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Carl Zeiss Jena GmbH
NRIAG Helwan/ Cairo

74" optics Kottamia

CZJ/Kott-Contract AG 13 95702

Kottepla/czj

Test Plan

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1 Scope

The scope of the test is to check the optical quality of the newly manufactured primary mirror for the Kottamia observatory of the National Research Institute of Astronomy and Geophysics (NRIAG).
The main task of the test is to verify, that the design specifications are met.

2 Applicable documents

- CALL OF AN INTERNATIONAL TENDER FOR THE SUPPLY OF THE BLANK OF THE PRIMARY MIRROR FOR ITS OPTICAL FIGURING AND COATING

  November 1993

- The Supply Of The Blank Of The Primary Mirror
  Its Optical Figuring, Polishing And Coating
  Technical proposal

  Carl Zeiss Jena GmbH
  January 94

- The Supply Of The Blank Of The Primary Mirror
  Its Optical Figuring, Polishing And Coating
  Commercial and Administrative Section

  Carl Zeiss Jena GmbH
  January 94

- Contract No. 7 Year 1994
  Supply and Installation of the Main mirror and Subsidiary mirror for the Kottamia Astronomical Observatory

3 Generally
The test results will be included in a test report.

The test procedures can be optimised by variants, which have the same or better accuracy and objectivity. These need an agreement of the two parties of the contract.

4 Tests:

4.1 Test of the mirror blank

4.1.1 Test definition

The blank will be supplied with a test certificate according to the conditions of the tender. The acceptance test for the blank consist of a visual check of the blank, especially of the surface to be used for grinding and polishing.

4.1.2 Test criteria:

<u>Blank specification</u>

Documentation
- according to drawing 161499:003.07 (3)

Geometrical dimensions (mm):
- diameter $\qquad$ 1930 ±2
- diameter of center hole $\qquad$ 188 $\quad+1$
- diameter of concave surface profile $\qquad$ 1910 ±2
- thickness at the outer edge $\qquad$ 230 $\quad+0.5$
- flatness (plan side) $\qquad$ ≤ 0.1
- concave radius $\qquad$ 18300
- Profile of concave surface $\qquad$ ≤ 2.5
- Chamfers at outer edge $\qquad$ 7 $\pm1/45°$
- Chamfers at center hole (concave side) $\qquad$ 8 $\pm1/45°$
- Chamfers at outer edge (plan side) $\qquad$ 5 $\pm1/45°$

-

Internal quality:
- Inclusions in the uncritical volume

- projected area of all inclusions in mm²
  per volume of 100mm³ $\qquad$ ≤ 2

- maximum diameter of individual inclusions
  in mm $\qquad$ ≤ 5

- average number of inclusions
  per 100 cm³ $\qquad$ ≤ 5.0

- Inclusions in the critical volume
- maximum diameter of individual inclusions $\qquad$ ≤ 2.0

- average number of inclusions
  per 100 cm³ $\qquad$ ≤ 4.0

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The critical volume is a material zone, which has its extension from the front side up to 30mm deepness.

Bulk stress compressive ≤ 10nm/cm

Surface quality
- Front side   Diamond polishing (D 76)
- Back side   Diamond polishing (D 107)
- Edge/ phases   Diamond polishing (D 64)

Material properties
- Density p 2.46 g/cm³
- Young's modulus of elasticity E 90.3 Gpa at T=20°C
-

Thermal properties

- Thermal length expansion α (0...50°C)

- Average thermal expansion coefficient
  $(10^{-06} K^{-1})$ 0 ± 0.10

- Homogeneity of thermal
  expansion coefficient$(10^{-06} K^{-1})$ ≤ 0.01

- Specific thermal conductivity   0.80 $Jg^{-1} K^{-1}$ at T=20°C
- Thermal conductivity   1.46 Wm^{-1} at T=20°C

General characteristics
Marking

Melting number, cooling number and 0°-marking with water-insoluble pen on the outer edge

4.2 Test at the completion of blank polishing

4.2.1 Test definition

In order to control the polishing process and in order to verify the optical quality of the KOTTAMIA primary we will use an interferometer procedure. The result is of this process is the wavefront error due to the mirror shape. The calculation of the encircled energy will be based on the measured wavefront. The interferometer and the subsequent calculation of the encircled energy are very precise.

In order to evaluate the focal length the E-value will be measured. (The E-value is the distance between the vertex of the primary and the vertex of the null corrector lens).

4.2.2 Test equipment

For interferometrical testing of the KOTTAMIA primary a vibration isolated optical table is situated close to the center of curvature at a height of about 16m above the mirror. At the table the complete interferometrical set-up of Twyman-Green type is mounted and adjusted. A HeNetype laser is applied as the light source. The measuring wavelength will be 633 nm. The used CCD-camera is connected to the host computer, where phase evaluation is performed.

For the alignment of the interferometrical setup with respect to the mirror the optical table and one folding mirror is adjustable.

4.2.2.1 Null Corrector

A Null corrector (designed for the Kottamia primary) producing a parabolic wavefront is used for interferometrical testing, because the primary under test is the autocollimation mirror and the shape of the primary is of aspherical (parabolic) type.

4.2.2.2 Phase evaluation

For phase evaluation our DIRECT 100 (interferometer) software will be applied. The DIRECT 100 evaluates the phase map in video real time (25 times per second). For each phase calculation only one frame (interferogram) will be taken. In combination with the very short exposure time the DIRECT100 is very insensitive to vibration. On the other hand it allows to average a large number of interferograms with a rate of 25 per second in order to reduce effects of air turbulences as well as residual mathematical errors without any artificial smoothing of the wavefront. Applying the test the light paths are very long, so single frame evaluation (with short exposure time) and real time averaging is very helpful to obtain results with the required accuracy.

4.2.2.3 Description of the direct measuring interferometry with the DIRECT100

The laser interferometer Zeiss DIRECT 100 solves two main problems in precision interferometry, namely vibrations and air turbulence.

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The instrument has been designed to meet the requirements of production and quality control at Carl Zeiss. When manufacturing the outstanding 3.5 m primary mirror for the New Technology Telescope (NTT) for ESO, a major problem had to be solved: in order to reduce the production time and to increase the quality of the mirror, high accuracy interferometric measurements had to be performed in a workshop environment where vibrations and air turbulence were present. To solve this problem, Carl Zeiss has developed the entirely new concept of "Direct Measuring Interferometry" (DMI). This procedure has now become an integral part of the new laser interferometer Zeiss DIRECT 100. This high-performance instrument has been designed in such a way that it is the ideal testing tool for polished precision components of any size: from lenses for microscopes and endoscopes, camera lenses, ceramic and metal spheres, wafers, gasket rings, metal mirrors, and aspheric lenses right up to large mirrors for telescopes.

– Real-time Processing
Every 2 to 3 ms an interferogram is recorded by a 480X480 pixel CCD camera. A phase map is then computed from one single interferogram using a computer with a video pipeline processor, i.e. within a cycle time of 40 ms, new phase fringes are displayed on the monitor: (real-time processing of interferograms into phase fringes). Unlike DMI, conventional phase shift interferometry uses at least 3 subsequent interferograms for calculating a phase map. For this reason, vibrations and air turbulence must be totally eliminated to ensure that exact results are obtained during the recording of these 3 interferograms. The extremely short interferogram recording time of 2 to 3 ms offered by the Zeiss DIRECT 100 with its DMI procedure and real-time processing, however, largely avoids problems caused by vibrations. As the real-time processing method of the DIRECT 100 means that the phase fringes are also displayed on the monitor in real time, the user can immediately see whether all areas of the test piece can be evaluated. This greatly facilitates an optimum alignment of the test piece. As in phase shift interferometry, it may happen that local gradients are too high for the processing of the phase map and that a complete measurement of the test piece is impossible. In this case the user of the DIRECT 100 - because of the real-time processing - can adjust the test piece in the beam more easily in such a way that the processing procedure becomes possible. This is also important for the measurement of aspheres described below.

– Real-time averaging
The short cycle time of only 40 ms required for processing an interferogram into a phase map makes it possible to average a large number of these phase maps. This averaging process considerably improves the measurement statistics and eliminates the influence of air turbulence . Typically, 1000 phase maps are measured and averaged in less than 1 minute. Together with the averaging the unwrapping from the phase fringes to the phase map/contour map is performed.
For measurements requiring extreme accuracy, "statistical" air turbulence is deliberately created in the test piece area by subjecting the air to whirling action with a ventilator. This prevents the formation of stationary air layers which would falsify the measurement. Averaging is possible over a maximum of 65,000 phase maps (1 hour).

– Measurement of aspheres
In the testing of aspheres it has been common practice up to now to use a complex and exact null-lens system to deform the wavefront of the test wave in such a way that it strikes the aspheric test piece perpendicularly. Unlike this procedure, the interferometer DIRECT 100 makes it possible to use a transmission sphere APLANAR together with a single lens

for partial compensation and to store the residual errors of this setup in the form of an "electronic hologram". This hologram is then used to correct the results of the asphere in real time. Thus, the authentic figure deviation of the aspheric test piece from the nominal value is shown on the monitor in real time, allowing optimum positioning of the asphere in the test beam. The interferometer system DIRECT 100 can tolerate considerable aspheric residual errors of the compensating lens, as both the interferometer and the transmission spheres feature excellent on-axis and field correction.

These advantages for the measurement of aspheres ("electronic hologram", on-axis and field correction) are features exclusive to the interferometer Zeiss DIRECT 100.

Unlike conventional interferometers, the DIRECT 100 features very good lateral resolution (typically 50 μm for a test diameter of 10 mm). For this reason, the DIRECT 100 is ideal for displaying, for example, the traces produced by diamond turning on an asphere .

4.2.3 Test procedure

4.2.3.1 Interferometrical testing

In order to separate the mirror inherent residual errors from non-rotationally symmetric errors of the test setup (including test tower), the mirror will be measured in different rotational positions relative to the interferometrical set-up. The phase maps will be rotate back to the original position of the mirror and will be averaged. This gives the information about the mirror inherent error.

4.2.3.2 Testing the E-value

To fabricate the KOTTAMIA primary two points are of highest importance. The null corrector has to produce the predicted aspherical wavefront and the correct distance between the vertex of the null corrector and the KOTTAMIA primary has to be guaranteed within a range relatively small compared to the absolute distance (E-value).

There is a fixed reference point at our vibration isolated table in the test tower where the interferometrical setup is located. Using this reference point for placing a theodolit the angle between two opposite points at the mirror surface will be measured with an accuracy of better than 1 arcsec. Additionally the distance between these two points will be measured with an accuracy of better than 0.2 mm and the height over vertex using the parabolic equation will be calculate.

With this known values the E-value will be determined with an accuracy of better than 2mm.

4.2.3.3 Optical parameter calculation

Based upon the measured E-Value and on the measured wavefront the optical parameters of the KOTTAMIA primary will be determine. Multiplying the measured wavefront by a factor of 0.5 the surface error will be obtained.

Based upon the measured wavefront the **encircled energy** concentration of the KOTTAMIA primary is calculated.

The **focal length** of the primary is calculate using the measured E-value and using the mathematical model of the test setup.

4.2.4 Test criteria:

Main criterium of the test is the 80% spot concentration of intrisic quality, i.e. the actual test result with adjustment errors removed.

Optical quality:	
spot concentration	80% in a diameter ≤0.30 arcsec

Focal length:	9144mm $^{-10mm}$

4.3 Test at the completion of coating of the mirror

4.3.1 Test definition

The test is the verification of the reflection of the mirror coating in different wavelengths.

4.3.2 Test procedure

The degree of reflection of the mirror surface is determined using test glasses, which are coated during the same coating process, appropriately distributed in the vacuum test chamber. The uniformity of the reflection coating is ensured by test glasses evenly distributed over the mirror area.

The reflectance will be measured at an angle of incidence of 0°.

A visual inspection of the mirror surface will complete the test.

4.3.3 Test criteria

Coating: Aluminium with a protective coating of Magnesium fluoride

Reflectance:

Wavelength	Reflectance
350	90% $^{-3\%}$
400	89% $^{-3\%}$
450	85% $^{-3\%}$
500	86% $^{-3\%}$
550	88% $^{-3\%}$
600	89% $^{-3\%}$
650	90% $^{-3\%}$
700	88% $^{-3\%}$
750	87% $^{-3\%}$
800	85% $^{-3\%}$
850	83% $^{-3\%}$

4.4 Test at the completion of the mountain cell

4.4.1 Test definition

The inspection of the mirror cell will take place according to the drawings of the cell, to DIN and ISO 9001-9004 standards.
The mirror will be weighted with a precision of at least 0.5%

4.4.2 Test procedure

With a standard measuring instrument the critical interfaces of the cell to the telescope tube will be checked. The position of the mirror in the cell will be checked.

The function of the mirror support systems will be test radially and axially. The mirror will free move at the balance weight systems, when the radial and axial fixation points are out of function.

4.4.3 Test criteria

The interface measures and the position of the mirror are defined in the assembly drawing 161499:001.25.

The free way for the movement of the mirror radially for this check must be ≥ 1mm.

Accuracy of the weight procedure ≤ 0.5%.

4.5 Test at the manufactures facility for the completed mirror

4.5.1 Test definition

The mirror will be tested, placed in the telescope mirror cell. The test will include a rotation by $90° \pm 30°$ on the support to test for any astigmatism effects.

4.5.2 Test procedure

4.5.3 Test equipment

For interferometrical testing of the KOTTAMIA primary a vibration isolated optical table is situated close to the center of curvature. At the table the complete interferometrical set-up of Twyman Green type is mounted and adjusted. A HeNe laser is applied as the light source. The measuring wavelength will be 633 nm. The used CCD-camera is connected to the host computer, where phase evaluation is performed.

For alignment of the interferometrical setup with respect to the mirror the optical table and one folding mirror is adjustable.

4.5.3.1 Null Corrector

A Null corrector (designed for the Kottamia primary) producing a parabolic wavefront is used for interferometrical testing, because the primary under test is the autocollimation mirror and the shape of the primary is of aspherical (parabolic) type.

4.5.3.2 Phase evaluation

For phase evaluation our DIRECT 100 (interferometer) software will be applied. The DIRECT 100 evaluates the phase map in video real time (25 times per second). For each phase calculation only one frame (interferogram) will be taken. In combination with the very short exposure time the DIRECT100 is very insensitive to vibration. On the other hand it allows to average a large number of interferograms with a rate of 25 per second in order to reduce effects of air turbulences as well as residual mathematical errors without any artificial smoothing of the wavefront. Applying the test the light paths are very long so, single frame evaluation (with short exposure time) and real time averaging is very helpful to obtain results with the required accuracy.

4.5.4 Test procedure

4.5.4.1 Interferometrical testing

In order to separate the mirror inherent residual errors from non-rotationally symmetric errors of the test setup, the mirror in telescope support will be measured in different rotational positions relative to the interferometrical set-up. The phase maps will be rotated back to the original position of the mirror and will be averaged. This gives the information about the mirror inherent error.

4.5.4.2 Testing the E-value

To fabricate the KOTTAMIA primary two points are of highest importance. The null corrector has to produce the predicted aspherical wavefront and the correct distance between the vertex of the null corrector and the KOTTAMIA primary has to be guaranteed within a range relatively small compared to the absolute distance (E-value).

There is a fixed reference point at the vibration isolated table where the interferometrical setup is located. Using this reference point for placing a theodolite the angle between two opposite points at the mirror surface will be measured with an accuracy of better than 1 arcsec. Additionally the distance between these two points will be measured with an accuracy of better than 0.2 mm and the height over vertex using the parabolic equation will be calculated.

With this known values the E-value will be determined with an accuracy of better than 2mm.

4.5.4.3 Optical parameter calculation

Based upon the measured E-Value and on the measured wavefront the optical parameters of the KOTTAMIA primary will be determined. Multiplying the measured wavefront by a factor of 0.5 the surface error will be obtained.

The encircled energy concentration of the KOTTAMIA primary is calculate based upon the measured wavefront.

This procedure will be performed in two positions of the mirror relative to the support.

A surface topography of the mirror for any position will be shown.

4.5.5 Test criteria:

Main criterion of the test is the comparisation of the 80% spot concentration of intrisic quality with the result of point 3.2.4.
No critical discrepancy must be found.

4.6 Test of the secondary mirror

4.6.1 Test definition

In order to control the polishing process and in order to verify the optical quality of the KOTTAMIA secondary mirror we will use an interferometer procedure. The result is of this process is the wavefront error due to the mirror shape. The calculation of the encircled energy will be based on the measured wavefront. The interferometer and the subsequent calculation of the encircled energy are very precise.

The test of the secondary mirror will be made in the scheme with a HINDLE sphere.

4.6.2 Test equipment

The secondary mirror will be hanging by means of steel tape along its cylinder surface in special installation, which has necessary movements for mirror centring in respect to the HINDLE mirror. The interferometrical set-up of Twyman-Green type is mounted close to the focus F1 at adjustable table. A HeNetype laser is applied as the light source. The measuring wavelength will be 633 nm. A CCD-camera is used for registrations of Interferograms.

4.6.3 Test arrangement

1 - Interferometer
    of Twyman Green type
2 - Hindle sphere
3 - Hyperbolic mirror
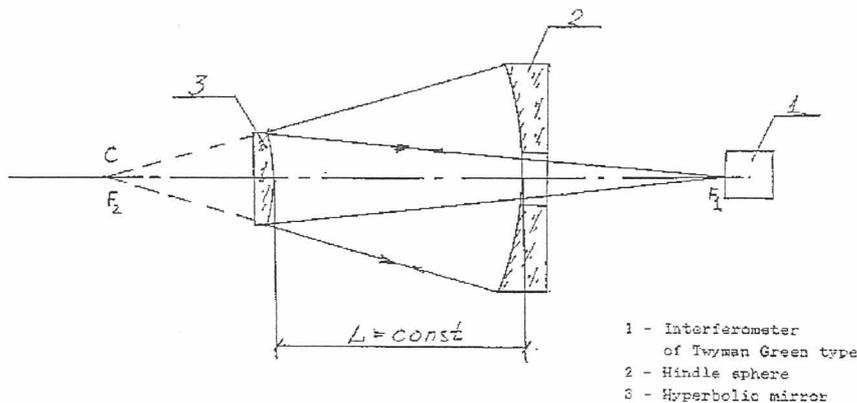
4.6.4 Test procedure

4.6.4.1 Processing of interferogram.

In the process of test the interferograms are registered in a very short time. The interval of this registration not exceeds 1-2 micro seconds. It is allows to avoid influence of vibration and turbulence streams. Fixed set of interferograms is consecutively processed at amplitudes. Using software and hardware parts of equipment allow to achieve very high accuracy.

4.6.4.2 Calculation of optical surface parameters.

To calculate optical parameters of the secondary mirror surface a special software is used. This program allows to obtain regular and irregular components of surface error, as well as to calculate encircled energy concentration in diffusion circle taking into account consideration diffraction effects.

4.6.4.3 Determination of optical parameters.

Location of focus positions F and F2 of secondary mirror are determined from test scheme by way of direct measurement of distance between mirrors, as well as location of focus F1 and curvature radius of Hindle sphere..

4.6.4.4 Test results

Following parameters will be documented in the test report:
- Focal length of the finished mirror
- Topography of the aspherized surface
- ZERNIKE coefficients
- Wavefront error
- Digital interferometer image

4.6.4.5 Test criteria

Main criterion of the test is the 80% encircled energy of the secondary mirror E(80) ≤ 0.26arcsec by use of a grid of 20 to 20 points.

4.6.5 HINDLE sphere
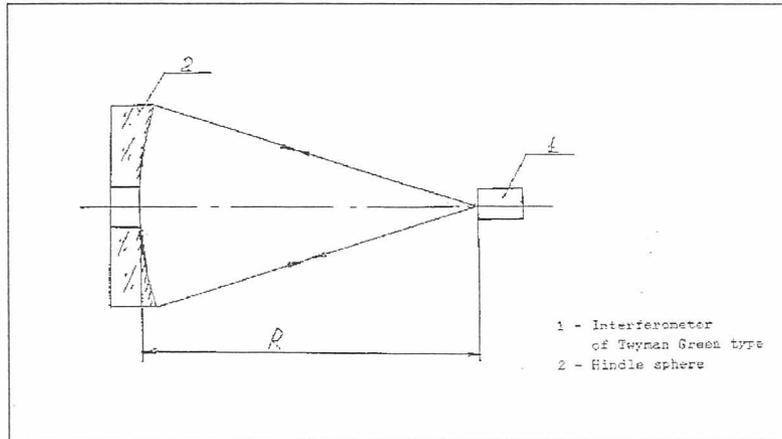
A Hindle sphere with following parameters will be used:

Optical clear aperture of the HINDLE sphere	1338mm
Radius of the HINDLE sphere	6138mm
Invisible diameter	275mm

4.6.5.1 Hindle sphere test.

For interferometrical testing of the Hindle sphere it will be hanging in special support by means of steel tape. Test is made from curvature centre with interferometrical set-up of Twyman Green type. A HeNe laser is applied as the light source. The measuring wavelength will be 0.6328 micro meters. CCD-camera is used for registration of interferogram.

4.6.5.2 Hindle test arrangement

1 - Interferometer
    of Twyman Green type
2 - Hindle sphere

4.6.5.3 Determination of curvature radius

Determination of actual value of curvature radius R of Hindle sphere is made by means of special tools with measurement accuracy better 0.1mm.

4.6.5.4 Hindle test sphere certificates:

Following parameters will be checked:

- Radius of the sphere
- Encircled energy of the sphere
- ZERNIKE coefficients

4.7 Test of the combined mirror system

4.7.1 Test definition

The test is the verification of the encircled energy of the combined mirror system.

4.7.2 Test procedure

The results of the test of M1 in the cell will be mathematically combined with the results of the tests of M2. This procedure save an objectively test result independent of the influences of air or additional test equipment elements.

4.7.3 Test criteria:

The criterion is the spot concentration of the combined system 80% in a diameter of 0.35 arcsec with a grid of 20x20 points.

4.8 Test at the Kottamia observatory after shipping the completed mirror

4.8.1 Test definition

The test consists of a visual inspection, that the shipment has arrived in good condition.

4.8.2 Test procedure

After unpacking the Mirror and the mechanical units will be checked visually for damages

After integration the critical interfaces of the cell to the telescope tube will be checked. The position of the mirror in the cell will be checked.

The function of the mirror support systems radially and axially will be tested. The mirror must freely move at the balance weight systems, when the radial and axial fixation points are out of function

4.8.3 Test criteria:

The interface measures and the position of the mirror are defined in the assembly drawing 161499:001.25.

The free way for the movement of the mirror radially for this check must be ≥ 1mm.

4.9 Test at the Kottamia observatory on the sky

4.9.1 Test definition

The test will confirm that the mirror is functional and has not received any form of damage in transit or during integration. The aim of the test is to check the alignment of the mirror system.
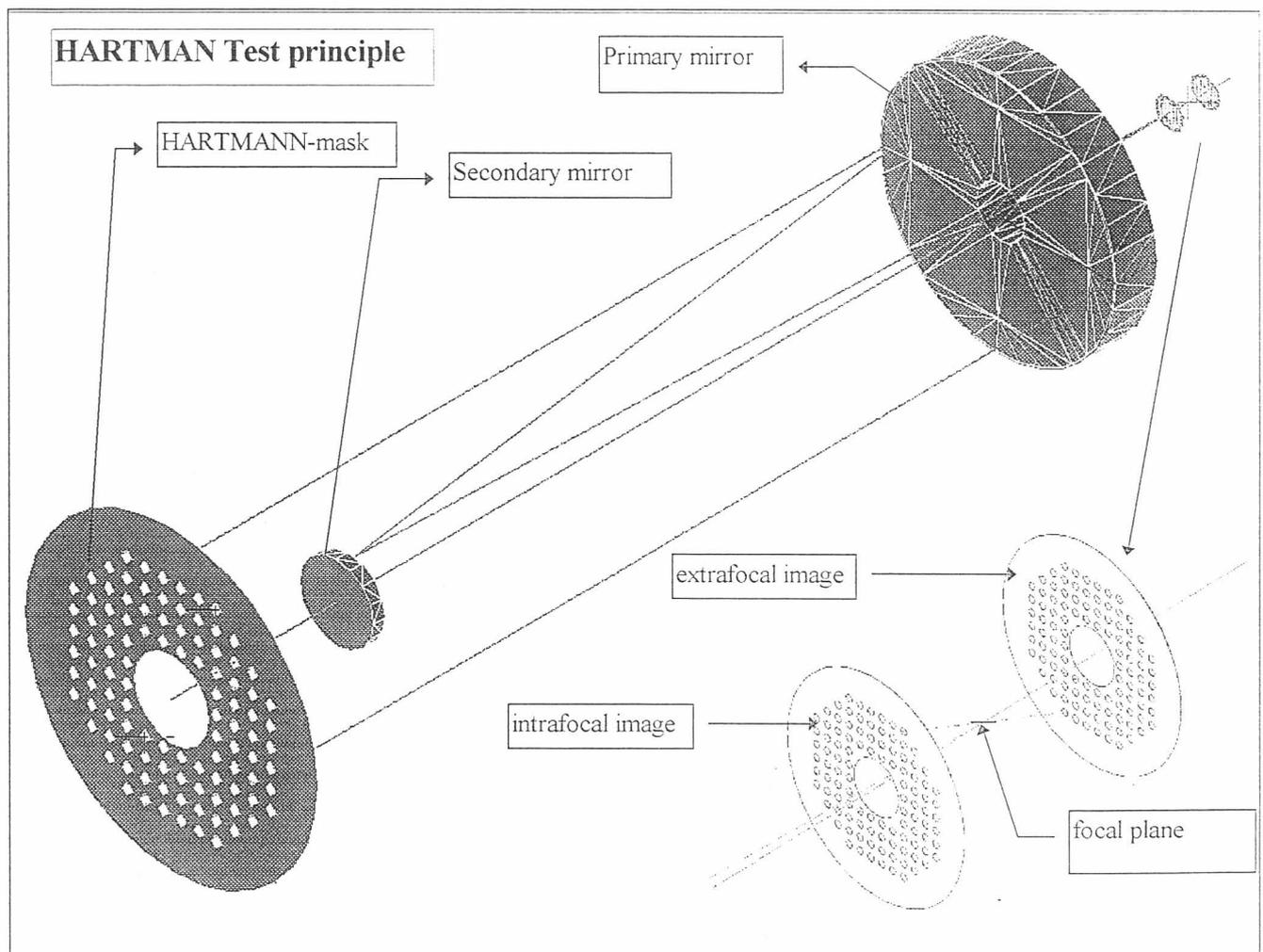
4.9.2 Test procedure

The test procedure will be a classical photographic HARTMANN Test or alternatively test with a SHACK-HARTMANN tester.
A mask of precisely located holes is placed in the pupil of the optical system under test. Each hole forms a particular ray converging towards focus.
Two photographic plates are exposed by use of a star on the sky, one in front of the focus (intrafocal), and one behind (extrafocal). By knowing the distance between the plates and by reading out the positions of the rays on the plate with a two co-ordinate measuring instrument, one can determine a slope for each ray in the pupil.
With the evaluation software „Hartmann-Auswertung" and „ZERNAL" the spot concentration can be determined.

HARTMAN Test principle — HARTMANN-mask — Secondary mirror — Primary mirror — extrafocal image — intrafocal image — focal plane

4.9.3 Test requirements

The seeing conditions for the system tests must be < 0,3 theoretical light concentration value.
For a realistic test result at least five nights with these conditions are necessary.

4.9.4 Test Equipment

4.9.4.1 Classical HARTMANN test

- Balanced and tracked telescope with mounted HARTMANN mask
- Photographic plate 6.5x9cm^2
- Photographic plate holder with shutter
- focusing unit for producing of the extrafocal and intrafocal distance
- photographic developing equipment
- two co-ordinate measuring instrument (e.g. ASTRORECORD or equivalent instrument)
- PC for evaluation of the measuring data
- Evaluation software: „ Hartmann-Auswertung"
                       „ZERNAL"

4.9.4.2 SHACK-HARTMANN tester

- Wavefront sensor system with lenslet array (used lens matrix 20x20)
- CCD sensor
- Evaluation software

4.9.5 Test description:

4.9.5.1 Classical HARTMANN test

The telescope will be tracked on the sky. On the front end of the tube the HARTMANN-mask is mounted. Light source is a bright star. The photographic plates are positioned in a defined distance of the focal plane. The image of the HARTMANN-diaphragm will be taken at photographic plates in an extrafocal and intrafocal position The photographic plates will be evaluated with the two co-ordinate measuring instrument. With this data will be calculated by aid of the special evaluation software „ Hartmann-Auswertung" and „ZERNAL", i.e. the ZERNIKE coefficients and the spot concentration.
This process will be repeated for variation of :
- the seeing conditions (more nights)
- the position of the secondary mirror (focussing position)
- the adjustment state (optimisation process)

4.9.5.2 SHACK-HARTMANN tester

The telescope will be tracked on the sky. On the front end of the tube the wavefront sensor is mounted. Light source is a bright star.

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The SHACK-HARTMANN method measures the positions of star images arising from sub-apertures. Those positions determine the local gradient of the wavefront, and the overall phase profile is reconstructed from these slope data.

The test results will be describe

- the wavefront,
- the ZERNIKE coefficients
- and and the spot concentration.

This process will be repeated for variation of :

- the seeing conditions (more nights)
- the position of the secondary mirror (focussing position)
- the adjustment state (optimisation process)

This method is an on-line procedure.

The distance between the mirror support flange and the optimum focal plane will be investigated

Note:

For both test procedures there is a strong influence of the seeing.

4.9.6 Test criteria

The accuracy of the adjustment state of the optical elements will be tested.

The criterion is the spot concentration 80% in a diameter of 0.35 arcsec plus the influence of seeing.