Discretized Aperture Mapping for wavefront sensing

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Abstract

DAM (Discretized Aperture Mapping) is an original filtering device able to improve the performance in high-angular resolution and high-contrast imaging by the present class of large telescopes equipped with adaptive optics (Patru et al. 2011, 2014, 2015). **DAM is a high-spatial frequency filter** able to remove the problematic phase errors produced by the small scale defects in the wavefront ***(Fig. 1, 2, 3, 4)***. Various effects are related to the high-spatial frequency content which is neither seen by any wavefront sensor (WFS) nor corrected by any adaptive optics (AO) and is transmitted up to the final detector. In particular, any wavefront sensor, due to its finite sub-apertures size, is fundamentally limited by the well-known aliasing effect, where high-spatial frequencies are seen as spurious low frequencies. **DAM can be used as an anti-aliasing filter** in order to improve both the accuracy of the WFS measurements and the stability of the AO compensation.

This paper deals with a new category of spatially filtered wavefront sensors, named DAM-WFS, where DAM, located at the front of a WFS, serves as an anti-aliasing filter providing accurate and stable measurements. Among the WFS concepts, the **spatially filtered Shack-Hartmann WFS (SF-SH-WFS)** (Poyneer 2004) is the unique concept of passive filtering proposed until now, which consists in using a single pinhole at the front of the sensor. However, it is a non-linear filter which generates spurious low spatial frequencies, contrary to DAM which is a priori linear and may exceed the performance of its precursor. Whereas a pinhole filter removes the high-spatial frequency content, DAM reduces more the mid-spatial frequency content close to the cutoff frequency ***(Fig. 5)***.

DAM upstream of a Shack-Hartmann WFS (DAM-SH-WFS) is free of aliasing. In addition, it reduces the spot distortion and improves the centroid computation. **DAM upstream of a Pyramid WFS (Ragazzoni 1996) (DAM-PYR-WFS)** cancels out the aliasing as well, even if it is not so strong in the Pyramid WFS with respect to the Shack-Hartmann WFS. However, the Pyramid WFS shows more phase residuals at the high-spatial frequencies, whereas the SF-SH-WFS is more sensitive to low frequencies. Significant noise propagation remains at the highest frequencies closed to the WFS cutoff frequency (function of the number of lenslet of the WFS). In this domain, DAM may help to reach the highest sensitivity of a Pyramid WFS thanks to its high-spatial frequency filtering properties ***(Fig. 5)***.

DAM, an anti-aliasing filter

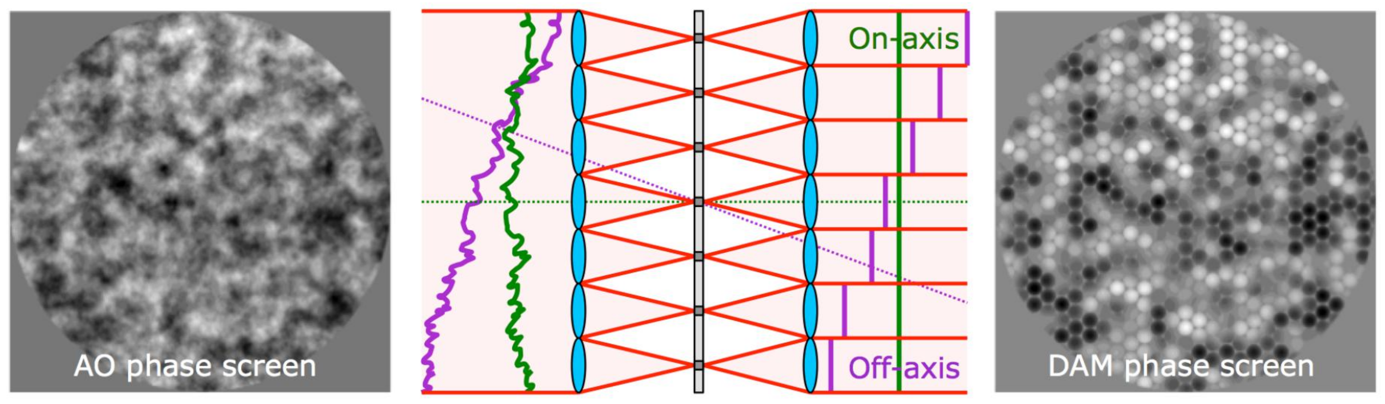

Figure 1. DAM optical scheme: The DAM device is composed of a double lenslet array matched with a filter array. Each sub-beam is diaphragmed by a lenslet, focussed into a spatial filter, and re-expanded onto a co-axial lenslet. DAM thus transforms a continuous and aberrated wavefront (on the left) into a discretised and smoothed wavefront (on the right). The small scale aberrations are spatially filtered within each sub-aperture (high spatial frequency rejection). An on-axis object (green line) transmits a flat wavefront while an off-axis object (violet line) yields a stair-shaped wavefront, thus preserving the tip-tilt information (low spatial frequency transmission). An off-axis object beyond the field of view imposed by the filter size is not transmitted.

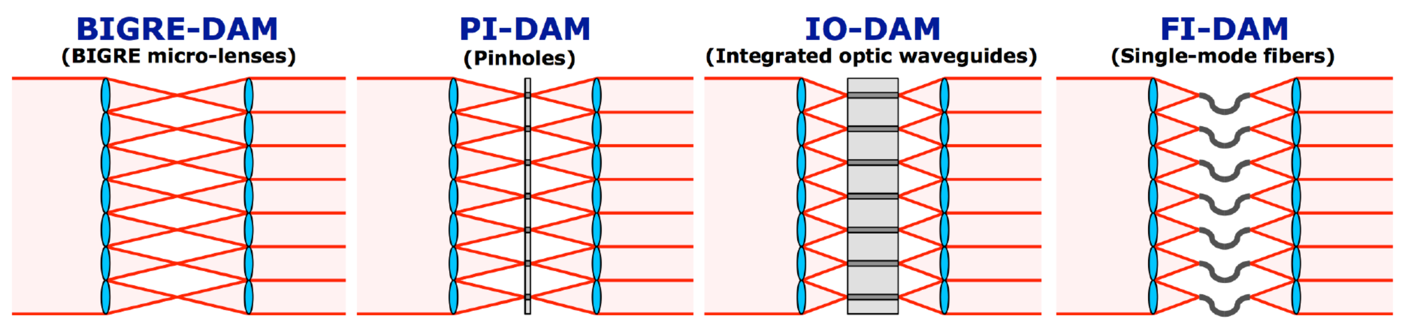

Figure 2. DAM technological solutions: The double lenslet array is matched with a spatial or modal filter array, providing respectively multi-mode or single-mode filtering properties. DAM can rely on spatial filtering by using an array of pinholes (PI-DAM) or solely a fine-tuned double lenslet array (BIGRE-DAM). DAM can rely on modal filtering by using an array of waveguides, either with a three-dimensional integrated optic composed of photonic circuits (IO-DAM) or with a bunch of single-mode fibers (FI-DAM).

DAM concept	BIGRE-DAM	PI-DAM	IO-DAM	FI-DAM
Sub-apertures device	Micro-lenses	Micro-lenses	Micro-lenses	Micro-lenses
Filter device	2nd lens	Pinhole	Int.opt.waveguide	Single-mode fiber
Spatial/Modal filtering	Spatial filtering	Spatial filtering	Modal filtering	Modal filtering
Number of sub-apertures	High	High	Moderate	Low
Field of view	Moderate	Moderate	Moderate	Small
Flux throughput	Moderate	Moderate	Moderate	Moderate
Complexity	Low	Moderate	Moderate	High
Need of R&T	Low	Low	High	Moderate

Figure 3. DAM technological solutions: Those solutions have their own pros and cons, and varying levels of complexity and development, so that the technological choice will be driven by the scientific requirements.

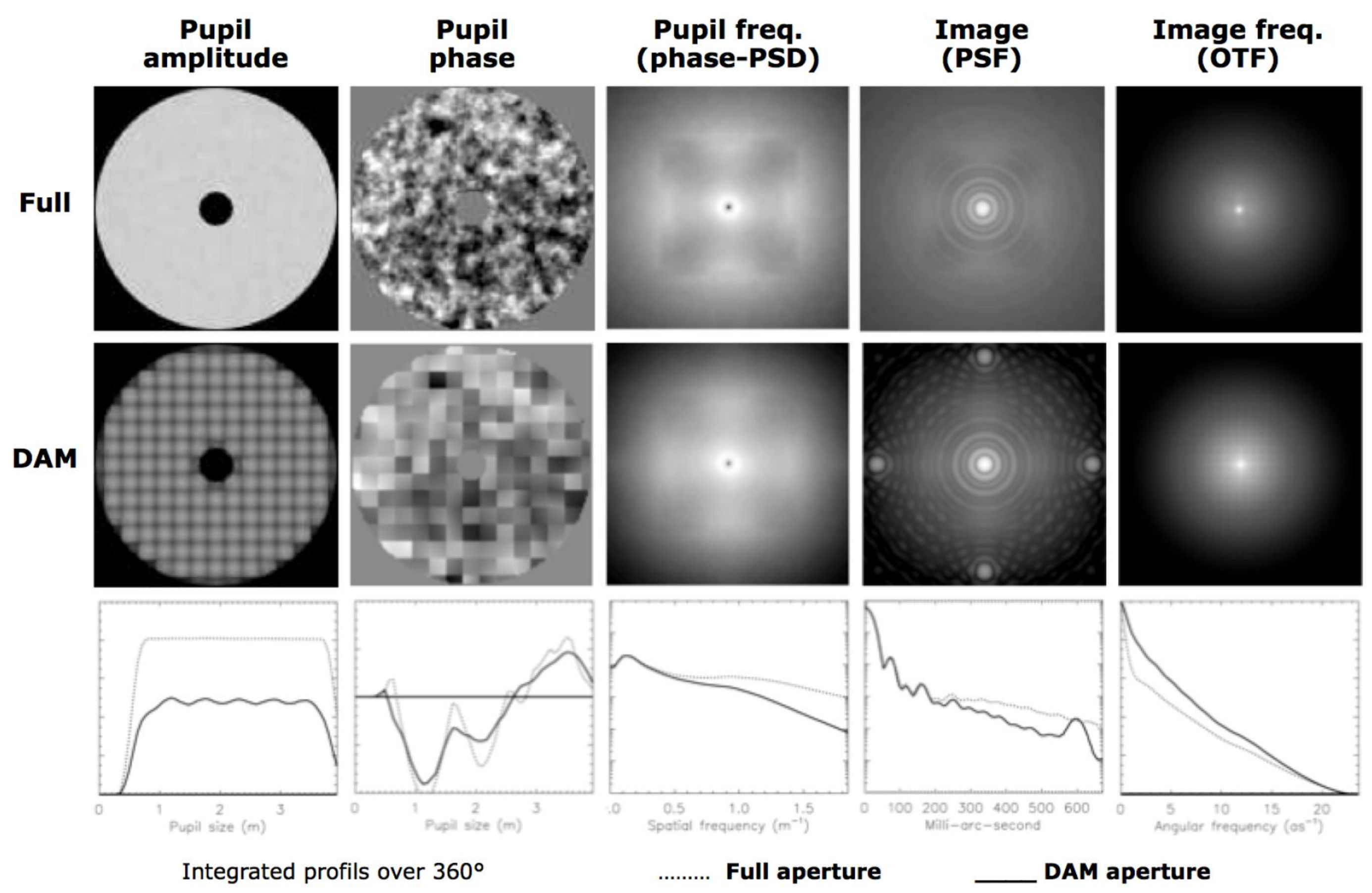

Figure 4. DAM optical properties (from left to right): aberrated wavefront in the pupil shown in amplitude and in phase, pupil spatial frequency content shown by the phase power spectral density (phase-PSD), aberrated image or point spread function (PSF), image angular frequency content shown by the optical transfer function (OTF). Comparison between solely the full aperture (top, dashed line) and the DAM aperture using a filter (bottom, solid line). DAM smooths the amplitude and phase aberrations in the pupil by attenuating the high spatial frequencies in the phase-PSD. Conversely, DAM dims the scattered halo and improves the contrast in the image by attenuating the low angular frequency aberrations in the OTF and by enhancing the high angular information. Consequently, the residual aberrations which cannot be corrected by an adaptive optics system are purely and simply removed by discretising the wavefront by means of a DAM device.

PI-DAM, a pinhole array (*vs* single pinhole)

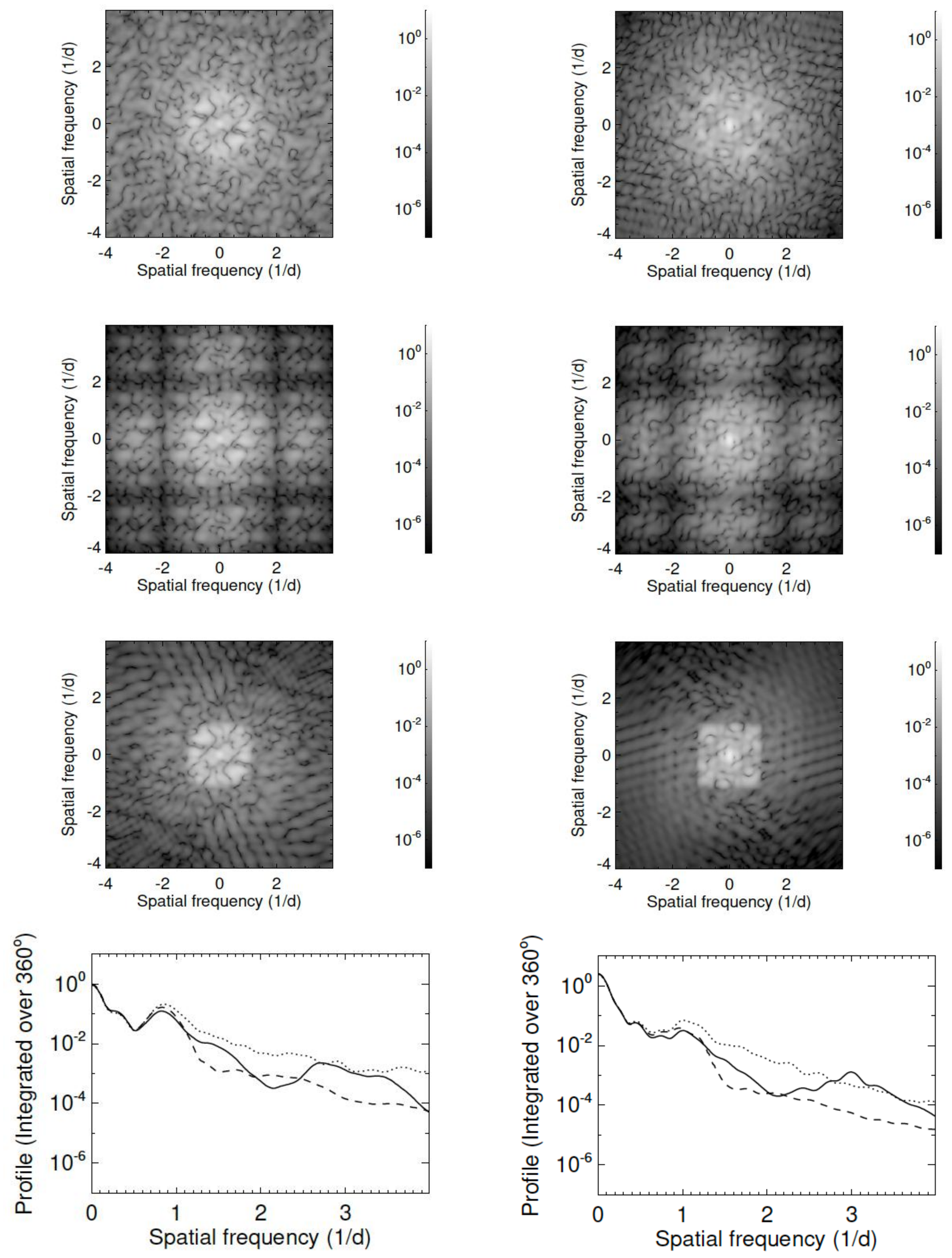

Figure 5: Phase power spectral density for a Shack-Hartmann wavefront sensor (left) and a pyramidal wavefront sensor (right).
No filter (top, dotted line). Pinhole filter (bottom, dashed line). PI-DAM filter (middle, solid line).

Conclusion

Those preliminary results are encouraging for developomg a new category of spatially filtered wavefront sensors, named DAM-WFS, where DAM, located at the front of a WFS, serves as an anti-aliasing filter providing accurate and stable measurements. **Finally, the anti-aliasing DAM filter is efficient and easy to operate. It seems suitable with various types of wavefront sensors (DAM-SH-WFS, DAM-PYR-WFS, etc.).** Also, the DAM filter is rather cheap and easy to integrate in a pupil plane conjugated with the entrance aperture and at the front of the wavefront sensor.

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