation needed) on this horizontal plane to reflect the beams towards the anti-stellar direction. The combiner can be a small telescope on a mount, with its axis intersection located in the center of the horizontal pupil plane.

Whatever the design chosen, these combiners unavoidably introduce an OPD depending on the star position. These piston offsets can reach 10 cm or more but could be compensated by the differential delay lines of PRIMA in open loop or with OPD sensing made by the densified field camera.

Lastly, optical fibers[14,15] provide a very attractive and compact solution for beam combination and densification. Each telescope focus can be relayed by one or several single mode fiber towards a camera. Thus the exit pupil array re-arrangement and densification are not constrained by complex opto-mechanical systems and do not introduce time dependant OPD variations. Moreover, the FOV of fibers (equal to the HOF) is not a restriction for the densified pupil imaging mode, where the FOV is narrower (ZOF<HOF).

4.2 Increasing the field of VIDA

The phase reference interferometry mode planned with PRIMA is an indirect way to extend the FOV of VIDA up to the OPD isoplanetic field (about 1 arcmin in IR). Indeed, small piston offsets between each beam, generated by the differential delay lines, translate the central interference peak, while the ZOF remains on the sub-aperture axis. An equivalent result is also obtained by tilting each beam in the same direction. Thus, any off-axis source can be centered in the ZOF and intensified, providing that its position is known. It is also possible to scan for searching exoplanets with coronagraph.

Lastly, the most powerful and simple way of extending effectively the FOV is to use an array of pupil densifiers spaced by λ/d_i (one HOF) (fig. 9). Integrated optics is of interest to build an array of miniaturized Galilean telescopes. The high resolution images, obtained on a single large camera, are not adjacent on the sky, but can be made adjacent by exploiting dispersed orders in each ZOF to reconstruct each HOF. This field reconstruction is possible only if the number of sources inside the HOF does not exceed the number of resels contained in the ZOF. This approach, combining the image intensification and a wide field, is very interesting for imaging extra-solar planetary systems and remote galaxies imaging with the VLTI.

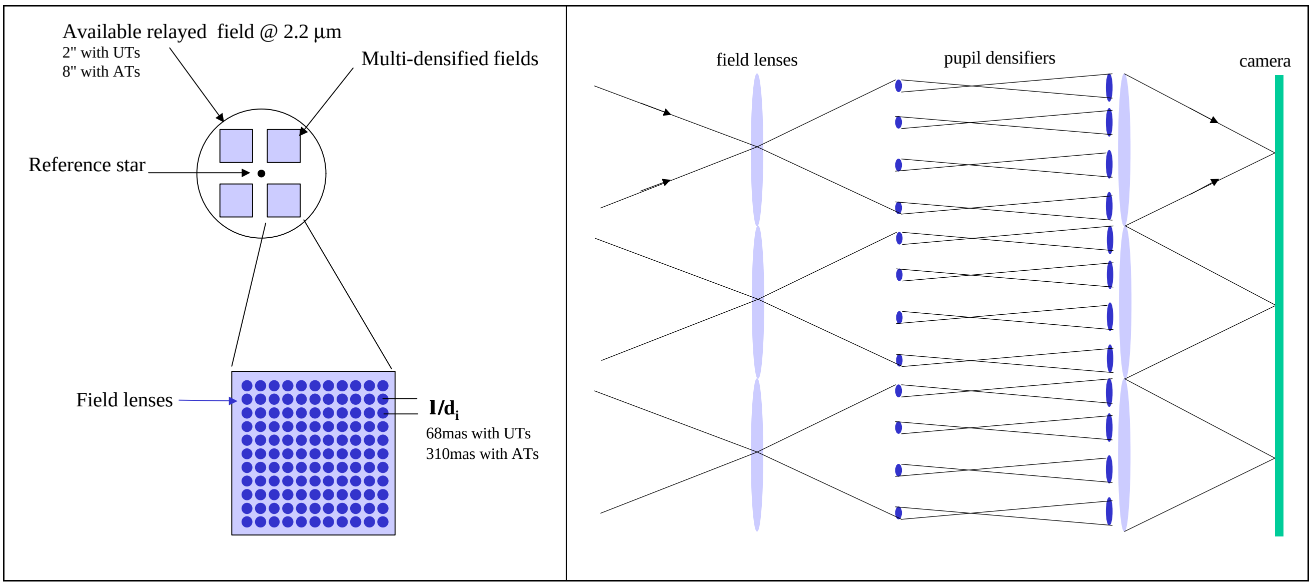


Figure 9: Multi-field imaging with VIDA using an array of miniaturized pupil densifiers spaced by l/d$_i$.

5. CONCLUSIONS

The small number of apertures currently considered for the VLTI, cannot take full advantage of the hypertelescope imaging, but this direct imaging mode can also perform significantly better at the VLTI than the other observing modes considered. This densified-pupil mode gives a luminosity gain of 3.8 and 7.9 mag, with respect to the Fizeau imaging, using respectively UTs or ATs.

In addition to the luminosity gain, there is a contrast gain particularly valuable for stellar coronagraphy and exoplanets finding. Simulations are under way to explore the coronagraphic observing schemes achievable behind a densified pupil. Several schemes are of interest for the VLTI, and can improve the star nulling. For example, separate coronagraphs for each telescope, before beam combination, do not benefit from the VLTI's high angular resolution but take advantages of the luminosity gain arising from the pupil densification. Other efficient optical schemes involving active multi-stage coronagraphy[16] are also considered.

The VLTI can be equipped for densified-pupil imaging by upgrading of the beam-combiner optics, without affecting the existing instruments. The proposed combiners for VIDA take advantages of the internal metrology facility planned for PRIMA. Effects of OPD errors on the densified-pupil imaging are currently studied to define the required performances. Further general studies, with an engineering approach, are also needed to define a feasible design compatible with the whole ESO-VLTI infrastructure.

In subsequent phases, up to 8 ATs may be accommodated, and this is are expected to increase the densified-pupil imaging performance. But ideally 20 ATs would be required to extend efficiently the FOV and the dynamic range of imaging. A major limitation is the limited space available for extra delay lines in the tunnel.

Like GENIE, the planned testing for nulling and precursor for the ESA-DARWIN mission, VIDA would aim at science targets while serving as a precursor for high-contrast imaging with large post-VLTI arrays and future hypertelescopes.

Finally, we note that the a densified-pupil imaging mode can also be installed at other forthcoming multi-telescope interferometers (KeckI, CHARA, NPOI, LBT…) provided that high order AO and real-time piston error correction are implemented.

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