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Abstract. We present a geometric sensor to restore the local tip-tilt in a segmented surface using the Van Dam and Lane algorithm [M. A. van Dam and R. G. Lane, *Appl. Opt.* **41**(26), 5497–5502 (2002)]. The paper also presents an implementation of this algorithm using graphical processing units as specialized hardware. This compute unified device architecture implementation achieves real-time results inside the stability time of the atmosphere for resolutions of up to 1024×1024 pixels. [DOI: 10.1117/1.OE.52.5.056601]

Subject terms: compute unified device architecture; graphical processing units; geometric sensor; segmented mirror; local tip-tilt; local piston; cophasing.

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1 Introduction

The alignment (of the order of nanometers) between the hexagonal segments of a giant mirror has a critical effect on the quality of the image, therefore, the alignment system and commissioning phase, called the "cophasing system," is essential for the optimal performance of the telescope. Thus, the development of new techniques for cophasing that are robust, instrumentally simple, and applicable to a large number of segments (in the thousands for a giant telescope) is extremely important.

For cophasing the segments, the Shack-Hartmann sensor is commonly used in which the microlenses or prisms must be aligned very accurately over the edges of the segments. In the extremely larges telescopes (ELTs), the number of microlenses and edges grows enormously and the difficulty of precise alignment requires the search for simpler solutions. To this end, the curvature sensor corresponds to a much simpler optical design, however, until now, it has not been demonstrated with sufficient precision to measure the phase differences in and between segments although the system is capable of measuring these differences with high sensitivity.

Our contribution, in this respect, is the application of the algorithm of Van Dam and Lane to recover the local wavefront phases in a segmented surface from the measurements provided by a curvature sensor.[1] In this case, the curvature sensor is interpreted as a geometric sensor and the key, for use, is the choice of defocus planes on which the measurement is done.

The algorithm has been tested for the recovery of the first 50 Zernike polynomials, piston not included, in circular and annular pupils with promising results. The first simulations, to detect local tip-tilt of a segmented pupil, demonstrate excellent sensitivity and precision. Furthermore, the algorithm has been optimized and implemented on compute unified device architecture (CUDA) graphical processing unit (GPU) language to get information of the local tip-tilt within the time stability of the atmosphere (10 ms in visible). All this combined with the known sensitivity of the local curvature of the piston allows for hosting the best expectations for cophasing the segmented pupils, provided that an additional algorithm other than the Van Dam–Lane algorithm, is used to restore the local piston from the same data.[2]

2 Van Dam–Lane Algorithm

2.1 *Description*

The algorithm of Van Dam and Lane describes a technique for deriving the wavefront aberration from two intensity measurements (I_1 and I_2), acquired at two different defocused planes by using the first derivative of the wavefront rather than contrast proportional to the Laplacian of the phase.[1]

This is a new scheme to detect the wavefront directly using the linear relationship obtained from geometrical optics between the slope of the wavefront and the displacement of the photon.

The intensity defines a probability density function of the photon arrival and the method is based on the evolution of the cumulative density function of the intensity with geometric propagation.

In one dimension, the problem is easily solved with a histogram specification procedure with a linear relationship between the slope of the wavefront and the difference in the abscissas of the histograms. In two dimensions, the method requires the use of the Radon transform. In fact, as the authors mention in Ref. 1: "The algorithm consists only of matrix multiplications including the Radon transform and the least-squares reconstruction and one-dimensional interpolations. Consequently, it is suitable for real time implementation in an adaptive optics system." Furthermore, the method is insensitive to scintillation at the aperture.

2.2 *CUDA Implementation*

The Van Dam and Lane algorithm, applied to the entire pupil of the telescope, can recover the atmospherical wavefront phase. The implementation of the algorithm of Van Dam and Lane on specialized hardware, GPU or Field Programmable Gates Arrays type, is needed to achieve real time (the characteristic time of the atmosphere). In our case, we have decided to implement it first in CUDA (GPU). As there is no data dependency in the calculations, it was decided to assign a thread to each pixel of the image. These threads are grouped into blocks of 256 × 256. Note, that all calculations are performed on GPU (not CPU) whether it be calculation of derivatives, diffractions, interpolations, or matrix products. The derivatives of the Zernike polynomials have been implemented using the definition by Noll for both derivatives ∂x and ∂y.[3]

Table 1 Computation times (ms).

Resolution	GeForce 8800 GT	GeForce 9800 GX2	Tesla C1060	GeForce GTX 285	Tesla C2075
128 × 128	1,104	1,085	0,707	0,697	0,628
256 × 256	3,075	2,956	1,568	1,183	1,202
512 × 512	8,865	8,787	4,529	3,055	3,056
1024 × 1024	33,662	32,819	15,921	10,474	8,357
2048 × 2048	152,452	148,464	48,738	40,104	33,551
4096 × 4096	874,117	894,807	182,397	153,834	121,510

After the atmospheric contribution to the wavefront is extracted, the algorithm of Van Dam and Lane is, again, applied in parallel over the 36 telescope segments in order to obtain the local tip-tilt. Table 1 summarizes the results of such an implementation on several GPU card models for various final resolutions of the wavefront phase map. As can be seen, it is possible to work within the time stability of the atmosphere, below the 10 ms, up to resolutions of about 1024 × 1024 pixels.

2.3 *Zernike Polynomials Restoration*

As an initial test of the algorithm, several recoveries of the wavefront phases have been done on circular pupils. The algorithm recovers the Zernike polynomials of the wavefront phase. The polynomials can be retrieved either individually or as a combination. In the combined case, the algorithm maintains the ratio between the coefficients.

As seen in Fig. 1, the algorithm is able to retrieve the Zernike polynomials that comprise the original phase. For this test, we used the first 50 Zernike polynomials on a 512 × 512 pixel image. The proportionality is maintained as can be seen by observing the similarity coefficients: mean squared error (MSE), peak signal-to-noise ratio (PSNR)[4] and mean structural similarity (MSSIM).[5]

The MSSIM index is a method for measuring the similarity between two images. The MSSIM index is the measuring of image quality based on an initial uncompressed or distortion-free image as reference. MSSIM is designed to improve on traditional methods, such as PSNR and MSE, which have proven to be inconsistent with human eye perception. The range of positive values in the MSSIM index is between zero and one. A value of zero means no correlation between images or vectors. A value of one means the two compared images are equal.

Figure 2 shows several recoveries comparing the original and the restored wavefront maps. The original phases are atmospherical wavefronts simulated using a 496 Zernike polynomial expansion.[6] An 8 m diameter telescope and a 20 cm Fried diameter were considered. The algorithm is able to retrieve the first 120 Zernike polynomials that comprise the simulated atmospherical wavefront phases.

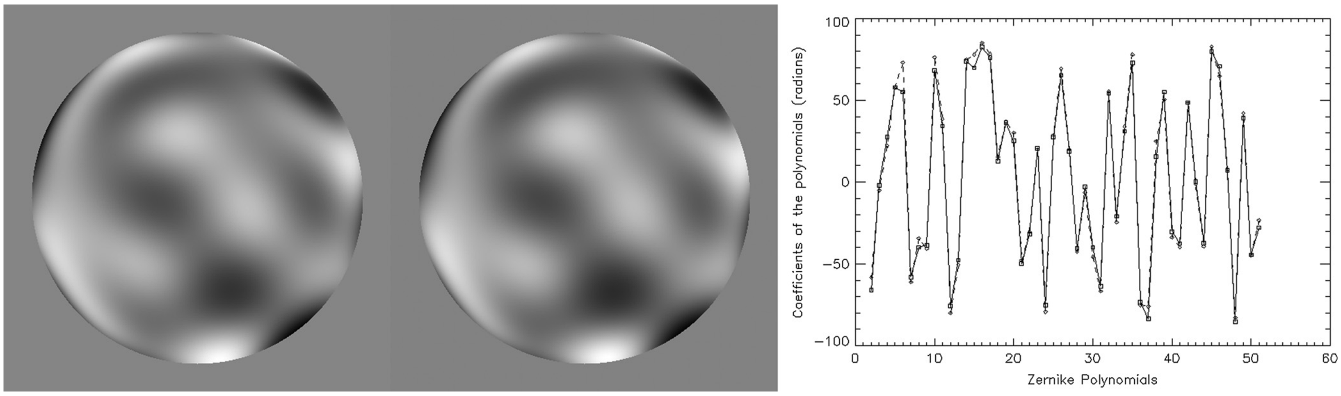


Fig. 1 (a) Left: original wavefront phase. Right: recovered wavefront phase. (b) Retrieved coefficients versus Zernike polynomials. With mean squared error (MSE) = 22.0772, peak signal-to-noise ratio (PSNR) = 34.6914, and mean structural similarity (MSSIM) = 0.992188.

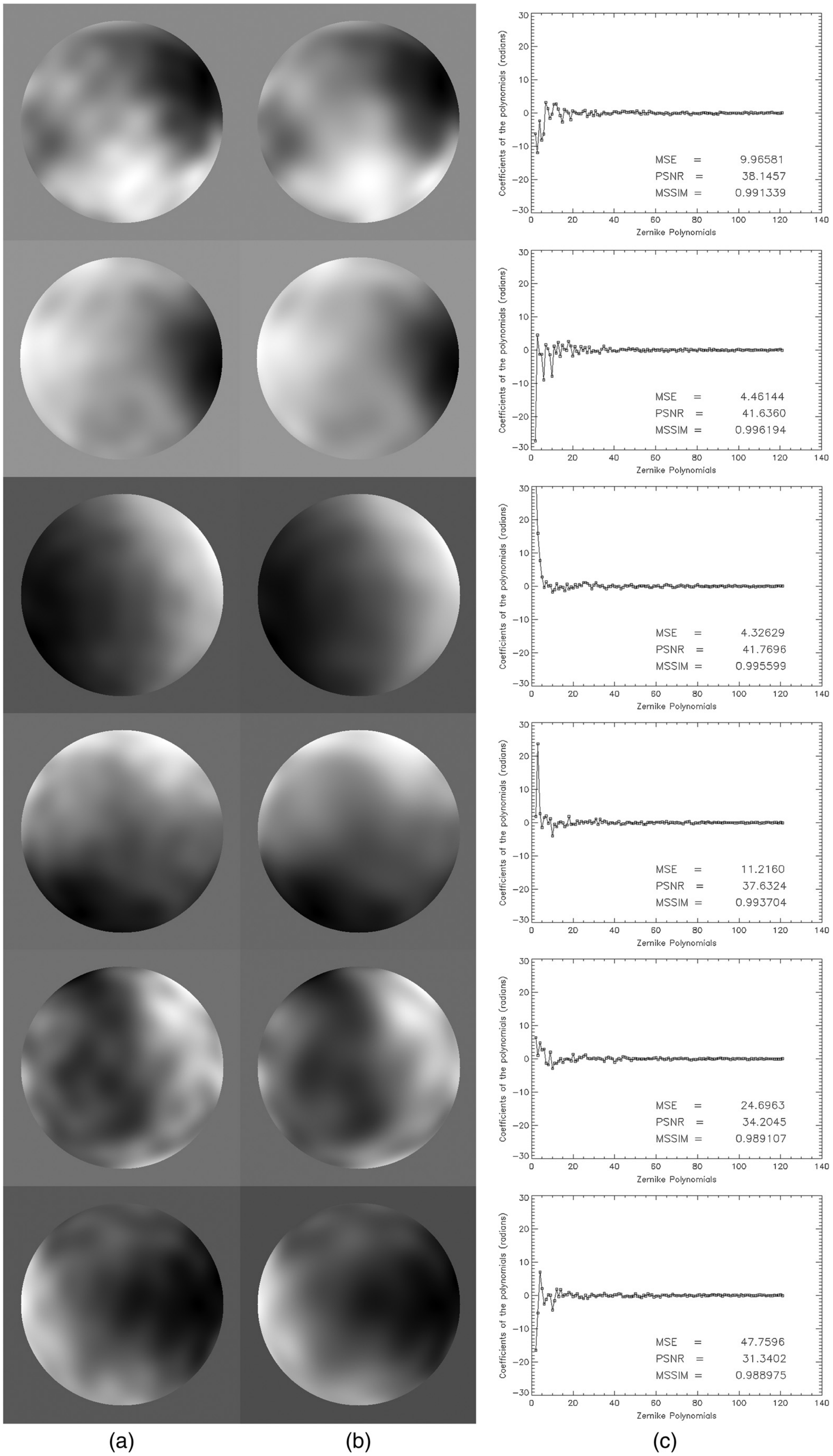


Fig. 2 (a) Simulated atmospherical wavefront phases. (b) Restored wavefront phases. (c) Retrieved coefficients versus Zernike polynomials. The MSE, PSNR, and MSSIM coefficients are included for each map restoration.

3 Tip-Tilt Restoration in Segmented Surfaces

3.1 *Simulated Data*

The simulations to demonstrate the results have included the generation of blurred images I_1 and I_2 of the geometric sensor from a wavefront phase containing a random distribution of tip-tilt (Z_2 and Z_3) in the 36 segments of a large telescope.

The images I_1 and I_2 have been generated using both Fresnel propagation and the Rayleigh-Sommerfeld propagation[7] (Fig. 3).

Figure 4 shows the recovery of the tip-tilt of each of the 36 hexagonal segments in a telescope type Keck. In an extremely large telescope, as the E-ELT would be talking about more than 900 segments, extracting the local tip-tilt from only two blurred images would be extremely useful.

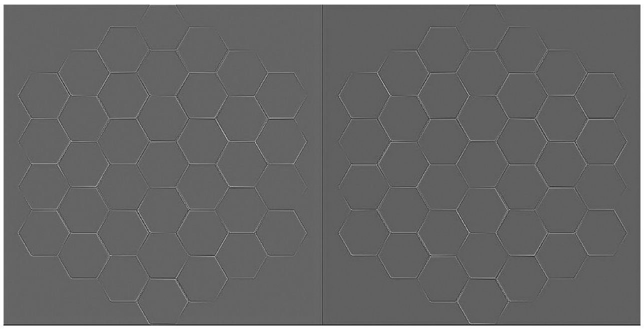
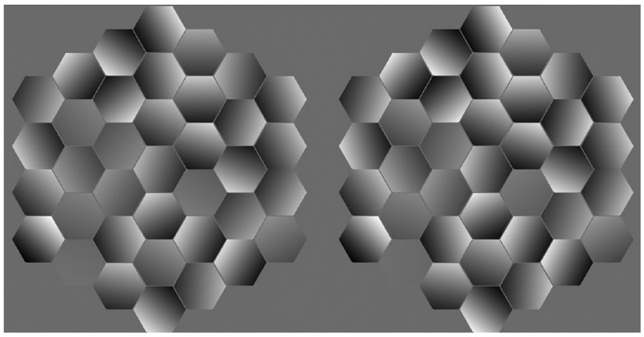


Fig. 3 Intra and extra defocused images obtained by Fresnel propagation.



(a) (b)

Fig. 4 Comparison between original segments (a) and recovered ones (b). Similarity coefficients: MSE = 117.128, PSNR = 27.4442, MSSIM = 0.958495.

Figure 5 shows a simulation in which the corresponding coefficients for Z_2 and Z_3 are retrieved. The vertical axis represents the coefficients of tip-tilt and the horizontal axis represents the corresponding segment (1 to 36). With regard to the strokes of the lines, dashed lines represent the initial coefficients and solid lines the coefficients obtained in the recovery.

3.2 *Experimental Data*

The adjustment for simulated data appears to be excellent, however, it is necessary to consider the presence of atmospheric phase and detector noise. What we have done is to use real observations to test the sensitivity of the method.

Images were acquired during the observing campaigns Active Phasing Experiment (APE) at the Paranal Observatory (Chile).[8] The aim of the experiment was to test four different techniques, Van Dam and Lane technique was not included, for cophasing the segmented mirror. As such, the instrument was installed with four sensors on the Nasmyth focus of Unit 3 of the Very Large Telescope with an APE subsystem with which the data was acquired by diffraction image phase sensing instrument (DIPSI). The segmented mirror [active segmented mirror (ASM)] was set to a known configuration and, then, the intra and extrafocal images were acquired (Fig. 6). Figure 7 shows the results of the tip-tilt recovery from the 36 central segments (three rings). The integration time was chosen to average the

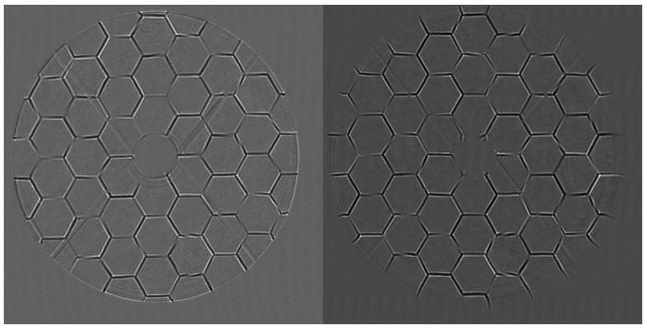
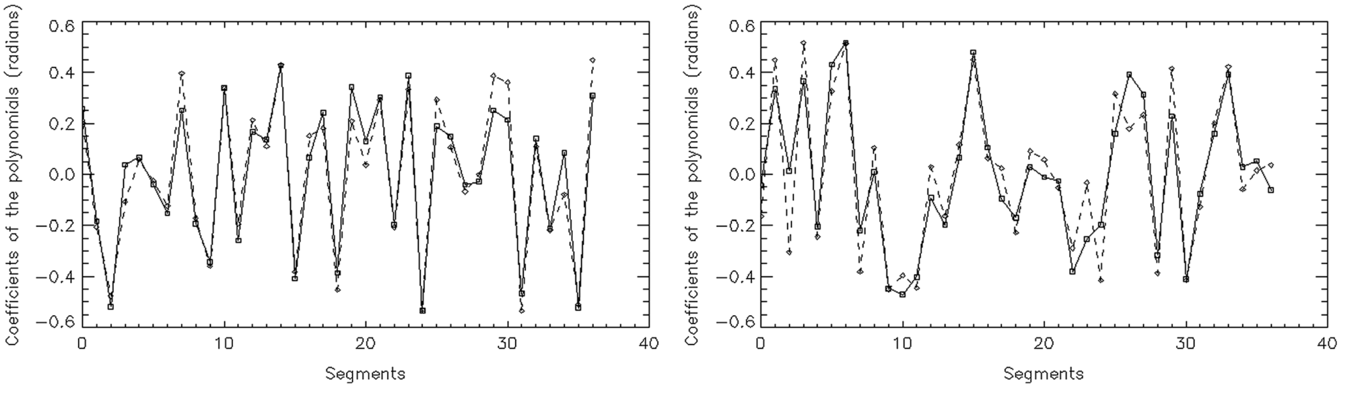
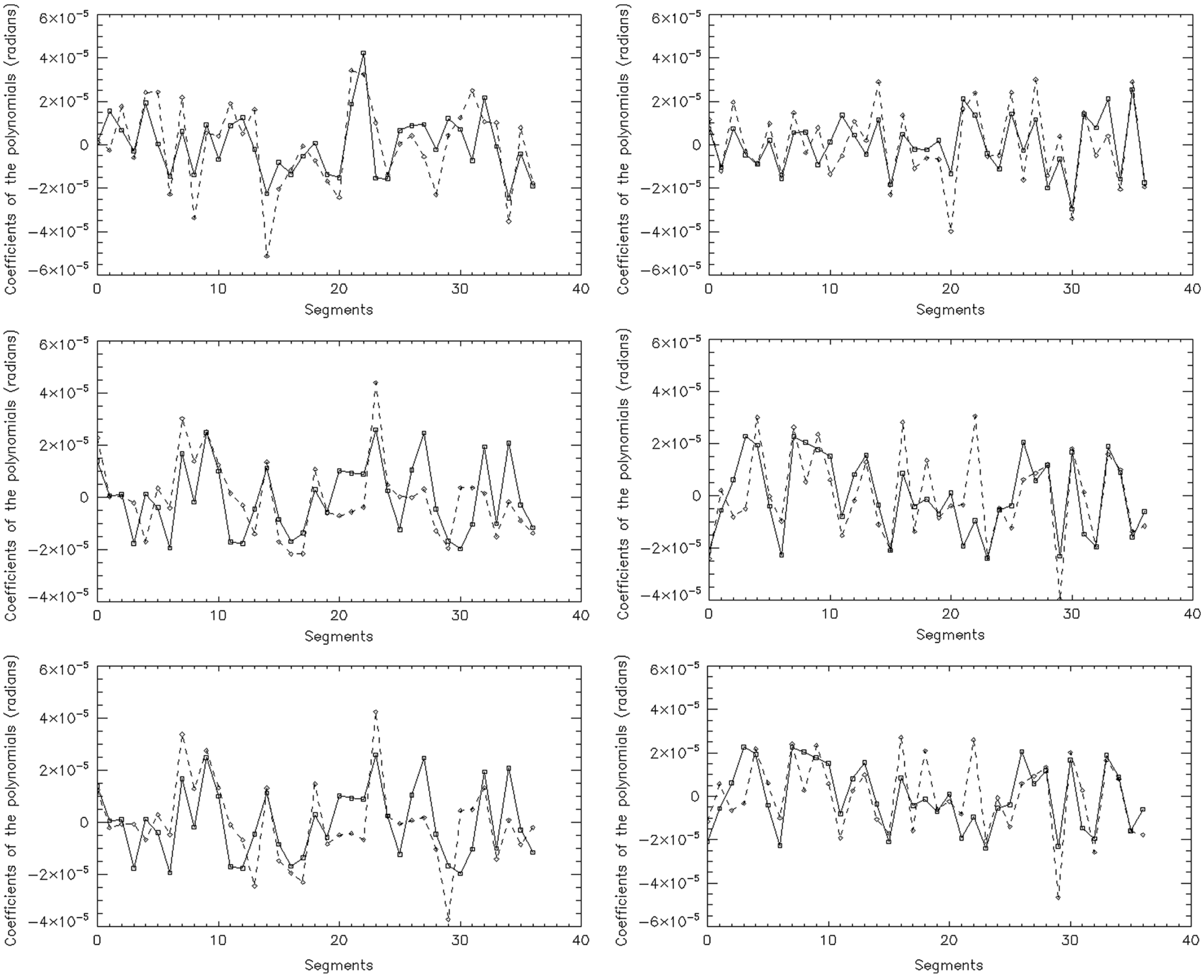


Fig. 6 Intra and extra defocused images obtained by diffraction image phase sensing instrument (DIPSI).



(a) (b)

Fig. 5 (a) Original and retrieved Z_2 coefficients for each segment (MSE = 7.97959e-7, PSNR = 109.111). (b) Original and retrieved Z_3 coefficients for each segment (MSE = 1.90616e-6, PSNR = 105.329).



(a) (b)

Fig. 7 (a) Original and retrieved Z_2 coefficients for each segment (from top to bottom: MSE = 1.8e-10, 1.5e-10, 1.6e-10 and PSNR = 145.4, 146.3, 146.2). (b) Original and retrieved Z_3 coefficients for each segment (from top to bottom: MSE = 1.1e-10, 1.4e-10, 1.6e-10 and PSNR = 147.7, 146.5, 146.2). Note that in the DIPSI, the size of a segment is approximately 1 cm, so 1e-5 radians mean sizes of about 100 nm tip-tilt.

effects of atmospheric turbulence (10 s) and measure only the contribution to the wavefront phase of the static aberrations of the deformable mirror. The extraction of the atmospheric contribution is not the aim of this article.

Note, that in the DIPSI instrument, the size of a segment is approximately 1 cm which corresponds to 1e-5 radians mean sizes of about 100 nm of tip-tilt. These values of large tip-tilt correspond to the first stages in the process of relocation of a segment recently aluminized. As can be observed, the recoveries are not completely accurate, however, they show similar behavior between original and restored local tip-tilts. New specific observations, with tip-tilt misalignments much smaller, must be done in order to assure the feasibility of this technique.

4 Conclusions

This paper shows that the algorithm of Van Dam and Lane could be applied for real-time retrieval of tip-tilt segmented surfaces. The fast processing time assures the possibility of extracting the atmospheric phase maps at the same time (inside the characteristic time of the atmosphere). Furthermore, this sensor is sensitive to local piston. Using a different algorithm for piston detection, combined with Van Dam and Lane algorithm for local tip-tilt detection, would allow the full cophasing of a segmented surface with a mounting and robust algorithm much simpler than the traditional use of the Shack-Hartman at the edges.

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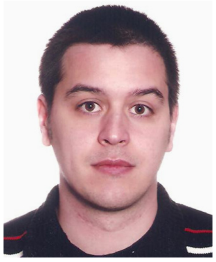

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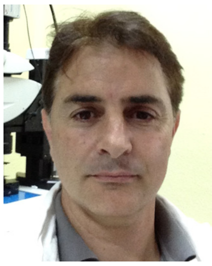

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