

Interferometric beam combination for a large number of telescopes

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Abstract. We revisit here the system design for the beam combinations of ground based interferometers in the single mode case. We propose an upstream beam distribution using splitting of individual telescope pupils. This solution aims at reducing the constraints of the turbulence, thanks to larger equivalent D/r_o values when injecting in single mode waveguides, and also to increase the field of view imposed by the optical étendue in single mode conditions. A set of elementary beam combiner devices operated in closure phase mode collects the beams delivered by the telescope sub-apertures. The concept brings along also additional interesting features like an easier distribution of the light in parallel instrument or a better use of telescopes of different diameters. Several practical implementations are presented to illustrate the potential of the concept in the case of the combination of 4 or 6 telescopes of the VLTI/ESO in Paranal or CHARA on Mt Wilson.

1. Introduction

Single Mode (SM hereafter) interferometry brings along several advantages that have been exploited many times in astrophysics first on IOTA and later on the VLTI and on Chara. The advantages of modal filtering using single mode optical waveguides have been demonstrated (Foresto *et al.* 1997; Mennesson *et al.* 2002). The impact on the achieved performances, the domain of application and comparison to other filtering solutions have been deeply analyzed (Tatulli *et al.* 2004; Tatulli *et al.* 2010).

It has been also identified that the photonics toolbox allows more advanced concepts where the whole beam combiner can be embedded in a single optical chip. Most of the system tasks required for the instrument purposes is then reported in the design of the component (Kern 2001; Malbet *et al.* 1999). It includes optical setups that implement robust and stable multi beam combination. These behaviors made such setups well suited for Closure Phase (CP) measurements. Telescope demonstrations have followed since early 2000s. Among important system features it has been demonstrated that the installation on site of such integrated instrument is highly simplified compared to bulk instruments as soon as the component is properly validated and characterized in laboratory (Berger *et al.* 2010; Le Bouquin *et al.* 2011). Based on photonics experience, we consider

here the benefits from the use of multiple identical well known beam combiner chips.

We consider a segmentation of the telescope individual pupils before any injection in SM waveguides that will reduce the turbulence effects (i.e. D/r_o equivalent value) and increase the field of view (FoV) seen by these smaller sub-apertures. The optimum theoretical injection in a SM waveguide is given for the optical étendue of λ^2 , that corresponds to the diffraction pattern of the injection optics. Since the point spread functions (PSF) at the focus of the telescopes is constrained by the atmospheric turbulence, the efficiency of the injection in SM waveguides is directly impacted. When the PSF is limited only by the diffraction conditions the injection in SM guides become theoretically optimum.

Once an optimum injection is performed in the SM waveguides all the delivered beams could be combined using a set of identical integrated optics modules. A first description of a design for interferometry based on these arguments has been given by Guyon (2002). Designs based on pupil segmentation is also the principle of the photonics based instrument dedicated to pupil masking in the single telescope case as proposed in the Dragoonfly and in the FIRST instruments (Perrin *et al.* 2006; Kotani *et al.* 2009; Jovanovic *et al.* 2012). Similarly to this pupil masking scheme we propose a beam combination that allows Closure Phase recovery techniques in order to reject all differential phase disturbances introduced between the optical paths (including atmosphere and optical trains).

2. Impact of the turbulence

The effect of turbulence on the injection in SM fiber optics has been analyzed by Cyril Ruilier (1998) showing the following results:

- as soon as $D/r_o \leq .8$ the efficiency of the injection reach 50%,
- the injection fluctuations is highly affected by the ratio R/r_o .
- When a tip-tilt correction is applied the fluctuation increases quasi linearly with D/r_o and reach 100% around $D/r_o = 10$.

The Table 1 recall typical value from Ruilier (1998) of the achievable injection and fluctuations according to the seeing condition.

Table 1.: *Injection efficiency (η) and relative fluctuations (F) according to the seeing condition, respectively without any correction, with Tip-Tilt correction, AO corrections with 11 and 21 Zernike modes.*

D/r_o	0.8		1.2		2		4		10	
	η	F	η	F	η	F	η	F	η	F
no cor	0.6	0.3	0.45	0.45	0.2	0.8	0.08	1	0.05	1
<i>TT</i>	0.9	0.3	0.8	0.45	0.65	0.15	0.35	0.4	0.04	1
<i>Z₁₁</i>	0.96	0.025	0.95	0.05	0.9	0.01	0.7	0.1	0.2	0.4
<i>Z₂₁</i>	0.98	-	0.97	-	0.9	-	0.8	0.05	0.4	0.2

Furthermore Ruiler has shown that under a given seeing condition the total coupled power in a SM waveguide saturates for values of $D/r_o > 1$ and

$D/r_o > 4$ respectively without any correction with a Tip-Tilt correction. Increasing the telescope diameter will not increase anymore the power injected in the SM waveguides as soon as this saturation level is reached. The paper analyzes also the impact of the central obscuration that also affect the injection efficiency. In the case of VLT UT, with 1.2m secondary for 8m pupil, the resulting loss for injection is close to 7%.

This analysis shows possible domains of operation. If any adaptive correction is foreseen, it is useful to reach $D/r_o < 1.5$ to achieve efficient injection ($\eta > 40\%$) and moderate fluctuations ($F < 50\%$). In case of higher ratio, the conjunction of AO and of aperture segmentation can be considered but will not bring real system simplification, and similar performances compared to a full AO corrected system using a single waveguide per telescope.

3. Setup concept

We decide in this concept to split the beam delivered by each telescope upstream before any other optical function.

A schematic optical layout of the concept is given in Fig. 3. The beam

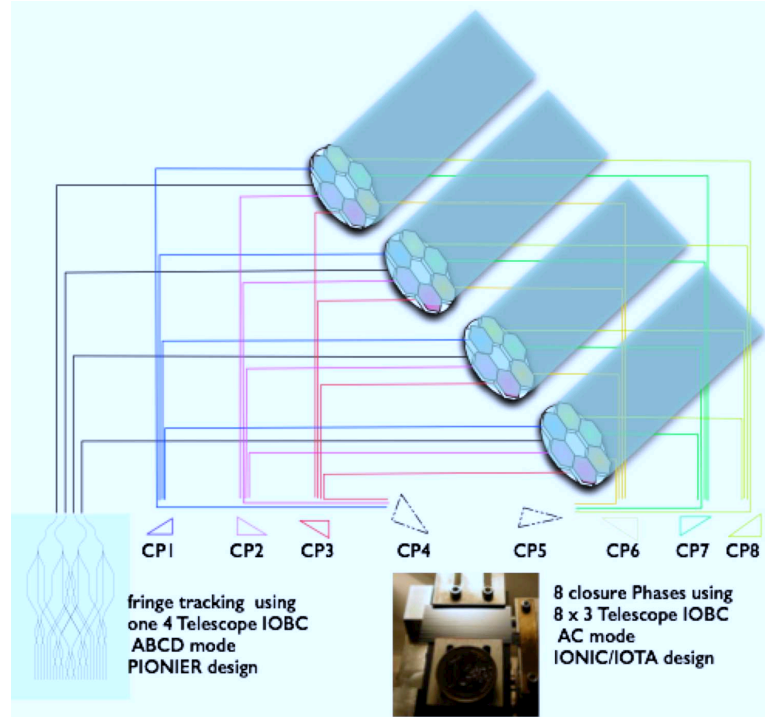


Figure 1.: *Proposed approach for the beam combination: The pupils of the telescopes are divided in sub apertures that fit the turbulent cells (r_o). The light from the sub-apertures are then combined to the light of corresponding cells of the other telescopes using SM waveguides. The division can be managed by a lens array that samples the whole telescope pupil image.*

splitting is performed in a plane conjugated to the telescope pupil plane in order to match the individual coherence cells at the highest level. For each sub-aperture, before any beam combination, the signal is injected in SM waveguides that will filter all remaining turbulence effects, providing at the output of the waveguides perfectly plane wavefront.

The central aperture that is strongly affected by the central obscuration of the telescope is not used, or can be used for service functions, for instance for metrology purposes. Consequently the other sub-apertures are not affected by any central obscuration and the overall resulting injection is slightly enhanced. The segmentation do not correct for all phase delays between the sub-apertures either due to atmospheric turbulence, instrumental errors or to SM injection mismatches.

We consider simple individual functions for the beam combination in order to reduce the complexity of the components and of the characterization processes. These characterizations become tedious for combination schemes that deals with large number of optical beams. In the layout presented in this paper, the interferometric combination is done by a set of triplets of beams (or more beams) in order to be able to use closure phase (CPs) technique to overcome any phase disturbance introduced by individual beam paths, either due to turbulence or instrumental effects. In the general case the number of CPs for N telescopes is given by

$$C_N^2 = \frac{N!}{2(N-2)!} \quad (1)$$

leading to 3 independent CPs in the 4 telescope case (4 possible triangles) and 10 independent CPs in the 6 telescope case (20 possible triangles). However the instrumental setup must insure that the maximum phase excursion is compatible with the detection of the resulting fringes because of temporal coherence, like for example in the IONIC/IOTA case. This effect can be reduced using a spectral dispersion providing a sufficiently large coherence length.

Beam combination through triplets in a co-axial mode brings the advantage to provide a measurement of the photometry over each individual sub-aperture without any additional dedicated channels. For larger groups of telescopes the beam combination scheme must be chosen properly to have access to this photometry (Blind *et al.* 2011).

For the beam combination, several schemes can be proposed using integrated optics beam combiner (IOBC) solutions. A set of IOBC as the one use for the IONIC/IOTA instrument (Berger *et al.* 2003) (3T-AC-IOBC hereafter) with an AC coding, is well suited for this purpose. One may propose also a component similar to the PIONIER beam combiner (4T-ABCD-IOBC hereafter) as described in Benesty *et al.* (2009) that delivers on-chip solution for the complete coding in 4 phase status without any temporal modulation.

The measurement of the single CP in the 3 telescope case is obtained from the 12 outputs when using an ABCD coding (3 baselines \times 4 samples). With 3 free pixels between each output, to avoid any crosstalk effects, each CP needs 48 pixels on the detector. One row of a regular $1K \times 1K$ detector array is able to manage up to 20 identical 3T combiners side by side on a single chip, corresponding to a 6 telescope case. The other dimension of the FPA is fully available for spectral dispersion or for polarization coding. For 6 telescopes at least 10 independent CPs

must be measured. The Table 2 lists the possible non-redundant configuration in the case of a 6 telescope array.

Table 2.: *Example of 10 non-redundant triangles using 6 telescopes.*

	T1	T2	T3	T4	T5	T6
1	x	x	x			
2	x	x		x		
3	x	x			x	
4	x	x				x
5	x		x	x		
6	x		x		x	
7	x		x			x
8	x			x	x	
9	x			x		x
10	x				x	x
11		x	x	x		
12		x	x		x	
13		x	x			x
14		x		x	x	
15		x		x		x
16		x			x	x
17			x	x	x	
18			x	x		x
19			x		x	x
20				x	x	x
#CP	10	10	10	10	10	10

When the pupil segmentation provides more beams than required to obtain the full set of independent CPs, the additional CPs can be used to add several identical measurements in order to improve the signal to noise ratio (SNR) especially for shorter base-lines where the visibility signal may become lower.

Some of the additional outputs can also be specifically dedicated to other functions like the fringe sensing, without any additional system complexity. Extra beams can also be used for additional useful functions (fringe tracking), or to improve the u,v plane coverage using slightly different baselines per main apertures. Finally the segmentation can be suitable to optimize the combination when using telescopes of different diameters (eg 8m and 1.8m telescope at VLTI) (see Fig. 5).

4. Example of dimensioning

We consider here a few illustrating examples, using the facilities of the ESO VLTI in Paranal with 4 main 8-m telescopes (UT) and possibly up to 6 relocatable auxiliary telescopes 1.8-m (AT)¹ and the facilities of CHARA on the Mt Wilson with 6 fixed 1m telescopes, in both cases with corresponding 6 delay lines.

Table 3 resumes the dimensioning parameters for medium seeing condition (for Cerro Paranal) for the VLTI and CHARA case.

In this median seeing conditions the phase error within a UT or AT pupil remains smaller than a few μm as expressed in term of Optical Path Difference (OPD). It means that the phase corrections required between the clusters are

¹4 ATs are actually operational on site

Table 3.: *Splitting ratio for a configuration of 1.8m telescopes considering the seeing median value at Paranal (according to the ESO web site the median seeing value is 0.66 arcsec that corresponds to $r_o = .15 m @ \lambda = .5 \mu m$)*

Spectral band	I	J	H	K
Central λ	$0.8 \mu m$	$1.3 \mu m$	$1.6 \mu m$	$2.2 \mu m$
r_o	24 cm	40 cm	48 cm	66 cm
D/r_o over CHARA pupil	4.2	2.5	2	1.5
CHARA / splitting ratio	7	7	7	7
resulting d/r_o over sub pupils	~ 1	0.84	0.65	0.5
D/r_o over AT pupil	7.5	4.5	3.7	2.7
AT / splitting ratio	19	19	7	7
resulting d/r_o over sub pupils	1.5	~ 1	1.3	~ 1
D/r_o over UT pupil	33	20	16	12
UT / splitting ratio	61	37	37	19
resulting d/r_o over sub pupils	3.6	2.9	2.3	2.4

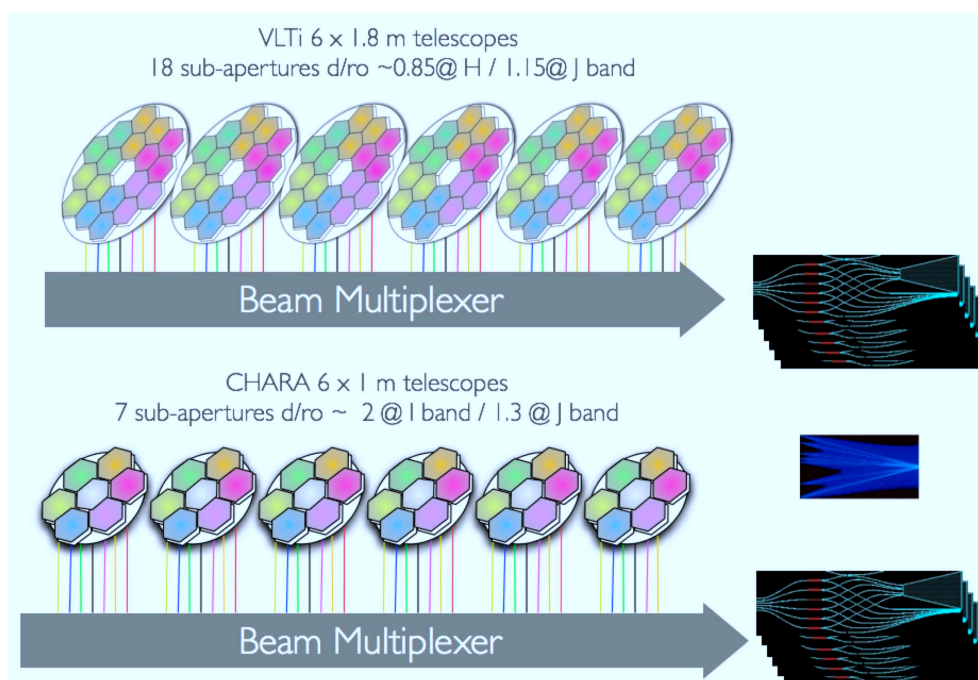


Figure 2.: *System setup for 6 telescopes using a 6T multi-axial combination. The VLTi case with $6 \times 1.8 m$ telescopes (top) and the Chara case with $6 \times 1 m$ (bottom) are shown. For the VLTi case a suitable d/r_o is reached when splitting the pupil into 19 sub apertures in J and H band, requiring $19 \times 6T$ beam-combiners. In the Chara case it is achieved with 7 sub-apertures requiring $7 \times 6T$ beam-combiners (the central aperture is not usable due to the central obscuration).*

smaller or equal to this value, as soon as the OPD between the telescopes are compensated using a coherencing system.

4.1 Near IR ($I/J/H/K$ band) configuration with 6 telescopes.

Splitting the main pupil in 7 sub-apertures (CHARA in I/J bands or VLTI in H/K bands) or 19 sub-apertures (AT/VLTI in I/J bands) allows to approach near diffraction limit conditions, with well optimized injection. For such configurations a correction of the tip tilt for each sub-aperture is sufficient to allow achieving a rather perfect injection.

The measurement of the minimum 10 independent CPs of the 6 telescope configuration requires also to split each telescope aperture at least into 7 sub-apertures.

The beam combination can be performed **by cluster of 3 sub-apertures**, for example using a set of 10 3T-beam combiners, similar to the one used for IONIC/IOTA (Berger *et al.* 2003). As mentioned above, this 3T combination does not require dedicated channels to extract the photometry. The measurement of the photometry of each telescope in this setup is naturally derived from the combination of the interferometric signals (Blind *et al.* 2011).

An all-in-one multi-axial 6T combiner can also be proposed as shown in Fig. 2). In this case the number of IOBC is the number of sub-apertures. We demonstrated during the phase-A study of the second generation fringe tracker for the VLTI that this "all-in-one" beam combination mode is the most efficient when using very low noise detectors (see for example Blind *et al.* 2011) with Read Out Noise lower than 2 electrons. Such low noise allows the number of pixels to be increased without a significant impact on the overall SNR of the interferometric signal detection (see Feautrier & Gach 2013 for the description of the RAPID/APD HgCdTe new generation detectors).

The large number of available 6T combinations allows various strategies of operation. For example to split them in two groups: a first one dedicated to fringe tracking, prevailing the shortest baselines in a boot-strapping mode to reconstruct the phase of the network from telescope to telescope and reducing the probability to deal with lower contrast due to resolved stars for the larger baselines. The second group may prevail the larger baselines. Increasing their number can improve the resulting SNR ratio. Depending to the needs for the fringe tracking one may use a more or less large number of sub-apertures for fringe tracking. In an other hand, it may be useful to keep more signal to feed a high resolution spectrograph. However high spectral resolution can also not be useful for all baselines. To conclude this shows that such a setup brings a lot of flexibilities.

4.2 Near IR (K band) configuration with $4 \times 8m$ telescopes

These conditions lead to a ratio $D/r_o = 12$ (Table 3). Splitting the main pupil into 19 sub-apertures (5 sub-apertures across) the ratio within each sub-aperture becomes $d/r_o = 2.4$. As mentioned in Roddier (1990) for this value a tip-tilt correction is well suited to achieve near diffraction limited conditions. Associated to the MACAO adaptive optics system operational on each UT, such configuration provide a very efficient injection (Table 1).

A possible scheme would be similar to the one described in Fig. 3. but with

19 sub-apertures (18 apertures operational). With an array of 4 telescopes it is required to record a minimum of 3 independent CPs.

For the beam combination a set of 18 PIONIER-like 4T-ABCD-IOBCs would be suited for the a direct coding of the fringes in groups of 4 sub-apertures (Le Bouquin *et al.* 2011).

A setup using “all-in-one design” multi-axial design is also possible.

If the multiple quadruplets use different positions within the UT main pupils it allows the number of achievable baselines to be increased, introducing new points in the uv plane providing additional lengths and angles, for the Fourier reconstruction. In the Fourier plane, instead of a strong frequency peak corresponding to the autocorrelation of the individual telescopes, the transfer function will have clouds of smaller peaks scaled by the smaller sub-apertures (see Fig. 4).

5. Practical implementation of the beam splitter

The splitting of individual telescope pupil can be done in the combination room, or even inside a cryostat. It requires to bring an image of the pupils of all the telescopes side by side with the suitable enlargement on a dedicated micro-lens array. Each micro-lens is associated with a fiber optics that will feed the proper input of one of the beam combiners (see Fig. 3 left). Standard micro lens arrays design for SM fiber injection, can be used. Silicon existing micro lens (Suss Optics) are available with an AR coating that allows an operation between 1.3 and $8\mu\text{m}$. To change the splitting ratio of the pupil (e.g. 7 to 19 sub-apertures) it requires to change the bundle fibers/microlens.

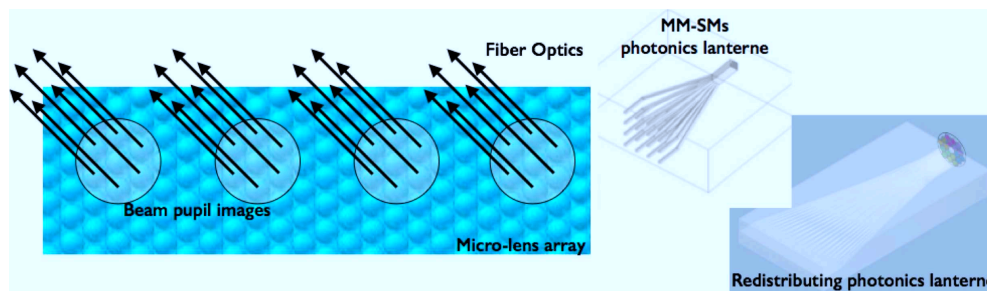


Figure 3.: *The selection of the sub-aperture is done using a micro lens array that feed the injection fibers of the integrated optics beam combiners (left). Photonic lanterns can also be used either to redistribute the beams coming from the different parts of the main pupils to the corresponding fiber optics (right/down), MM/SM lanterns can also be used to collect the flux at the telescope focus and to distribute it in a set of SM waveguides through an adiabatic transition (upper center, credit Robert Thomson). In this case no memory of the location in the pupil is kept.*

An alternate solution to split the beam of individual telescope pupils consists in using photonic lantern (Leon-Saval *et al.* 2005; Thomson *et al.* 2011). This device handles at its input a multi mode (MM hereafter) field, and distributes the

light into a set of SM optical fibers thanks to proper adiabatic transitions (see Fig. 3 upper center). The field of view of the MM structure is much larger than the diffraction limited conditions of SM fibers, and can deal with a speckled image. Near infrared devices have been tested and characterized with efficient transmission, a demonstrative device that handles 61 mode exhibits transmissions from the MM to the SM section as low as 0.76 dB (**e.g. 84% transmission**) (Noordegraaf *et al.* 2010). More recent results demonstrate the efficiency of lanterns in near IR spectroscopy (J band) after an adaptive optics system on the WHT with the Canary AO system (Harris *et al.* 2014). An interesting behavior for future mature components of this solution is the possible reduction of the injection losses that is induced by overlapping the fiber mode with the Airy pattern of the image delivered by the telescope (Shaklan & Roddier 1988). In the SM case the injection efficiency is limited to 78%. Much more efficient injection can be expected with MM waveguides, theoretically limited only by Fresnel losses that can also be managed by suitable anti reflection coatings. An implementation of these lanterns in an interferometric setup requires several verifications. Even if first characterizations of lantern have been published, laboratory tests must be performed to analyze how phases are handled in the device. The phase behavior of the lantern is an issue that must be evaluated even if the proposed setup allows rejecting the phase induced effects thanks to a CP detection setup. It must be characterized how the incoming modes contained in the MM field are spread in the individual single mode waveguides, and what is the phase behavior for each SM waveguides. In other word also, what is the effective lobe on the sky due to the MM structure, and what is its stability.

6. Discussion

A major advantage of the proposed concept is the possibility to adjust a setup that match the **seeing conditions** at the **wavelength of operation** and the **size of the telescope** to a ratio $D/r_o < 2$.

The flexibility of the proposed setup can be used to match the mode of observation, choosing to put emphasis on specific functions according to the observing conditions, for instance putting more signal either on the FT instrument or to the science instrument.

The **Field of View** is enlarged since it is not any more scaled by the Airy disk of the individual telescopes but by the diffraction pattern of each sub pupil in the lens array case (enlarged by the D/d ratio) and by the MM FoV of the input fiber in the lantern case. For the lantern developed by the Danish team, the MM port has a core diameter of $60\ \mu\text{m}$ and an estimated numerical aperture of 0.06. These values (FoV and aperture) corresponds to $9''$ for an 1.8 m telescope and $2''$ for an 8 m telescope.

U-V coverage: Compared to standard case, breaking all telescope pupils give access to additional CPs. Playing over the diameter of individual telescopes one may have access to slightly different baseline configurations. For instance in a 8m telescope configuration split into 7 sub-apertures one may use external sub-apertures of the main telescope pair for some combinations, and internal ones for some other ones, with difference of lengths between the built baseline of 10.4m. This behavior can be used to improve the uv coverage, with additional available baselines (see Fig. 5). This possibility to improve the uv coverage does not apply

in the lantern case, where the input modes are not spatially located within the pupil. This point needs to be properly investigated. Further investigations are required to address the question of the lobe center location in the lantern case.

An improvement of the **SNR** can be expected without any additional correction (Tip Tilt or AO correction) as soon as $d/r_o < 1$ after the splitting of the pupil. In this case the efficiency of the injection can reach $F > 50\%$ and its fluctuations be $\eta < 50\%$. For example in the AT case this d/r_o ratio is obtained by a splitting in 7 segments for H/K bands and in 19 segments for I/J bands where the injection efficiency become respectively $\eta_{HK} < 20\%$ and $\eta_{IJ} < 5\%$ inducing a SNR improvement of a factor 2 to 10 according to the setup and the seeing conditions and when the detection is limited by the photon noise. The evaluation of the SNR improvement in low flux condition cannot be estimated directly and depends strongly of the chosen strategy for the detection, for instance it depends strongly of the number of pixels and of the read out noise for the considered detector. With a noisy camera it is not a good strategy to disperse the collected signal on a too large number of pixels, prevailing for example a co-axial AC or ABCD detection of the fringe over a multi-axial detection. With new APD NIR HgCdTe cameras this limitation will be overcome opening the possibility to use new beam combination strategies.

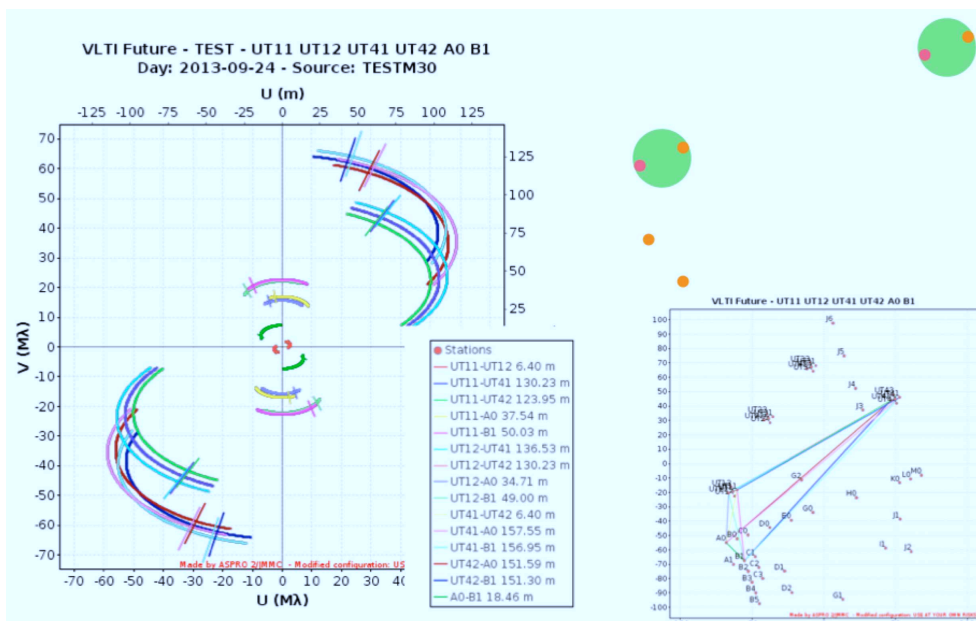


Figure 4.: *Hybrid array case with 1.8 and 8 m telescopes, resulting uv coverage enhancement for a compact array case (credit Gilles Duvert, IPAG).*

Another very interesting capability is to use this flexibility to combine **telescopes of various sizes** (e.g. AT and UT for the VLTI) and splitting them in

sub-apertures of equivalent dimension (see Fig. 5). Such a setup avoids a SNR loss due to the difference of diameter of the combined telescopes.

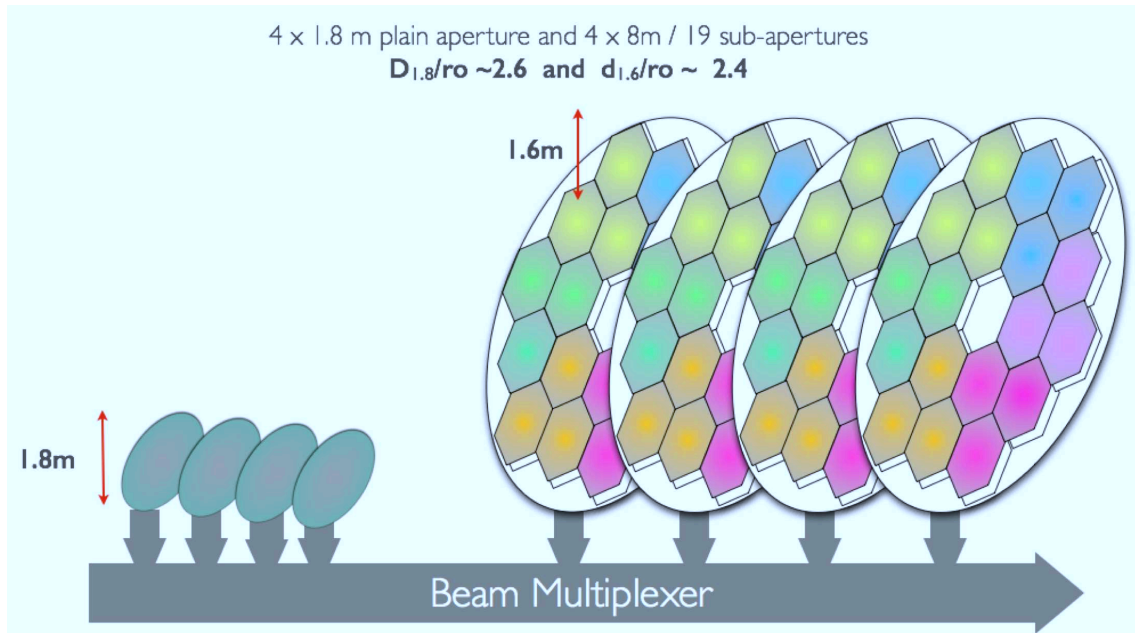


Figure 5.: *Hybrid array case with 1.8 and 8 m telescopes.*

7. Conclusion

We proposed a setup for single interferometry interferometry, where the beam distribution is performed in the input pupil plane by a pupil division scaled by the turbulence coherent area R_o , leading to a easier injection in the single mode waveguides, and by consequence reducing the need of a correction using an adaptive optics with a large number of actuators.

The proposed interferometric setup is able to simplify a multi-telescope instrument, using simple individual building blocks that have been fully validated for years on IOTA (IONIC/IOTA 3T) or on the VLTI (PIONIER 4T). The main behavior of the proposed setup is to be able to operate a complex interferometric array of telescopes without the need of complex AO systems under high D/r_o

conditions, while the combinations are performed between smaller sub-apertures lightly affected by the atmospheric turbulence.

It offers also an enlarged field of view thanks to smaller equivalent instrument pupils. The concept allows to reach shorter wavelengths down to the visible domain using SM waveguides. An other interesting behavior is the possibility to introduce additional points in the U-V plane for short baselines issue from nearby large telescopes.

The proposed setup would be suited for flexible operation according to the considered astrophysical program and to the seeing conditions. It is able to handle a large number of parallel channels, facilitating the realization of small series of simple unit components that can be easily tested and duplicated. Further instrumentation of existing or future telescope arrays (CHARA, VLTI, MROI with up to 10 telescopes), could contemplate such concept that provides an interesting modularity to deal with various astrophysical applications. The application to an hybrid network dealing with telescopes of different sizes is also applicable.

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References

- Benisty, M., Berger, J.-P., Jocou, L., et al. 2009, *A&A*, 498, 601
- Berger, J.-P., Haguenaer, P., Kern, P. Y., et al. 2003, *Interferometry for Optical Astronomy II*. Edited by Wesley A. Traub . Proceedings of the SPIE, 4838, 1099
- Berger, J.-P., Zins, G., Lazareff, B., et al. 2010, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, Vol. 7734, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*
- Blind, N., Absil, O., Bouquin, J.-B. L., Berger, J.-P., & Chelli, A. 2011, *A&A*, 530, 121
- Feautrier, P., & Gach, J. 2013, in *Proceedings of the Third AO4ELT Conference*, ed. S. Esposito & L. Fini (Firenze: INAF - Osservatorio Astrofisico di Arcetri)
- Foresto, V. C. D., Ridgway, S., & Mariotti, J.-M. 1997, *A&A Supplement series*, 121, 379
- Guyon, O. 2002, *A&A*, 387, 366
- Harris, R. J., MacLachlan, D. G., Choudhury, D., et al. 2014, *Audio, Transactions of the IRE Professional Group*,
- Jovanovic, N., Tuthill, P. G., Norris, B., et al. 2012, *MNRAS*, 427, 806
- Kern, P. 2001, *Comptes Rendus de l'Académie des Sciences - Séries IV - Physics*, 2, 111
- Kotani, T., Lacour, S., Perrin, G., Robertson, G., & Tuthill, P. 2009, *Optics Express*, 17, 1925
- Le Bouquin, J., Berger, J., Lazareff, B., & Zins, G. 2011, accepted in *A&A*

- Leon-Saval, S., Birks, T., Bland-Hawthorn, J., & Englund, M. 2005, *Optics Letters*, 30, 2545
- Malbet, F., Kern, P., Schanen-Duport, I., et al. 1999, *A&A Supplement series*, 138, 135
- Mennesson, B., Ollivier, M., & Ruilier, C. 2002, *J. Opt Soc Am A*, 19, 596
- Noordegraaf, D., Skovgaard, P. M. W., Maack, M. D., et al. 2010, *Optics Express*, 18, 4673
- Perrin, G., Lacour, S., Woillez, J., & Thiébaud, E. 2006, *MNRAS*, 373, 747
- Roddier, N. 1990, *Optical Engineering*, 29, 1174
- Ruilier, C. 1998, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 3350, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, ed. R. D. Reasenberg, 319-329
- Shaklan, S., & Roddier, F. 1988, *Applied Optics*, 27, 2334
- Tatulli, E., Blind, N., Berger, J. P., Chelli, A., & Malbet, F. 2010, *A&A*, 524, A65
- Tatulli, E., Mège, P., & Chelli, A. 2004, *A&A*, 418, 1179
- Thomson, R., Birks, T., Leon-Saval, S., Kar, A., & Bland-Hawthorn, J. 2011, *Optics Express*, 19, 5698