A versatile wavefront simulator

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ABSTRACT

A new concept for a device able to simulate evolving athmospherically distorted wavefronts for the Adaptive Optics system of the Italian facility Telescopio Nazionale Galileo (TNG) is presented.
The goodness of performances of an Adaptive Optics system depends upon the testing accuracy of its components made under different seeing conditions. Moreover, in order to do not loose good seeing nigths, the possibility to perform tests during day-light can become strongly important. Introducing a simulator able to generate the image of an astronomical object deformated by atmosphere can help to solve many of such problems.
In order to create the wanted distortion we use Phase Changing Plate (PCP) screens. A system of moving screens and adjustable zooms provides to change, over a wide range, some fundamental parameters of the atmosphere turbulence like Fried parameter r_0, *Greenwood frequency* f_G *and the isoplanatic angle* θ_0.

Keywords: adaptive optics, atmospherical turbulence, atmospherical simulation, holography.

1. INTRODUCTION

An Adaptive Optics (AO) module is an extremely complex system that, because of the great number and different nature of its sub-components, requires several adjustements, calibrations, upgrades and maintenances during its operational life.

Both hardware and software need to be continously tested in order to understand incoming problems, system limits or simply to prepare the telescope to be fully operating in case of very good seeing nights. It is obvious that such operations should not be performed during night time that is mostly used for astronomical observations.
In this framework a device that is able to simulate a wavefront deformated by atmospherical turbulence becomes an essential part of an AO module although only true atmosphere can provide the final benchmark. The complexity of a wavefront simulator depends upon parameters like the correction accuracy required or flexibility of the system to different atmospherical turbulence conditions; the possibilty to control the wavefront generation tuning fundamental parameters of the atmosphere like r_0, f_G and θ_0 becomes strongly important.
Several systems for wavefront simulation have been proposed and realized using different techniques such as LCD wavefront correctors, turbulence generator based in gases or liquids[1], Computer Generated Holograms[2] or Phase Changing Plates[3]. Some techniques have drawbacks: LCDs are in strong developement but their time response is still too slow (up to few tens of Hertz); generating turbulence in gases or liquid can cause an ambient degradation around the telescope corrupting the usually very tight thermal requirements.
Computer Generated Holograms (CGH) and Phase Changing Plates (PCP) seem to be quite close to wavefront simulation pourposes and in this paper we present a project for an optical device based on PCPs in wich fundamental atmospherical parameters should be easily changed in order to cover a wide range of seeing conditions.

2. OPTICAL CONFIGURATION

In order to cause distortion in a plane wavefront we use particular refractive elements, PCPs: they are transparent plates with variable thickness following, for our pourposes, a pattern generated using a bidimensional Kolmogorov spectrum. A phase retardation $\Delta\varphi$ of the wavefront occurs where the plate is thicker and, for a thickness difference d, it is equal to:

$$\Delta\varphi = \frac{2\pi}{\lambda}\left(\frac{n_2}{n_1} - 1\right) d$$

where λ is the wavelenght of incident radiation, n_2 the refractive index of the retarding medium and n_1 that of the air.
The optical design of the wavefront simulator must follow some constraints due to the telescope configuration and atmospherical considerations. Many authors[4,5,6] believe that a quite good atmosphere model can be simulated with a limited number of layers having proper r_0, altitude and wind velocity. In our case we use two layers, one for the ground contribution and one for high altitude turbulence.
When we simulate a star–field affected by atmospherical turbulence its scale must be the same of the TNG Nasmyth focus ($180\mu\text{m}/''$ being a $D = 3.5\text{m}$, $F/11$ telescope), and the beam exiting from the simulator must preserve this focal ratio.
The optical arrangement is shown in Fig. 1. The star–field is created projecting a collimated light beam onto a dark screen drilled in correspendence of the stars (holes diameter is about $10\mu\text{m}$).
A zoom objective, set to a focal ratio equal to the telescope's one, provides to collimate light coming from the simulated star–field; a re–imaging system *extracts* the pupil plane from the zoom optical train in order to project the pupil onto the first PCP simulating the ground layer. The PCP is wheel shaped and can rotate around an axis perpendicular to the plate itself obtaining a time–evolving wavefront.
After the first PCP and along the collimated beam another PCP wheel is placed giving the high altitude layer. Finally a second zoom objective with the same focal lenght and focal ratio provides a 1:1 re–imaging of the star–field that gets into the AO module. Obviously one can increase the number of PCP wheels making more realistic the simulation but taking into account relative contributions of each layer.
This system configuration, as said before, allows to change most fundamental parameters of atmospherical turbulence. Changing the collimated beam section produces a variation of D/r_0 ratio and it can be easily made through changing simultaneously the focal lenght of two zooms (but retaining a constant focal ratio). The Greenwood

frequency f_G strictly depends on the PCP speed rotation and the isoplanatic angle θ_0 is related to the distance between wheels: while for the first wheel the wavefront modifications are identical in the whole star field, for the second wheel, because it is located far away from the pupil position, the deformations become field-dependent. The major drawback of such kind of simulators is the wavefront repetition. The real atmosphere has a stochastic behaviour and each wavefront realization is totally indipendent by the previouses or by the followings.

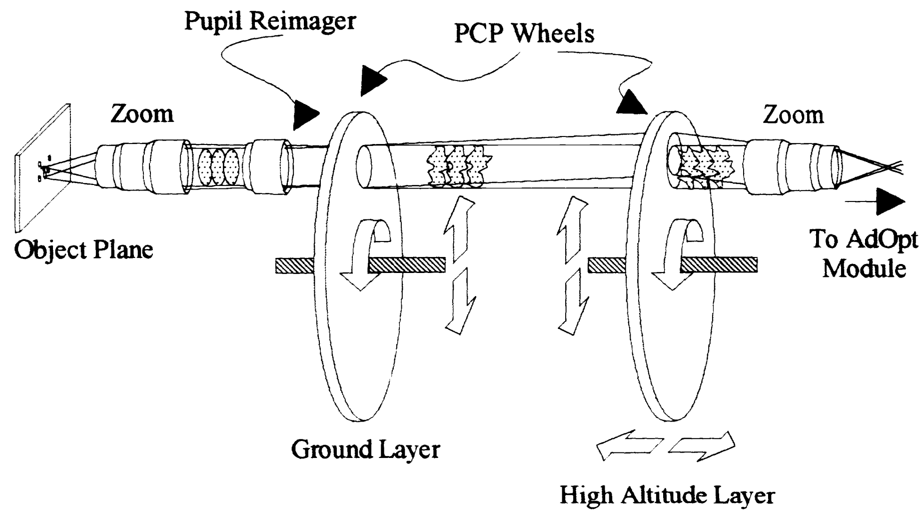

Figure 1: Optical layout of the wavefront simulator.

After a complete rotation of a PCP wheel the deformation induced returns to be the same and this situations is very far from the reality. The periodic repetition affects the time spectral behaviour of the system giving spurious components in the spectrum located at the spinning wheel frequency and its multiples (see Fig. 2 Right). In order to reject this effect we proposed the non-recursive path solution[3]: it consists to apply a linear oscillating motion to the wheels axes so the portion of PCP interested by collimated beam does not coincide to itself after each complete rotation as shown in Fig. 2 Left. One must take care to choose oscillation frequency other than integers of the spinning frequency; in this way most of spurious frequency components are suppressed or at least strongly reduced (see Fig. 2 Right).

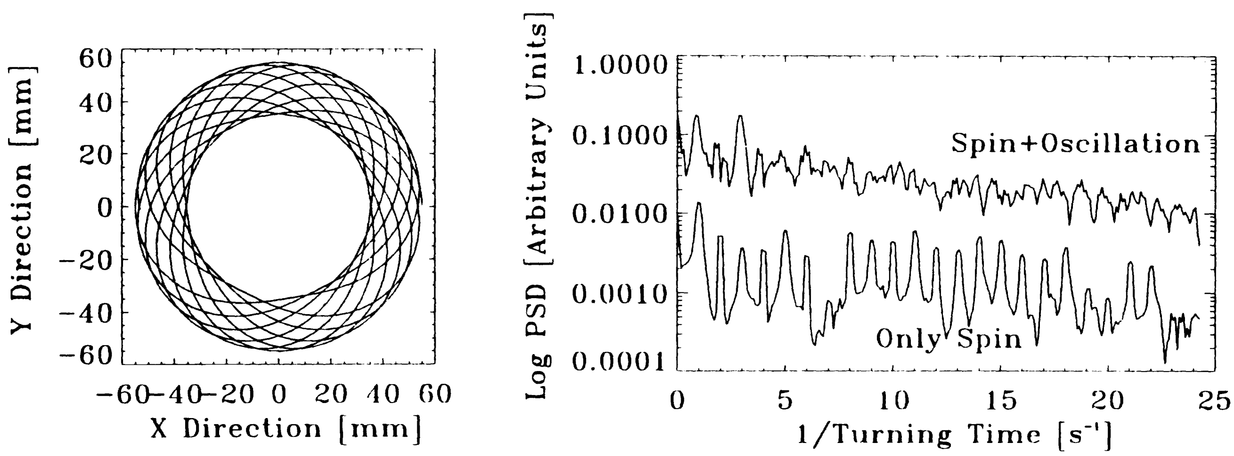

Figure 2: **Left)**: tipical non-recursive path projected on a PCP wheel. In this case the beam is about 10mm diameter located 40mm apart from the center of rotation and the ratio between oscillating and rotating frequencies is equal to $\approx$ 1.82. **Right)**: spectrum of a time-evolving wavefront generated through a PCP whell. After introducing a supplementary oscillation most of spurious frequencies are suppressed.

3. MAKING PHASE CHANGING PLATES

The PCP fabrication comes from techniques used in the generation of Holographic Optical Elements (HOE) or Diffractive Optics[7]. Currently the most followed ways are microlithography, a technology adopted from integrated electronic circuits manufacturing, and holography[8].
A tipical material used in HOE fabrication is photoresist[9]: a light–sensitive organic compound which forms imaged relief pattern upon exposure and developement[10,11]. Photoresist is deployed on optical flat surface and then exposed to light: if it is of negative type visible radiation acts on it and exposed areas become insoluble so that upon developement only unexposed (soluble areas) are dissolved away, while in positive type the opposite is true and deepness of relief is proportional to the amount of the light received. Several photoresist techniques has been experienced in order to obtain good results in HOE fabrication[12,13].
Another method, called *bleaching*, to obtain surface relief comes from techniques for production of phase holograms in Silver Halide materials[14]. In silver halide photographic emulsion areas exposed to light occurs a separation of salt compounds in Ag^- and Br^+ (see Fig. 3); when the emulsion is developed Ag^- ion reduces in metallic Ag and dark silver grains take place inside gelatin.

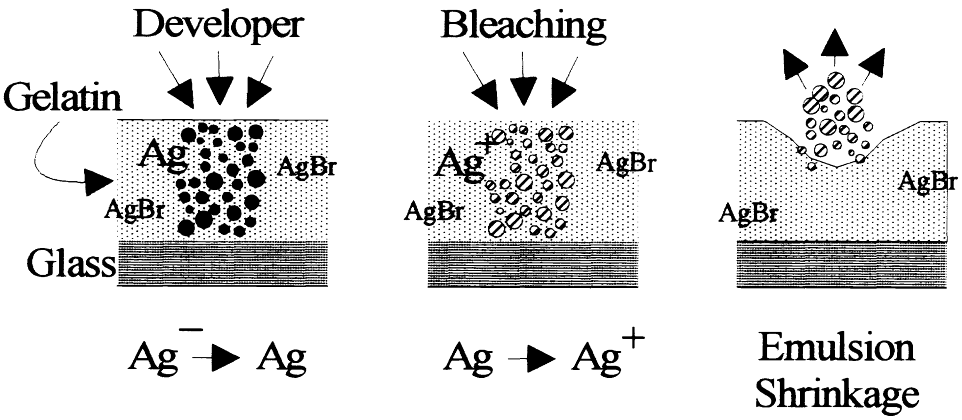

Figure 3: Solvent bleaching process: the bleach bath oxidizes metallic silver that passes in solution giving a volume decreasing in gelatin emulsion. The effect is proportional to developed silver.

The introduction of developed gelatin into an oxidizing bleaching bath (a weak acid solution of water and an oxidizing salt, like ammonium dichromate or potassium dichromate) transform metallic silver into Ag^+, which passes into solution decreasing gelatin volume af an amount proportional to the oxidized (exposed) silver. As the *solvent* bleaching process ends, the emulsion substrate results thinner in the exposed areas and thicker where AgBr persists. If the gelatin is fixed the remaining silver halide is washed out and surface relief disappears.
This technique is not the only involving bleaching procedures. In *rehalogenating* bleaching[15,16,17] the salt solution reacts with metallic silver transforming it in a dielectric compound with different index of refraction. No relevant surface relief is produced and phase changing is due only to refractive index modulation inside photographic emulsion. Surface relief can also be obtained using tanning properties of developers or of the bleaching baths[18,19,20,21].
In order to realize PCPs it is required to implement solvent bleaching process on silver halide coated plates. At the very first step we have used Agfa–Gevaert AVIPHOT PAN 100 plates which presents panchromatic sensibility and low resolving power ($\approx$ 100 lines/mm) developed in Kodak D–19 (5 min at 20°C). After exposure and development, the plate must be rinsed for about 2 minutes and then bleached for 1 minute after silver grains are completely disappeared, in a solution of composition (for $\approx$ 1 liter):

water	$700cm^3$
potassium dichromate	50g
add water to	$950cm^3$
Add, slowly, stirring constantly:	
sulfuric acid, concentrated	$70cm^3$

After bleaching bath another rinsing is needed for about 5 minutes, in order to stop bleach action and to partially remove yellow coloration due to potassium dichromate, and, finally, the plate is dryed (at least 30 minutes). The aspect of bleached plate could appear slightly opaque because it has not been fixed but loss light or scattering effects are negligible; one can clear the plate using a solution of sodium sulfite and sodium hydroxide[22].

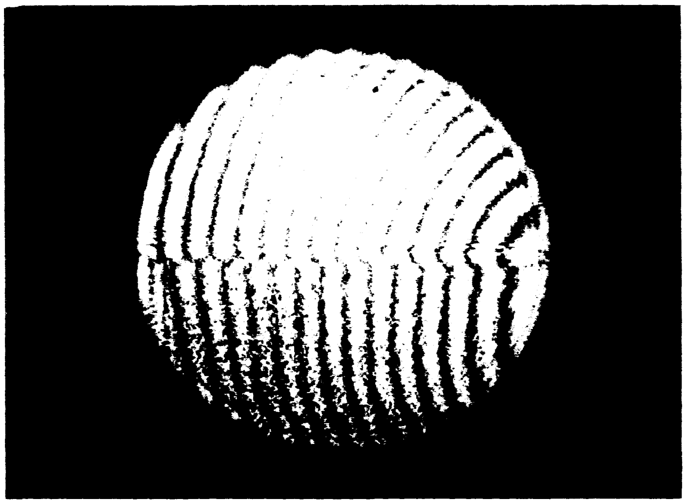

Figure 4: Interferogram of PCP: bleaching procedure causes gelatin shrinkage and a relative phase delay.

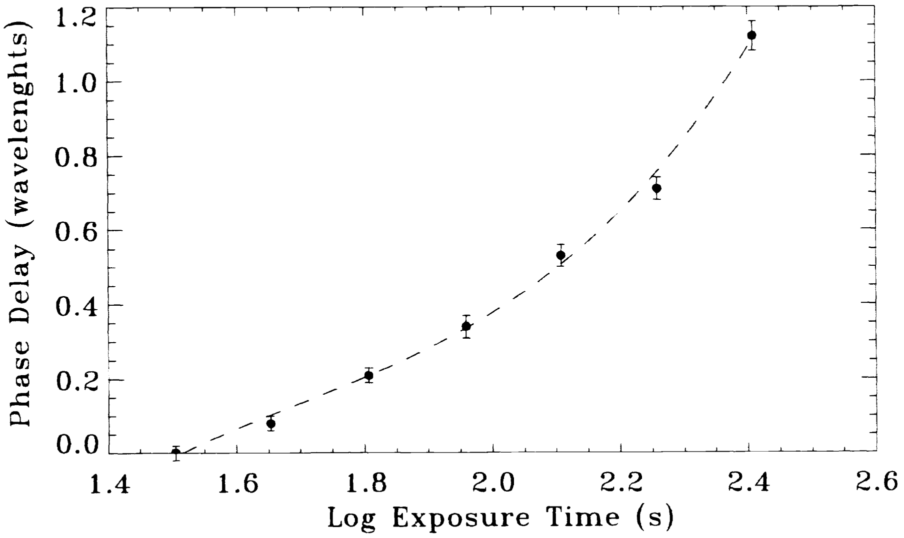

Figure 5: Calibration curve for phase delay vs. logarithm of exposure time; the curve is obtained with an arbitrary zero–point illumination.

We performed several tests exposing a plate at different light quantities (an example is in Fig. 4) and measuring the phase shift with a Michelson inteferometer in order to reconstruct phase delay vs. exposure time curve; an experimental result is shown in Fig. 5. The relation between surface depth and the logarithm of exposure time is not linear probably because it is necessary a fine tuning between the different phases of bleaching process.
The following step is the production of a surface relief that modifies a wavefront with a phase spectrum close to a Kolmogorovian one. After it has been generated via computer such a shaped wavefront phase map, a wrapping in values between 0 and 2π and discretized in 8 equally-spaced steps is performed as shown in Fig. 6.

Eight binary masks must be produced, each associated to one step, completely opaque in the areas where step value are equal or inferior to it and totally transparent in the rest. Each mask is projected on the photographic plate for the time necessary to obtain the wanted phase delay associated to that phase step; finally surface relief is produced after developing and bleaching processes.

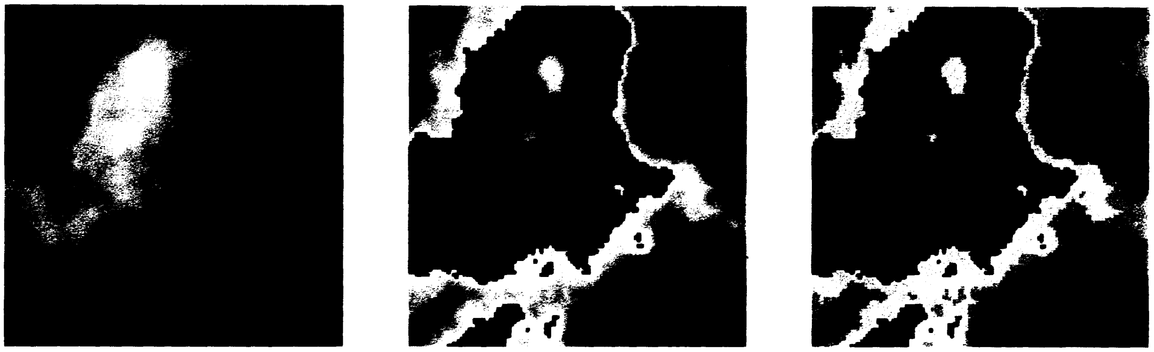

Figure 6: Example of an atmopherical phase screen (left), wrapped (center) and discretized in 8 phase levels (right). More accuracy could be obtained if the number of discretization levels is increased.

4. CONCLUSIONS

We have shown that a device able to simulate an atmospherically deformated wavefront evolving in time in which some fundamental turbulence parameters can be changed is feasible. Use of PCPs makes more simple the optical project of simulator and a such similar system will be permanently mounted in the Telescopio Nazionale Galileo AO module. We have also shown how PCPs fabrication could be even performed via bleaching technique, not too expensive and easy to implement, with encouraging results. Work is still in progress.

5. ACKNOWLEDGMENTS

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