

Diffraction limited imaging with Dense Aperture Mapping

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Résumé Dense Aperture Mapping (DAM) is a new interferometric technique allowing high-angular resolution over a narrow field of view (FOV) imaged by the present class of mono-pupil telescopes equipped with adaptive optics (AO). DAM is realized by a suited afocal double lenslet array (BIGRE), mapping the telescope pupil into coherent sub-pupils, and adopted as sub-pupils spatial filter and focal plane re-imager. Based on the densified pupil concept for diluted telescope arrays- hypertelescope - it is applied here on a segmented mirror telescope turned into a filtered direct imaging Fizeau combiner. We explain here as first why DAM is a pupil remapping technique. We define the Clean FOV (CLEAF) where an object-image convolution relation is preserved. We show how DAM and AO can match to reach high Strehl image quality, highlighting on the low spatial frequencies filtering property intrinsic to DAM.

1 Introduction

DAM is an interferometric technique allowing direct images over a narrow FOV around the optical axis to image exoplanets close to their hosting star. DAM is diffraction-limited once a suited AO system is available[20]. The optical device shaping DAM is the BIGRE lenslet array[1], and adopted here as a sub-pupils spatial filter and a focal plane re-imager[2]. Such lenslet array is mounted in a collimated beam and conjugated pupil plane before the scientific detector, in such a way that the collimator provides the image of the telescope pupil onto the BIGRE-DAM[2]. Moreover BIGRE-DAM by design is a passive (no control loops in) and modular (easy plug-and-play) device.

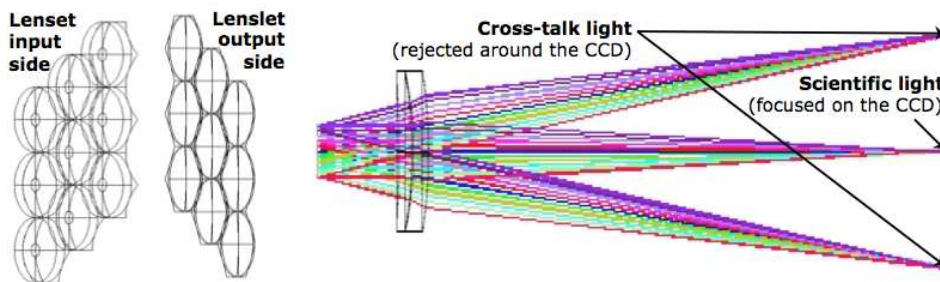


Fig. 1. BIGRE-DAM is composed of two consecutive micro-lenses array set in an afocal configuration, so as to provide an equivalent spatial filtering in the intermediate focale plane between the 2 lenslet arrays, and so as to reject the diffraction pattern in a circle outside of the CCD camera.

The spatial filtering of each sub-pupil is achieved by DAM thanks to the BIGRE lenslet array concept. Initially developed for integral field spectroscopy[1], BIGRE is composed of two consecutive micro-lenses array set in an afocal configuration (Fig. 1), and adopted here to subdivide the telescope

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pupil in many sub-pupils[2]. Each couple of input-output micro-lenses induces a spatial filtering in the intermediate focal plane conjugated with the detector plane. By adjusting the focals of the two micro-lenses, the irradiance of each beam is diaphragmed by the exit surface of the second micro-lens enough to transmit only the central Airy peaks[2]. Thus, the optical power of the last micro-lens re-images a spatially filtered sub-pupil, which in turn gets a Gaussian profile. An optical component has been fully designed[2] in H band in the case of NACO[23,7] at the VLT.

2 DAM as a pupil remapping technique

Continuous pupil remapping, namely called "phase induced amplitude apodization" or PIAA[9], achieves an apodization of the telescope pupil by geometric redistribution of the light. By pupil remapping is intended to be a system of lenses or mirrors that takes a flat input field at the entrance pupil and produces an output field that is amplitude-modified but still flat in phase (at least for on-axis sources)[4]. This technique is very similar to the pupil remapping of sparse interferometer's pupils : light is geometrically rearranged in the pupil plane without introducing phase aberrations for an on-axis source[10].

Discrete pupil remapping was first used by Michelson to "fit" a 6.5 m interferometric baseline into a 2.5 m telescope[15]. Discrete pupil remapping in interferometers was later studied by Labeyrie[12]. This technique, used to create a compact pupil from a sparse interferometric pupil, was named "pupil densification", and led to the concept of a "hypertelescope"[10].

In the same manner, Dense Aperture Masking[20] is part of the pupil remapping techniques and is close to the hypertelecope concept[12,13,18]. More in detail DAM represent a step beyond in the real of interferometric imaging : initially proposed by Fizeau[6], firstly densified by Michelson[15], generalized to a large array by Labeyrie[12], coupled with the spatial filtering techniques[16,17] and conceptually revisited for mono-pupil telescopes applications[20].

In the case of DAM, the sub-pupils are regularly spaced with a highly redundant configuration on an hexagonal pattern. The entrance pupil of DAM is dense in the sense that the sub-pupils are tangent and cover most of the entrance pupil of the full aperture. The output pupil shape is the same thanks to an homothetic mapping of the pupil. The input-output sub-pupil layout is preserved. The optical transformation concerns only the sub-pupils, by changing the window function of each sub-pupil thanks to the spatial filtering.

More in details, discrete pupil remapping is achieved by changing the sub-pupil distribution (remapping, densification) and/or by changing the sub-pupil size (densification) and/or the sub-pupil shape (spatial filtering). In the case of DAM, there is no remapping, only mapping. There is no densification, the entrance pupil is already dense. There is no masking, no obstruction of light. That is why DAM, initially named Dense Aperture Masking[20] is now called Dense Aperture Mapping for clarification.

3 DAM as a high spatial frequency sampler

The Point Spread Function (PSF) equals by definition to the autocorrelation of the exit pupil in a perfect case (monochromatic light without any turbulence). The array configuration of DAM benefits from a quasi-complete output pupil filling rate, so that the PSF is close to the diffraction function of the full telescope[18]. The imaging properties of the PSF (resolution, FOV, dynamic range) are directly related to the entrance pupil configuration[18].

Whereas the PSF of the full aperture is a diffraction pattern (Airy rings with a circular aperture), the PSF of DAM can be defined as the sum of interferometric pattern (fringes). The PSF of DAM is produced by the superimposition of fringes of each baselines (i.e. each pair of lenses of a BIGRE lenslet array). DAM can be seen as an encoder of diffraction pattern into interferometric pattern, providing the same PSF as a full aperture but on a limited FOV. In presence of turbulence, the fringes are added coherently so as to maximize the Strehl, as long as the beams of each sub-pupil are cophased with a residual piston lower than a fraction of wavelength.

A telescope of diameter D is analog to a low-band filter up to the cut-off frequency D/λ . DAM is a pass-band filter, between D/λ and s/λ , with s the diameter of a sub-pupil - the pitch of the lenslet array - and λ the wavelength. In the image plane, it corresponds to a resolution element (*resel*) equal to λ/D and to a Clean FOV width equal to λ/s [13]. This FOV is a window function[13,16], with a width equal to the diffraction lobe of a sub-aperture. This windowing effect is redundant in the PSF with a periodicity of λ/s and induces the confusion problem[22] including aliasing effect and crowding effect[18].

The Clean FOV, noted CLF in the case of the hypertelescope[13], is noted CLEAF in the case of DAM. The CLEAF equals both to the CLF and to the coupled field of view (CF)[13] corresponding to the FOV seen by a filtered sub-aperture. The CLEAF in unit of resel returns then D/s for a redundant array. An object-image convolution relation is preserved within the CLEAF[20].

DAM is a pass-band spatial frequency sampler, which transmits only the frequencies of interest of the object, as long as the object remains smaller than the CLEAF. The high spatial frequencies (above s/λ) seen by the baselines are sufficient to provide a high-resolution image on a narrow FOV equal to the CLEAF. At the opposite, the low spatial frequencies of each sub-pupil (below s/λ) are useless on a narrow FOV. In the case of a hypertelescope, these low frequencies are removed thanks to the highly diluted array configuration, so that the object is unresolved by a sub-pupil. In the case of DAM, the low spatial frequency tail - from s/λ to 0 - are removed by spatial filtering, which in turn is the same for each sub-pupil[2].

4 DAM as a low spatial frequency filter

In Aperture Synthesis techniques[3], a concept close to DAM is the pupil single-mode filtering and remapping (FIRST)[21], however limited in number of sub-apertures due to the complexity of the use of fsingle-mode fibers. It has previously been shown in Aperture Synthesis that the spatial filtering can drastically improve the performances of a large interferometer in presence of residual piston errors [5]. However, the use of spatial filtering comes at the expense of a small FOV, which is the size of the diffraction lobe of the largest telescope in the array [8].

This FOV imposed by the spatial filtering equals in fact to the CLEAF provided by DAM, which is the diffraction lobe of a sub-aperture. Moreover, this spatial filtering induces no information loss with a hypertelescope or DAM, since we are only interested in the high spatial frequencies measured by the baselines, and not in low spatial frequencies measured by one sub-aperture [13]. Thus, the spatial frequency filtering of each sub-pupils is perfectly suitable for DAM.

Each filtered sub-pupil provides a sub-image with only a piston phase error and a photometric fluctuation (amplitude error). In a first approximation, the piston is more critical than the amplitude error for direct imaging[17]. Since the intra-sub-pupils piston is spatially filtered, only the inter-sub-pupil differential piston remains. Whereas an infinite number of points within the entrance pupil must be cophased with the full aperture, only a finite number of sub-pupils must be cophased with DAM, thanks to its spatial filtering property which averages out the intra-sub-pupils residual piston. Hence DAM can cope with the turbulence effects by filtering the low spatial frequency orders, useless for narrow FOV imaging like companion detection close to a hosting star.

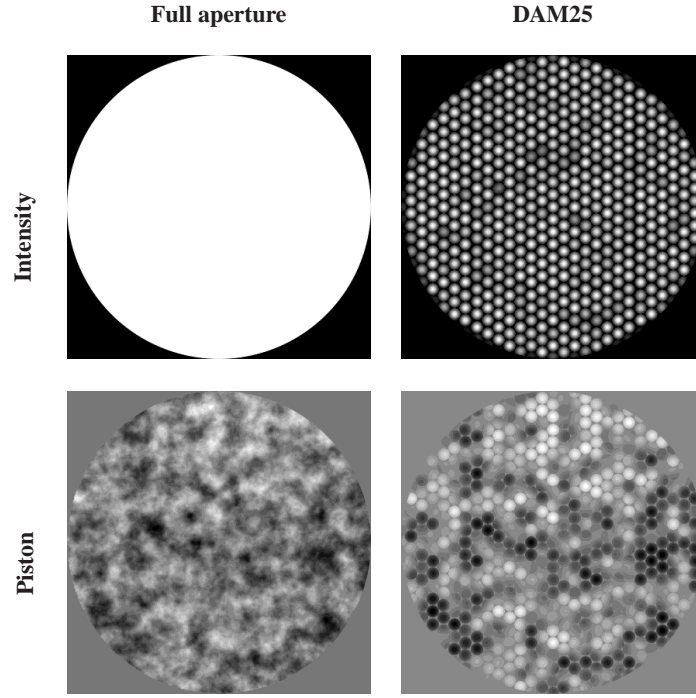


FIG. 2. Instantaneous wavefront screen in intensity (top) and in piston (bottom) with the full aperture (left) and with DAM25 (right). The wavefront of the full aperture is digitized by DAM. Whereas an infinite number of points within the entrance pupil must be cophased by the AO with the full aperture, only a finite number of sub-pupils must be cophased with DAM, thanks to its spatial filtering property which averages out the intra-sub-pupils residual piston.

5 DAM imaging capabilities

DAM is a suited spatial frequency filter for AO with respect to high-contrast imaging techniques based e.g. upon coronagraphy, apodization or data reduction algorithms such as Angular Differential Imaging (ADI)[14]. We are only interested in the high spatial frequencies measured by the baselines, not by the low frequencies as long as small field of view is used[13]. In other words, DAM allows a correct sampling of the telescope high-spatial frequency content while the low spatial frequency tail is filtered out. Such tail is fixed by the sampling frequency of the BIGRE lenslet array, which in turn depends on its pitch[2].

DAM can also be defined as a segmented aperture (multi-pupil) mapped in coherent sub-apertures (sub-pupils) and re-imaged downstream. DAM is an imager mounted on a single-dish telescope turned into a segmented telescope, where each segment has a diameter equal to the pitch and is spatially filtered, and where the entrance and exit pupil layout is homothetic. The pupil configuration with the dense hexagonal array provides a PSF with replicated aliased peaks with a periodicity of λ/s (with s the segment size), in the same way that a large segmented telescope with hexagonal segments (like the E-ELT) provides a PSF with similar features, with replicated peaks around the central peak. The position of these peaks depends on the segments diameter. The intensity of these peaks depends on the gap between the segments.

The flux throughput of DAM is almost the same as the full aperture, since the flux loss is mainly due to the spatial filtering. The coupling efficiency of DAM is also a function of the turbulence. The flux throughput of DAM reaches up to 80% in good conditions and few pourcents in bad conditions,

compared to the 100% of transmission of the full aperture whatever the turbulence level.

The spatial resolution should be the same in both case, but since DAM provides a diffraction-limited image, it can recover in principle the ultimate resolution of λ/D , with D the external diameter of the mono-pupil telescope.

The FOV of the full aperture is infinite (in theory), whereas the FOV of DAM is quite small by definition (CLEAF). The CLEAF can be enlarged by increasing the number of sub-apertures - decreasing the pitch of the BIGRE-DAM lenset array[20].

The dynamique range is the same within a narrow FOV in the perfect case (without turbulence), since the PSF is close to the diffraction limit in both cases. However, DAM is less sensitive to the turbulence than the full aperture, as shown in the following simulations.

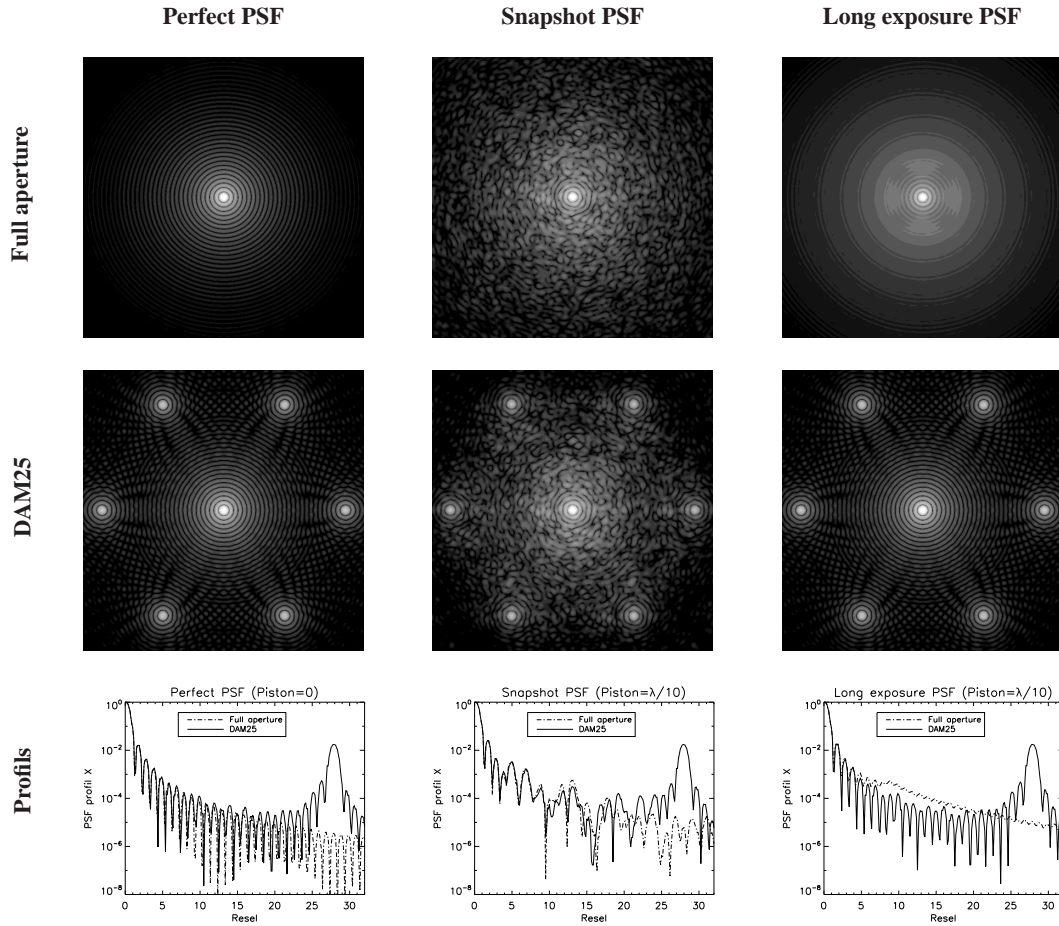


Fig. 3. Perfect PSF, snapshot PSF and long exposure PSF of 1000 frames using an AO with residual $Piston = \lambda/10$, either with the full aperture alone (top) or with the full aperture filtered by DAM25 (middle) located at the front of the CCD. The theoretical PSF profiles along the X axis (bottom) show that the theoretical PSF are equal in both cases within the Clean FOV of radius $12.5resels$ with DAM25. In presence of AO piston, the long exposure PSF of the full aperture is smoothed and the Airy rings are destroyed. DAM dams the way of the residual piston of the AO and provides a PSF close to the theoretical one. 2D images of 64×64 resels and profiles, with the maximum normalized to 1.

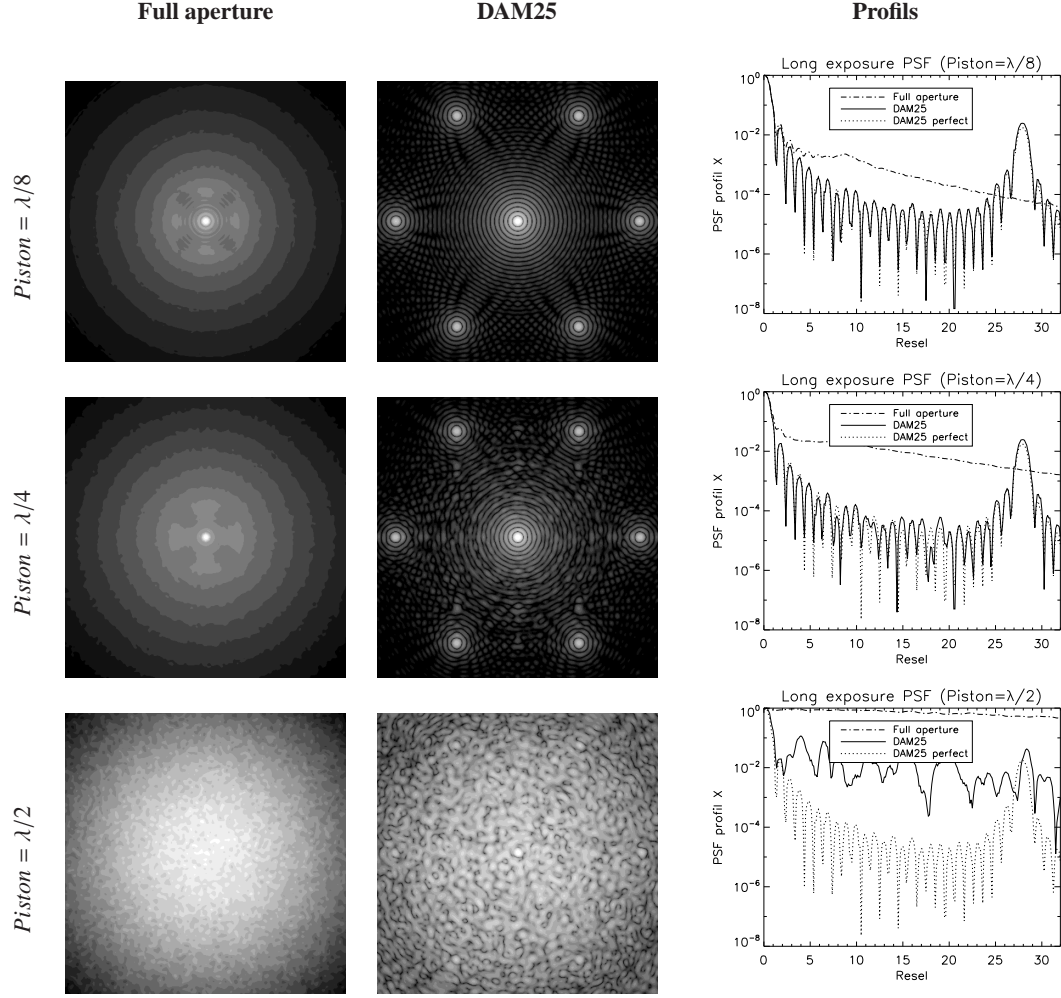


FIG. 4. Long exposure PSF of 1000 frames using an AO, either with the full aperture, or with the full aperture filtered by DAM25. DAM recovers a PSF close to the theoretical one as long as $Piston < \lambda/8$. $Piston = \lambda/4$ is the theoretical limit of DAM to recover the diffraction limit in long exposure. With $\lambda/4 < Piston$, DAM allows to recover at least the central peak, whereas the long exposure of the full pupil is completely smoothed. At 10 resels from the axis, DAM provides a gain of contrast higher than 10 with $Piston = \lambda/8$ and higher than 100 with $Piston = \lambda/4$. 2D images of 64x64 resels and profiles, with the maximum normalized to 1.

6 DAM simulations

In the studied case, DAM25 is composed of 25 sub-pupils along the diameter, corresponding to 660 sub-pupils in total. The CLEAF diameter in elements of resolution (resel) is a function of the number of sub-pupils along the diameter and equals here to $CLEAF = 25resels$. The CLEAF diameter in angular size (*mas*) depends on the wavelength λ and on the external diameter of the entrance pupil D , with $resel = \lambda/D$. For instance, $resel = 40mas$ in H band with a 8 m class telescope, and $CLEAF = 1as$.

Fig. 2 shows how the wavefront of the full aperture is digitized by DAM. Figure 3 shows an example of the PSF behaviour in the presence of a realistic residual error of piston RMS of the AO, computed with the AO modeling code PAOLA[11], so that $Piston(RMS) = Piston = \lambda/10 \approx 160nm$ in H band. Figure 4 shows that as long as $Piston < \lambda/8$ in long exposure mode ($Piston = \lambda/4$ is the theoretical limit), the diffraction-limited image is preserved[17,19].

7 Conclusion

In is essential, DAM is a filtered multi-pupil sampler and so it can be exploited both for interferometric imaging as for AO filtering. In practice, coupled with an AO system it provides diffraction limited images, even with a residual piston, up to $\lambda/4$, in long exposure mode (see figure 4). Such images get the requested level of high-angular resolution to explore the inner region of sub-stellar systems. Moreover, thanks to the respected convolution relation between object and image on a narrow FOV, it allows to exploit new de-convolution techniques tailored for compact sources, like for instance the one proposed to spatially resolve the surface of Betelgeuse[19]. DAM is a simple, stable and passive optics, easy to mount on any telescope equipped with AO. Hence, DAM represents a novel and smart opportunity to enlarge the use of interferometry to a broader community working on high-angular resolution. Finally, DAM is complementary either with other focus instruments such as a coronagraph, an apodizer or an IFU spectrograph, or with differential imaging techniques such as ADI[14].

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