Shack-Hartmann wavefront sensor and its problems

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To correct for the phase aberrations an adaptive optical system is usually used. The standard adaptive optical system consists of a wavefront corrector, an electronic control unit, some sensor to analyse the beam phase, and the software to determine the control voltages to be applied to the corrector (Fig. 1).
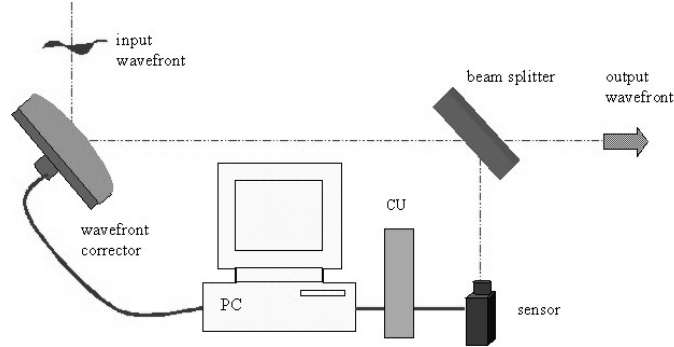

Fig. 1. Principle scheme of Adaptive Optical System

As a wavefront corrector we use bimorph deformable mirror [1, 2]; this type of corrector allows to compensate for the low-order laser beam aberrations. To control for the mirror we usually use phase conjugate algorithm and Shack-Hartmann wavefront sensor [3] to measure the wavefront aberrations. But we found out that sometimes the result of correction is not ideal and we can improve it manually.

The principle of Shack-Hartmann wavefront sensor is based on determination of local slopes ΔS of a distorted wavefront relative to the reference flat wavefront [3]. Laser beam is divided into a number of beamlets by a two-dimensional sub-apertures of the lenslet array. Each subaperture provides a separate focus on the detector. The position of each spot is displaced by local wavefront aberrations. The local slope of the wavefront on each subaperture of the lenslet array is proportional to the displacement of the focal spot center ΔS.

The idea of closed-loop is to minimize the displacement of real focal spots from the reference ones (Fig.); merit function could be represented as $\Phi = \min\left\{ \sum_i \Delta S^2 \right\}$, i – number of lenslet subapertures.

As a first step of correction response functions **b** should be measured. They are represented in terms of displacement of the focal spots $b_{j\,x}^{\;i} = \Delta x_i / u_{0\,j}$ and $b_{j\,y}^{\;i} = \Delta y_i / u_{0\,j}$; here $u_{0\,j}$ is the unit voltage used to measure response functions, j = number of electrode.

Then the displacements of the focal spots for the wavefront to be corrected are measured and following equation is written: $S_i = \begin{vmatrix} \Delta x_i \\ \Delta y_i \end{vmatrix} = \sum_{j=1}^{N} u_j \cdot b_j^i$; here **u** is an array of voltages.

As a last step the voltages to be applied to minimize the displacements are calculated using least square method:

$$\min\left\| \vec{S} - b \cdot \vec{u} \right\|^2, \; u = \|B\| \bullet S, \; B = (b^T b)^{-1} b^T .$$
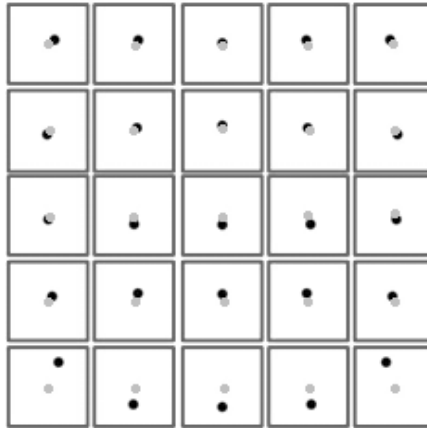
Fig. 2. View of Hartmann image with reference (grey) and real (black) spots

The problem of displacements minimization is that the minimal $\Phi = \min\left\{\sum_i \Delta S^2\right\}$ does not always correspond to the best wavefront. One of the reasons is the following: different combination of displacements can lead to equal value of Φ but different wavefront amplitude. Four examples of such behavior are shown on Fig. 3; merit function Φ is the same for all four linear cases on right picture – displacement of all spots is equal, the only directions of movement differ. P-V for case #1 is 12 while for case #4 P-V=1. So from the point of view of minimization algorithm all four examples are equal to each other while the reconstructed wavefronts have different P-V.
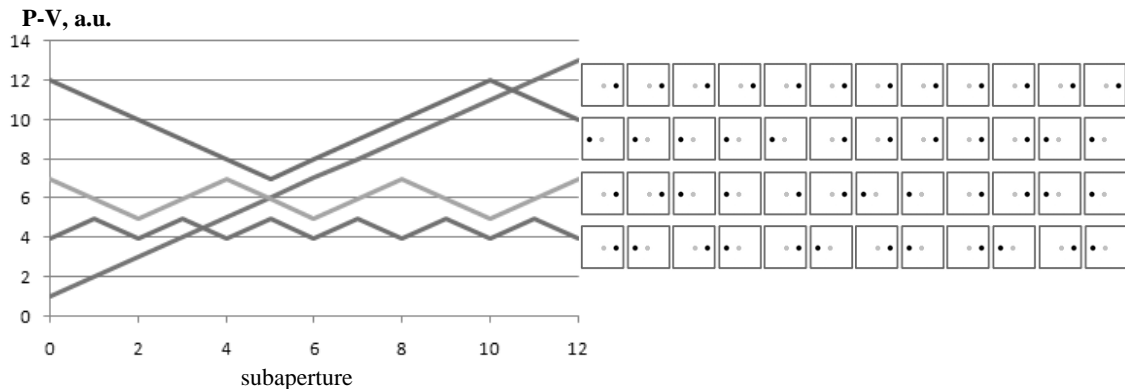

Fig. 3. Examples of focal spot shifts

This problem we face when we start using Shack-Hartmann wavefront sensor in a closed loop adaptive optical system. The standard algorithm is organised in such a way that it minimizes merit function Φ and as we showed before this function does not means the minimum of phase distortion. And adaptive system thus does not perfectly correct for the income aberrations of the wavefront.

References

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