# Analysis of Hartmann testing techniques for large-sized optics

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The quality control of large-sized astronomical optics frequently is produced by a Hartmann technique. For check of accuracy and efficiency of the various schemes of this method it is nesessary to create the mathematical model. In paper the results of microlens array based sensor simulation and comparison of it with other modifications of the testing schemes are presented.

**Keywords:** Shack–Hartmann , Zernike, optical surface testing, high diameter telescopes, microlens array.

## 1. INTRODUCTION

For quality control of large-sized optics Hartmann techniqueis are widely used. Accuracy and efficiency of the various schemes of this method gives various outcomes.

The classical scheme of Hartmann technique assumes use full-sized Hartmann mask for quality control of optics [1]. This testing technique is hampered because of complexity of installation and preliminary adjustment of the mask of such diameter.

During manufacturing and adjustment of the telescope Big Telescope Alt-Asimuthal (BTA) in Russia for quality surveillance of a reflecting surface of a main mirror was used specially developed technique, based on principles of a classical of a Hartmann technique, but with application of computer processing of results and with reception of the more complete information about errors of a mirror, which were represented by decomposition on Zernike polynomials. Besides for the control of mirrors on a telescope there was applications the specially developed circuit with so-called small-sized Hartmann mask, not requiring at the control of manufacturing and installation full-sized big mask. For telescope BTA online testing was used developed in IFMO method distinguished from a classical Hartmann technique by application specially developed scheme with small-sized mask [2-5]. Besides it is natural, the appropriate modern computer methods of data processing were applied.

From the moment of development of this method of the requirement to accuracy and operating of the control of optics have much increased, opportunities of electronic registration and computer processing of a picture have also increased. A method, based on microlens array allows sharply to raise accuracy and efficiency of the control. Essential lacks of a method are first, the still enough large size of Hartmann mask, and secondly, necessity for division and reliable recognition of spots on the hartmanogram of introduction significant defocisind of a the receiver and, as a consequence of application of a CCD receiver of the non-standardly large size or use block of several matrixes, (no less than four), that is extremely inconvenient.

For elimination of these lacks expediently to use the newest updating of a Hartmann technique (so-called Shack-Hartmann), based on use microlens array. Thus necessity in any Hartmann mask is eliminated in general, raises information density of a method at the expense of increase of quantity of trial points and, that for us most essential, opportunity of use CCD receiver of any standard size is provided. In turn, the application of this method requires precision array of microlenses both development and manufacturing special rather exact objective lenses. In the given work an investigation phase of the alternate circuit of the control on a method Shack-Hartmann on a basis array of microlenses, excluding application stop of Hartmann is submitted. Designing, modeling and optimization of the optical circuit of a method is spent, requirements to elements of the circuit are determined, mathematical apparatus and general algorithm of processing of results of the given circuit is developed.

The microlens array based technique gives higher accuracy and efficiency of a control. Therefore it would be expedient to use the newest modification of the Hartmann technique (Shack-Hartmann technique). Thus the necessity in any Hartmann mask is eliminated, the selfdescriptiveness of a method is increased by mounting of the amount of sampling points and the possibility of use CCD of any standard size is ensured.

## 2. ASTRONOMICAL OPTICS TESTING BY THE SHACK-HARTMANN TECHNIQUE

On a case history (Fig. 1) a schematic diagram of Hartmann sensor operation is shown. This scheme demonstrates layout of the sensor of a rather main mirror. As it is visible, it is located with the receiving platform directly in the primary focal plane, and in the field of sight of the sensor the single star is output.

### 2.1. Schematic of the hartmann sensor microlens array based

On the principal optical scheme of the sensor(Fig. 2) is clear, that in a primary focal plane FP where is located the aberrated image of a single star, placed the collective lens C. This lens, being located in image plane, practically does not influence an aberration of a primary mirror and, therefore, on results of measurements. Objective O will transform rays, incident on it from the image of a star in a parallel beam. Filter F limits the radiation spectral interval to not present the superrigid requirements to objective. The raster of microlenses divides incident onto it beam on set of the subapertures according to amount of microlenses in the raster and will transform it to converging beams, each of which forms the image of a star on CCD.

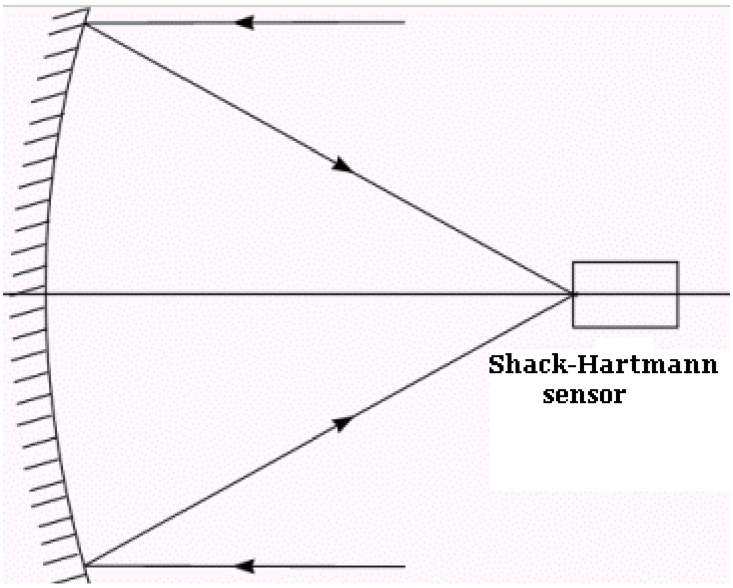



Fig. 1. The Shack-Hartmann technique scheme of main mirror testing.

Thus, if the surface of a mirror is ideal, the image of a star in a primary focal point in approximation of geometrical optics represents a point, placed in the objective O front focal plane. If, in turn, objective O does not bring in aberrations, on the raster of microlenses the parallel pencil of rays falls ideally and the grid of the images of a star on CCD precisely repeats a grid of the microlens array. Thus, on CCD we also shall receive a regular grid of spots.

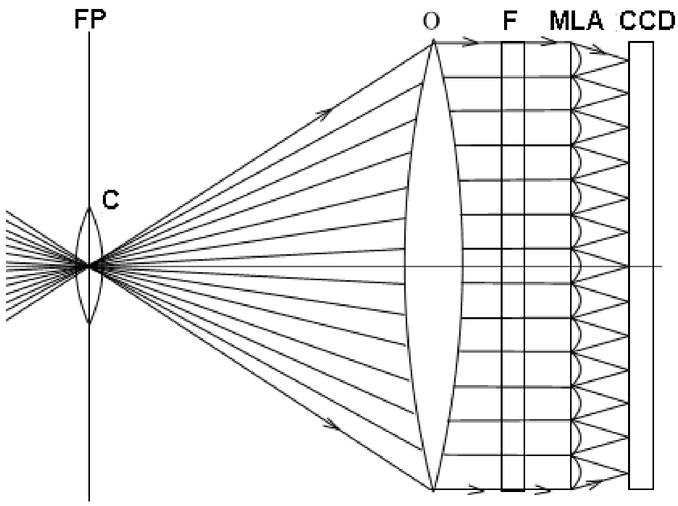



Fig. 2. The principal optical scheme of the sensor.

The ray trace in Hartmann sensor through one microlens in case of availability of main mirror deformations is shown in a Fig. 3.

Let part of mirror optically conjugated with microlens of the raster, has deformation expressed by perpendicular deviation on some corner, and reflected ray will deviate twice, that will cause transverse aberration in a primary focal plane:

$\Delta y' = 2\alpha \cdot f$ , where $f$ - mirror focal length. (1)

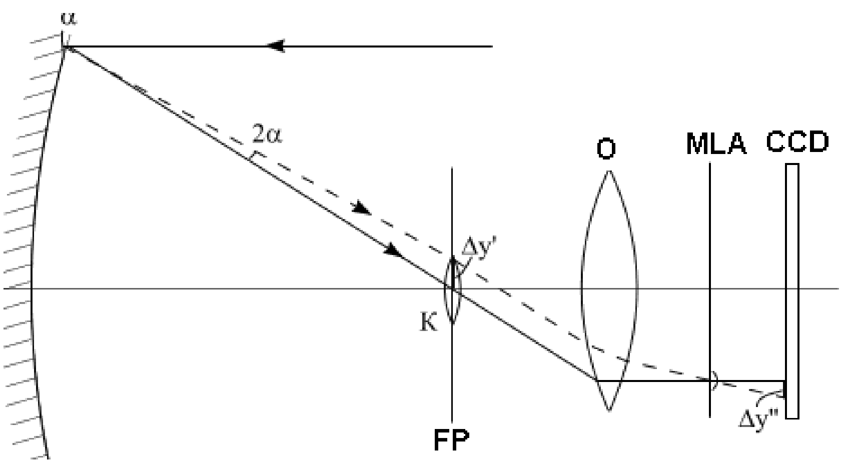



Fig. 3. Ray tracing through the scheme

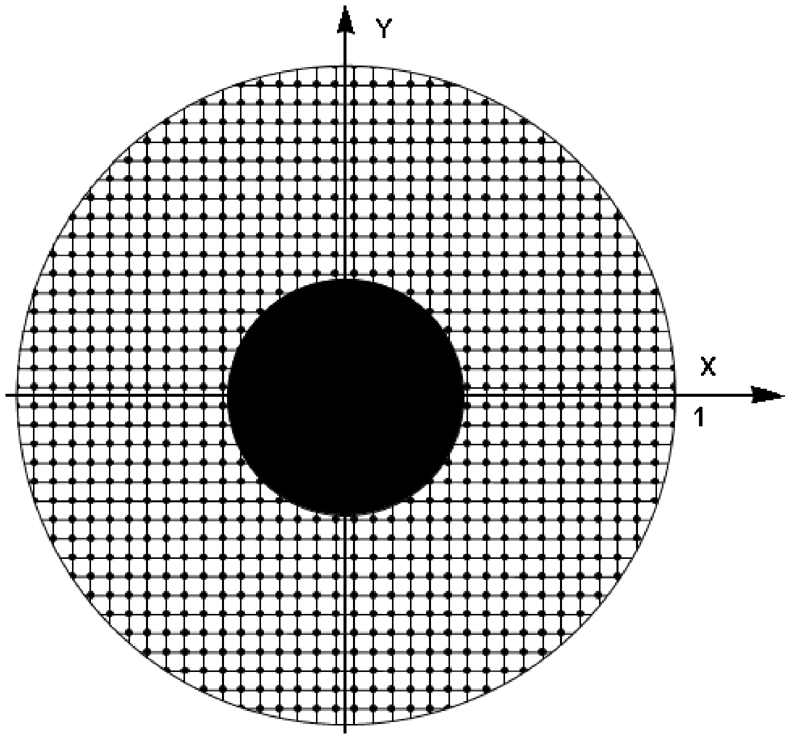



Fig. 4. Layout of sampling points on the mirror surface.

The ray further will pass through the objective O and microlens the raster, then aberrated ray will cross a plane of CCD in the point, deviating from the ideal position on the value:

$$\Delta y'' = -\Delta y' \cdot \frac{f_{ml}}{f_o} , \qquad (2)$$

Where the ratio of focal lengths of microlenses and objective $\frac{f_{ml}}{f_o}$ - constant value for the given sensor participates.

As a result we have values of deviations in set of the regularly located points on a surface of a mirror, and the grid of sampling points on a surface of a mirror remains regular and the position of these points does not depend on deformations of the mirror. Fig. 4. shows the layout of sampling points on the mirror surface with selected configuration of the raster.

It is easy to see, that we have a rather dense and regular grid of sampling points on a mirror, that allows to receive information about significant more fine surface deformations, than in a classical scheme.

## 3. ELEMENTS OF THE SCHEME

Objective for the given scheme should be a high NA apochromat lens. The collective for Hartmann sensor can be executed as flat convex lens from the glass K8. The accounts show, that the distortion does not exceed 6 mm, on the mirror surface that is 0.2 %, that is quite acceptable.

The choice of the microlens array. It is a purchase item. For a right construction of a stage of simulation in the Adaptive Optics Assoc corporation catalogue the raster with step 500 microns, focal length of 10.4 mm, dimensionality 36x36 microlenses, with working square 18x18 mm was selected. The raster forms practically nonaberrational images of a star on the receiving platform CCD matrix.

The choice of a the lenslet array can be made on the basis of modeling results of the control, therefore concrete data have no importance.

For the receiver we were oriented on used on BTA matrix ( VPCCD ISD017A), have the format 1040x1160 of pixels on 16 on 16 microns, size of a photosensitive zone 16.6x18.6 mm. That with is overlapped by working square of a matrix of microlenses practically lost-free of information.

## 4. SIMULATION OF THE HARTMANN SENSORS OF VARIOUS SCHEMATIC

Advantages of a method with microlens array are: higher selfdescriptiveness, possibility of application standard CCD matrixes, simplifications of data processing algorithms.

Table 1. Comparison of the data processing stages in the various Hartmann testing schemes

| Data processing stages of the Hartmann sensor | The scheme with small-sized mask in a converging beam | The scheme with microlens array |
|---|---|---|
| 1. Location of the ideal spot centers | Location of the sample points on the mirror and ideal spot centers locations definition | - |
| 2. The hartmanogramm processing | | |
| 2.1. The spot identification | Scanning for spots detection and separation | - |
| 2.2. Location of the real spot centers | Definition of a barycentre and approximating for obtaining coordinates of spot center | |
| 3. Obtaining of wavefront deviations | Obtaining coefficients of wavefront decomposition on Zernike polynomials | |

### 4.1. The hartmanogramm measurement

The measurement of deviations of an actual position of spots on the CCD matrix from layout appropriate to a grid of the raster of microlenses is produced

**Definition of the spot centers on the hartmanogramm**

We are oriented on used on BTA matrix (VPCCD ISD017A), format 1040x1160 of pixels on 16 on 16 microns, size of a photosensitive zone 16.6x18.6 mm. The separated part of the image of a hartmanogramm spot takes on CCD area 30x30 pixels.

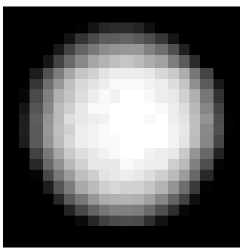
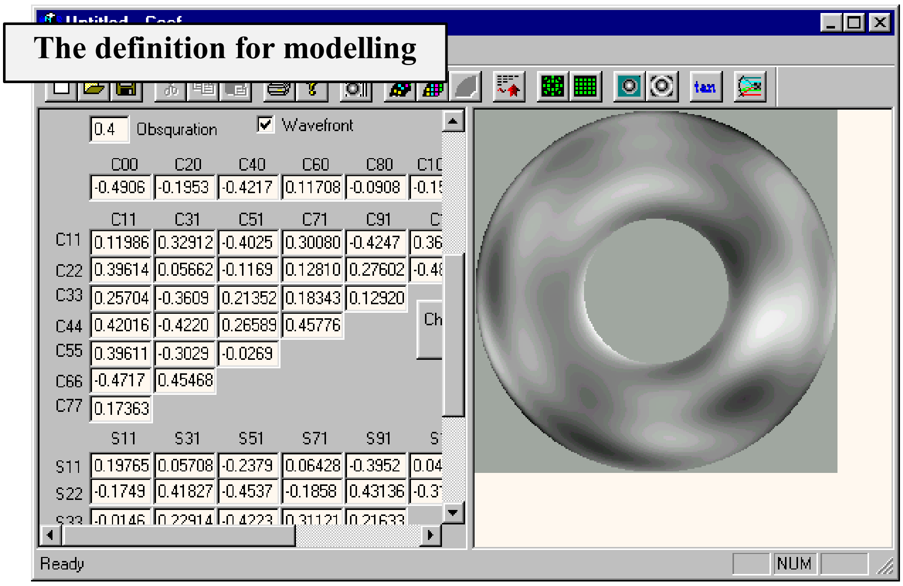


Fig. 5. The area selected on hartmanogramm

At First is defined approximate value of spot centers coordinates as barycentres (average geometrical) area selected on hartmanogramm. Then for reaching required accuracy the sample of intensity on separated area is approximated with the help of least squares method, and then the coordinates of the spot center are determined. The position of center is minimum difference from hartmanogramm is fixed.

Simplification is the absence identification of spots - each stain is located always within the limits of the zone appropriate to the size of a microlens. The application of an iterative improvement during scanning allows to ensure accuracy of measurement 0.1 pixels, that is about 1.5 microns.



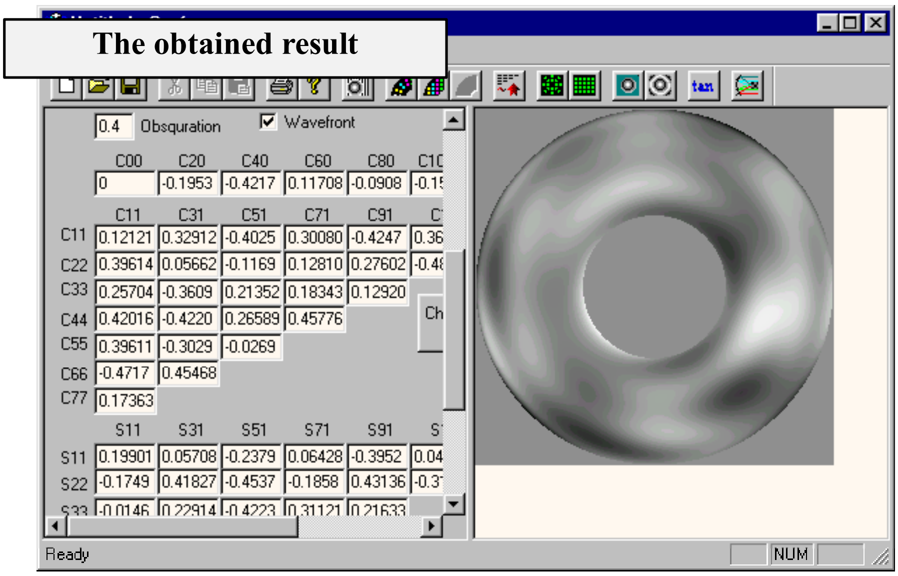




Fig. 6. Windows for the definition of task and results of wavefront deformation restoring

### 4.2. Mirror surface deformation restoring

The stage of inspected surface deformation restoring is constructed on approximation by Zernike polynomials up to 13 order. This process is identical to restoring of deformation in the scheme with small-sized mask [2], and includes stages:

1. Construction of the decomposition basis

2. Approximating transverse aberrations by Zernike polynomials. The stage of obtaining of coefficients of decomposition includes least-square technique with an orthogonalization procedure by the Gram-Shmidt method.

The simplification of algorithm is achieved due to a fixed grid of points on a mirror, that makes possible preparation of a matrix of polynomials beforehand. The rise of accuracy is reached at the expense of possibility significant increase an amount of sampling points and their more often layout on a mirror.

The information on execution time of operations by the software package are represented in Table 2.

Table 2 . Execution time of separate operations by the software package.

| Title of the stage | Execution time, s |
|---|---|
| 1. Definition of the spot centers on the hartmanogramm | 31 |
| 2. Definition of wavefront deformation | 0,8 |
| 2.1. Creation of base of decomposition | 0,1 |
| 2.2. Least-squares technique (with orthogonalization) | 0,7 |
| 2.2.1. The Gram-Shmidt orthogonalization | 0,5 |
| 2.2.2. Least-squares technique | 0,2 |
| 3. Creation of wavefront sample (with creation of base) | 3,2 |

## 5. CONCLUSIONS

Thus, the use of the raster system, allows to refuse from Hartmann mask. Advantages of this method are it higher selfdescriptiveness, possibility of application standard CCD matrixes, more simple algorithms of data processing using of.

The matching of stages of data processing in the various schemes of the optics testing by the Hartmann technique shows, that significant advantage has the Shack-Hartmann scheme. The identification of spots stage absence and application of an iterative improvement allow us to achieve necessary accuracy. Due to a fixed grid of points on a mirror, it is possible to prepare the polynomials matrix beforehand. The rise of accuracy is achieved by the possibility of useful increase of sampling points amount and their more often layout on the mirror.

The use of the Shack-Hartmann scheme in the considered modification significant simplify and speed up the process of large-sized astronomical optics testing.

## REFERENCES

1. Optical shop testing / edited by Daniel Malacara. - A Wiley – Interscience Publication, John Wiley & Sons, Inc, 1992, 773 pp.
2. Tolstoba N.D. Gram-schmidt technique for aberration analysis in telescope mirror testing, - Proc. SPIE Vol. 3785, 1999, p. 140-151, Advanced Telescope Design, Fabrication and Control
3. Zverev V.A., Rodionov S.A., Sokolsky M.N., Usoskin V.V. The BTA main mirror testing in observatory conditions, - Soviet Journal of Optical Technology, 1977, № 4.
4. Zverev V.A., Rodionov S.A., Sokolsky M.N., Usoskin V.V. Mathematical bases of the BTA main mirror Hartmann test, - Soviet Journal of Optical Technology, 1977, № 2.
5. Zverev V.A., Rodionov S.A., Sokolsky M.N., Usoskin V.V. Technological control of by Hartmann technique, - Soviet Journal of Optical Technology, 1977, № 3.