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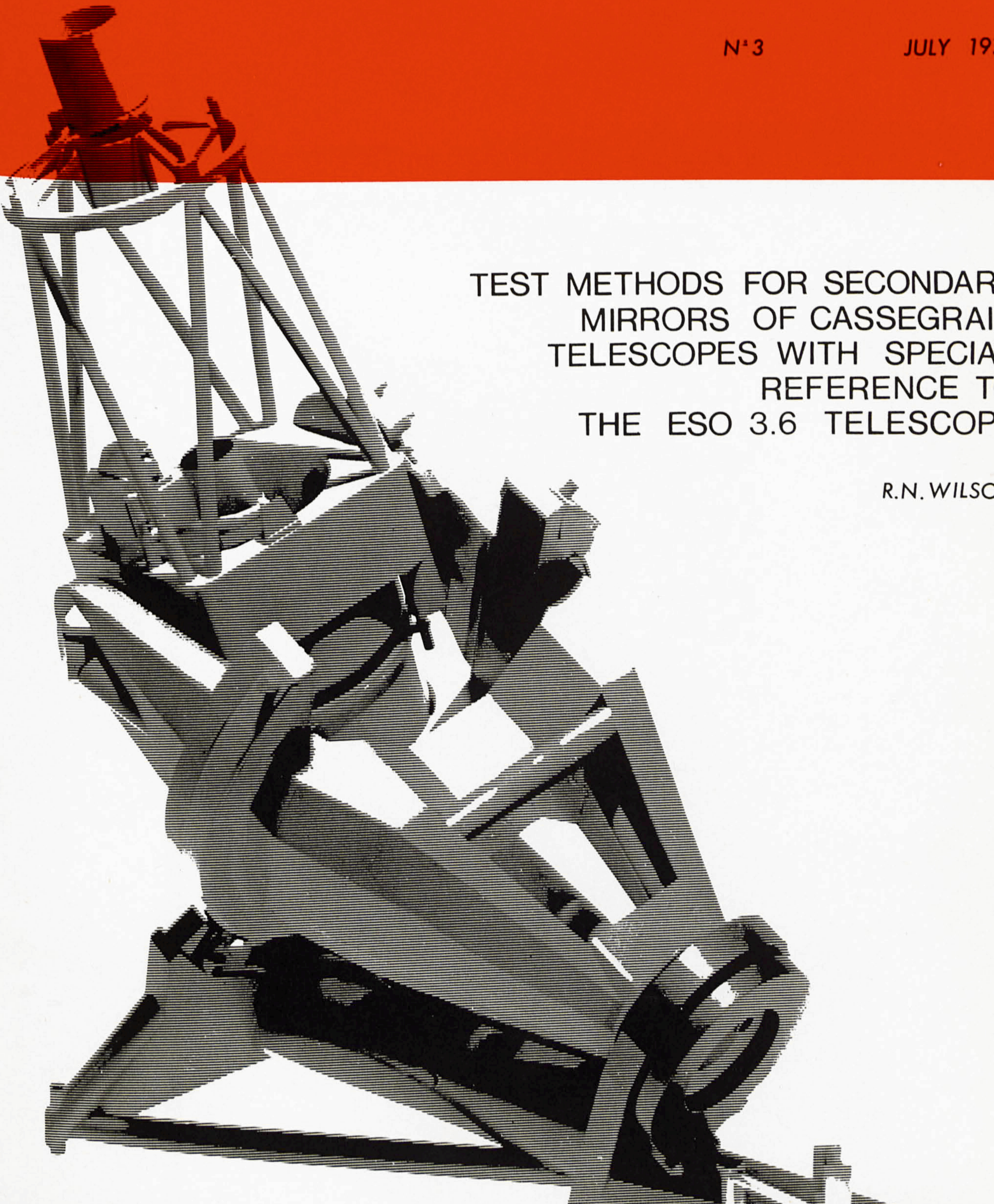

TEST METHODS FOR SECONDARY MIRRORS OF CASSEGRAIN TELESCOPES WITH SPECIAL REFERENCE TO THE ESO 3.6 TELESCOPE

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by

R.N. Wilson

PREFACE

The European Southern Observatory (ESO) is the result of a scientific collaboration for astronomical research in the Southern Hemisphere between the six European member countries, Belgium, Denmark, Federal Republic of Germany, France, Netherlands and Sweden.

Situated 600 km north of Santiago de Chile, the observatory is located on a mountain named La Silla, 2400 m above sea level in the southern tip of the Atacama Desert.

According to the prescriptions of the ESO Convention, signed in 1962, the principal instrument of the observatory will be the 3.6 m telescope, currently being built and due to be commissioned in 1976. This instrument will be installed on the highest summit of La Silla.

Designed as a general-purpose instrument, it will be used for furthering a wide range of research programmes in the visible and infrared part of the spectrum. Research with the observatory's existing telescopes has underlined the need for such a large instrument.

The ESO Telescope Project Division, established on the CERN site in Geneva following an agreement on co-operation reached between the two organizations, is responsible for the design and construction of the observatory's newest and largest telescope. This Division has now begun to issue a series of Technical Reports treating the various design and construction aspects of the different parts of the telescope. The present report is the third of the series and will be followed in the near future by others.

S. Laustsen

Leader of TP Division, ESO

Test methods for secondary mirrors of Cassegrain telescopes with special reference to the ESO 3.6 m telescope

This report is intended to give a resumé and critical analysis of all the methods known to the author which have been proposed for testing convex secondary mirrors. For the sake of completeness, methods which cannot be applied to the 3.6 m telescope have been included so that it can be made clear why they are inapplicable.

The report is divided into three sections:

1. Introduction:
   This defines the nature of the problem and two basic characteristics (A and B) for the classification of methods.

2. Resumé of methods:
   For each method, the discussion is subdivided under:

   a) Classification A and B.

   b) Brief technical description and references.

   c) Advantages and disadvantages.

   d) Applicability to the ESO 3.6 m telescope.

3. Resumé of suitability for secondaries of the ESO 3.6 m telescope

References to literature have been given in all cases where they are known.

As a result of this analysis, it was decided that the test method used for the manufacture of the secondaries of the ESO 3.6 m telescope (paragraph 2.2.4 - Pentaprism method) should be supplemented by the method of paragraph 2.4.4 (LYTLE test). A detailed account of these tests is given in a separate ESO technical report.

CONTENTS

Page

1. Introduction 1

2. Resumé of methods 3

2.1 Functional test with natural stars 3

2.2 Autocollimation or equivalent in functional geometry and unchanged ray-path 4

2.2.1 Full-size plane mirror 4

2.2.2 Double telescope 4

2.2.3 Reduced size plane mirror 5

2.2.4 Pentaprism or double pentaprism 6

2.2.5 Mach-Zehnder 7

2.2.6 Prism band 8

2.2.7 Zenith mirror 9

2.3 Tests with artificial source in functional or quasi-functional geometry and with or without focal shift 10

2.3.1 Source at finite distance without auxiliary surface 10

2.3.2 Source at finite distance with auxiliary surface 11

2.4 Autocollimation tests using primary and secondary mirrors in non-functional geometry and ray-path 12

2.4.1 Double reflexion at primary 12

2.4.2 As paragraph 2.4.1 but with an auxiliary mirror in front of central hole 16

2.4.3 As paragraph 2.4.1 but using refracting optics in front of the secondary 17

2.4.4 Lytle test 19

2.5 Test methods of secondary alone without primary and without large auxiliary optics 21

2.5.1 Test through back surface 21

2.5.2 Refraction through mirror as Cartesian lens 22

2.6 Test methods of secondary alone without primary but with large auxiliary optics 24

- 2.6.1 Hindle sphere 24
- 2.6.2 Meniscus Hindle sphere used in transmission 26
- 2.6.3 Auxiliary lens in front of secondary 29
  - 2.6.3.1 With spherical surface 29
  - 2.6.3.2 With aspheric surface 30
- 2.6.4 Concave matrix mirror-interference test 31
- 2.6.5 Richardson test 32

3. Resumé of suitability for secondaries of ESO 3.6 m telescope 34

Literature 38

Test methods for secondary mirrors of Cassegrain telescopes with special reference to the ESO 3.6 m telescope

1. Introduction

Tests of optical surfaces all rely in some form or other on the formation of the image of a point source by an optical arrangement containing the test surface. The errors of the test surface are impressed on the incident wavefront and are determined by analysis of the image. Since the object source is by definition real and only a real image is accessible for analysis, it follows that the optical arrangement must be capable of yielding a real image of a real object. A convex reflecting surface is incapable of doing this without auxiliary optics. This characteristic, combined with its high eccentricity, makes the manufacture of the secondary one of the major problems - if not the major problem - of modern telescope manufacture.

All test arrangements can be classified according to two fundamental characteristics which we will call classifications A and B.

Classification A refers to the state of correction of the final image. If this image is free from spherical aberration for the required theoretical form of the test surface without additional lens compensating systems, then the basic optical arrangement is a true "Null Test" and is classified here as A1. The wavefront aberration of the final image is then a direct measure of the wavefront error of the test surface. If the required theoretical test surface yields an image with spherical aberration in the optical arrangement used, the method is classified here as A2. Either the test surface must be manufactured to produce the specified aberration or a "Null Test" must be achieved by an additional compensation system. The technology of compensation systems is now well developed. They may use simple lenses (1) giving incomplete compensation or compound systems (2) (3) (4) (5) giving full compensation. Single lens-hologram combinations (5) give a powerful and flexible solution.

Classification B refers to the amount of the pupil (test surface) *instantaneously* observed by the test. If the *whole pupil* is covered instantaneously, then the method is classified as B1. If the pupil can only be established by the integration of time-dependent observations, then the method is classified as B2. In some cases, a method is classified as B1*, implying that the B1 characteristic only applies to the area of the secondary covered by the beam forming the *axial* image in the telescope without the annular area at the edge required for the field.

The methods of analysis of the real image are not specifically related to the problem of convex secondaries. The analysis may be performed by any of the well-known methods such as Hartmann, Foucault, Ronchi, Scatter-Fringes, Wave-Shearing interferometer, Laser-Interferometer or others. Suffice it to comment that the Laser Interferometer provides all the advantages of sensitivity, complete coverage of the pupil and directness of quantitative and qualitative interpretation. Methods B2 often implicitly contain a special technique of analysis.

2. Resumé of methods

Every method known to us is included in the following review, for the sake of completeness, even if it is obviously inapplicable to the 3.6 m telescope.

For each method, the discussion is subdivided under:

a) Classification A and B.

b) Brief technical description and references.

c) Advantages and disadvantages.

d) Applicability to the ESO 3.6 m telescope.

2.1 Functional test with natural stars

a) Classification A1 and B1*.

b) This is the oldest and most direct method. The edge zone of the secondary can be included in the test by observing stars near the edge of the field and in different positions. To eliminate seeing effects, evaluation is normally by means of the Hartmann test. An alternative is the Shearing-Interferometer which eliminates seeing effects with wavelengths appreciably longer than the amount of linear shear.

c) Advantages: Good A and B classification. Directness. Entirely functional nature. No auxiliary optics required - cheap.
Disadvantages: Seeing rules out most evaluation methods or greatly reduces their sensitivity. Test can only be performed after installation at the observatory where optical workshop facilities are lacking. B1* not B1.

d) The method is fundamentally applicable to any telescope regardless of its size.

2.2 Autocollimation or equivalent in functional geometry and unchanged ray-path

2.2.1 Full-size plane mirror

a) Classification A1 and B1*.

b) The ideal method for small telescopes which can, however, hardly be considered for large ones because of the great cost and technical difficulty of manufacturing, testing and supporting a plane mirror of such a size. The edge zone of the secondary can be tested by tilting the plane mirror relative to the telescope or vice-versa to achieve the necessary field angle. Liquid (Mercury) mirrors are attractive in principle but not technically solved.

c) Advantages: Optimum method in almost all respects. Double pass of system. Functional nature.
Disadvantages: B1* not B1. Very high cost and unsolved technical difficulty for large telescopes. The testing of coudé secondaries requires considerable space.

d) Can hardly be considered for a 3.6 m telescope.

2.2.2 Double telescope

a) Classification A1 and B1*.

b) Two telescopes are set up opposite each other, the one serving as collimator for the other. By introducing a relative tilt and lateral shift, the edge zones of the secondaries can be tested. The method has been suggested but not implemented for the two identical 2.2 m telescopes of the MPIA.

c) Advantages: A cheap and efficient method if two telescopes of similar size are available. Functional nature.

Disadvantages: Two telescopes must be available at the same time and in the same place. If errors are present, it would be very difficult to determine which telescope is responsible. The testing of coudé secondaries requires considerable space.

d) Transport costs and the limited number of large telescopes probably rule the method out for the ESO 3.6 m instrument.

2.2.3 Reduced size plane mirror

a) Classification A1 and B2.

b) The method is ideal except for the reduced size of pupil testable. Methods have been proposed (using additionally a pentaprism and an interferometer) to maintain the normal direction of the mirror to high accuracy but the problem is technically so difficult that it cannot be considered as solved. Thus the method only gives certain information about the freedom from errors of high spatial frequency over the area of the plane mirror.

c) Advantages: Entirely functional nature.

Disadvantages: Classification B2. (The method is most interesting if combined with a B1 method). The testing of coudé secondaries requires considerable space.

d) Of doubtful advantage for the ESO 3.6 m telescope because a similar method with classification B2 is already in use.

2.2.4 Pentaprism or double pentaprism

a) Classification A1 and B2.

b) The use of a pentaprism mounted on a rail to produce an effectively plane test wavefront built up of elements about the size of the pentaprism aperture was probably first suggested by Wetthauer(6). It has also been described by Hendrix and Christie(7) and by Hochgraf (8). A double-pentaprism modification was suggested by Räntsch (unpublished) and by Espiard and Favre (9) who analyse practical results in detail. The work of Espiard and Favre seems to be some of the most systematic and refined to date using the pentaprism method. Essentially twice the angular spherical aberration of a zone of the collimated beam from the telescope is measured <u>differentially</u> as the difference in the direction of the beams deflected by two pentaprisms disposed at equal distances above and below the telescope axis on a diameter across the pupil. By its differential nature, the test eliminates decentering coma. This must be considered an advantage although comatic type errors in the system also become undetectable. Of course, the <u>absolute</u> deflections of the beams still retain comatic information. Since a new reference sphere is normally established for two diameters at right angles, the test usually provides no information concerning astigmatism. However, Brown(19) reports experience of this method at Grubb-Parsons in which reliable information on astigmatism has been extracted.

The effective size of the "pentaprism" can be increased by the use of a mirror system with the same characteristics, a method used successfully by Espiard at REOSC.

The edge zone of the secondaries requires a tilt of the pentaprism axis corresponding to the telescope field angle and tests combined with the corrector. The coudé secondary requires considerable test space or a modified test arrangement, using an auxiliary mirror. The (small) edge zone due to the coudé field can be tested by tilting but the field coma will be present.

c) Advantages: Functional nature - very favourable for avoiding systematic errors (third order spherical aberration) due to errors in the mirror eccentricities.

Disadvantages: Classification B2 - no overall picture of smoothness of surface. No information on comatic errors or (more serious) astigmation.

d) The method has valuable advantages for testing large telescopes but should ideally be complemented by a B1 method.

2.2.5 Mach-Zehnder

a) Classification A1 and B2.

b) The suggestion of this method is due to M. Mächler (unpublished). It is based on the fact that it is possible to adjust the four mirrors of a Mach-Zehnder interferometer of large aperture parallel to each other with very high accuracy - better than 0.1 arcsec.

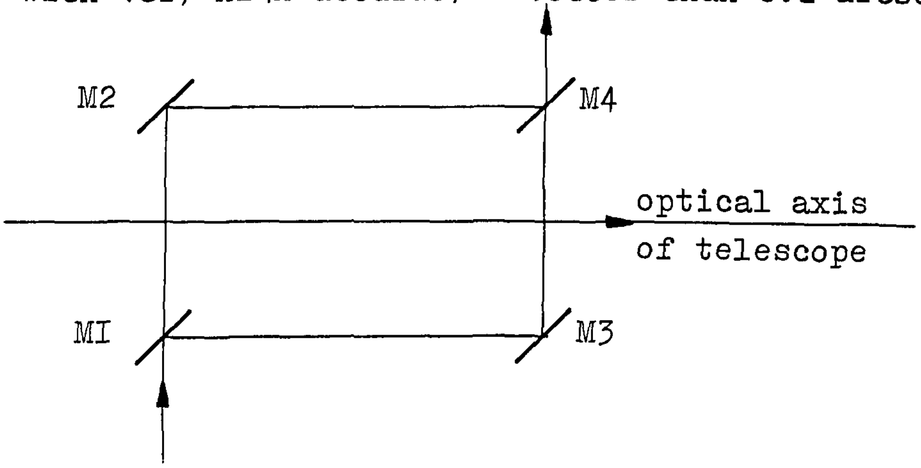

Fig. 1

After the interferometer adjustment, mirrors M3 and M4 are removed leaving M1 and M2 in parallelism. The method can then be used exactly as the pentaprism method in conjunction with a collimator but has the advantages of permitting a larger aperture and adjustment of parallelism in two dimensions.

c) Advantages: As for pentaprism paragraph 2.2.4 but with larger aperture and more rigorous two-dimensional parallelism.

Disadvantages: As for pentaprism. Adjustment procedure for different zones probably more tedious than pentaprism method.

d) The method has not yet been tried out in practice. Since it suffers the same limitation of classification B2 and is similar in principle to the pentaprism method, it is not to be recommended as a complementary test for the ESO 3.6 m telescope.

2.2.6 Prism band

a) Classification A1 and B1*.

b) A collimator can be built up across a diameter of the telescope aperture by a band of prisms operating at minimum deviation and whose angles increase with the height of the zone (prism) above the telescope axis (suggestion R. Wilson - unpublished). At minimum deviation the prisms yield a deviation which is relatively insensitive to their tilt while in the other section they are completely insensitive. The method thus offers the advantages of the pentaprism method but has the major advantage of classification B1 since points over the whole pupil can be tested instantaneously. The method is from its nature particularly suitable to analysis by the Hartmann test.

Its insensitivity to vibrations is a major advantage over a "mirror band" which would be technically extremely difficult.

c) Advantages: Classifiaction B1. Functional nature with all advantages. Insensitivity to vibrations. Disadvantages: Production of high quality prisms expensive. Technique of production for necessary standard of collimation untried and requires development work. Same limitation as Hartmann test that only sample areas over pupil diameter are tested.

d) Not to be recommended for the ESO 3.6 m telescope because of high cost of prisms and untried nature of the method.

2.2.7 Zenith mirror

a) Classification A1 and B2.

b) This method was suggested by Drodofsky (10) for the determination of the zenith direction to very high accuracy for adjusting astrometric instruments. Since Drodofsky claims a directional constancy within 0.01 arcsec., the method is also clearly of interest for testing a telescope. The method is in principle the same as the simple pentaprism method except that the zenith mirror establishes a constant direction by means of the direction of gravity.

c) Advantages: Functional nature.
Disadvantages: Classification B2. Only applicable with telescope axis vertical.

d) Although the method is untried in practice, it might be applicable to the ESO 3.6 m telescope at a relatively low cost. However, because of its classification B2 and its similarity to the pentaprism method, it does not seem very suitable as a complementary method.

2.3 Tests with artificial source in functional or quasi-functional geometry and with or without focal shift

2.3.1 Source at finite distance without auxiliary surface

a) Classification A1 or A2 and B1 (but test of the edge zone for field of secondary causes difficulties).

b) This method is very old - Fraunhofer used it on his refractors. There is an old rule, governed by the Herschel condition, that the change of spherical aberration in a telescope is negligible if an artificial star is at least 40 focal lengths away (classification A1). Such distances run into kilometers, however, for large modern reflectors. The seeing problem is probably prohibitive for horizontal distances of this order.

If the object is set up considerably nearer, then a considerable focal shift occurs and spherical aberration is introduced - the classification becomes A2. This is in itself, not serious; a real image in a position of unchanged accessibility can be achieved by moving the secondary away from the primary so that its distance from the virtual image formed by the primary remains unchanged. The real limitation of the test is the obstruction ratio. An additional linear obstruction of about 25%

results if the source is set up at a distance $2r_1$ from the primary. This is probably larger than acceptable, so that $3r_1$ is about the practical minimum. For the ESO 3.6 m telescope

$$3r_1 \simeq 65 \text{ m}$$

This is hardly possible with vertical telescope axis and very long with horizontal telescope axis.

The testing of the edge zone of the secondary for the field may involve an unacceptable focal shift.

c) Advantages: Classification B1. No additional large mirror optics.

Disadvantages: Very large space requirements because of minimum source distance. Classification A2.

d) The space requirements and accompanying turbulence problems probably rule the method out for a telescope as large as the ESO 3.6 m.

2.3.2 Source at finite distance with auxiliary surface

a) Classification A2 and B1 (with limitation as paragraph 2.3.1)

b)

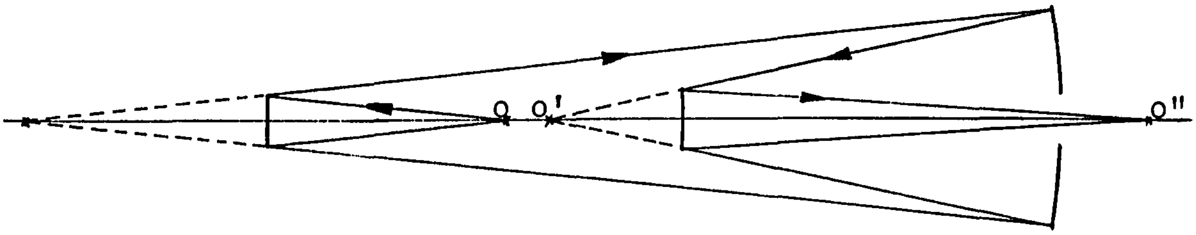

Fig. 2

If a plane mirror of about the same diameter as the secondary, (say the coudé M3) is used as a folding element, the test length is reduced by about one third or less and may be reducible to about $2r_1$. However, even with this reduction, the test length remains about 43 m for the 3.6 m telescope. The coudé system would probably require folding by a concave mirror situated roughly at the central hole, but this problem is not different from that obtaining with all the "functional" methods dealt with in 2.2.

c) Advantages: As paragraph 2.3.1.
Disadvantages: Although the space requirements are reduced to about 2/3 compared with paragraph 2.3.1, they are still very serious.

d) The reduction in space requirements is hardly sufficient to make the method interesting for the ESO 3.6 m telescope.

2.4 Autocollimation tests using primary and secondary mirrors in non-functional geometry and ray-path

2.4.1 Double reflexion at primary

a) Classification A2 and B1.

b) This method was suggested as a possible test method for the QRC secondary of the ESO 3.6 m telescope in 1964 (Zeiss internal report) and briefly mentioned in a later publication (3). A real image in autocollimation is produced by performing two reflections at the primary whose form must therefore be known and free from errors of high spatial frequency (ripple). The only additional optical element necessary to produce the real image is a plane mirror which would have a maximum diameter of about 40% of that of the secondary and probably considerably less. The method is a true classification B1 method, i.e. the whole surface of the secondary is tested simultaneously including the edge zone required for the field coverage.

Fig. 3 shows the set-up for the final dimensions of the ESO 3.6 m telescope. Light from the

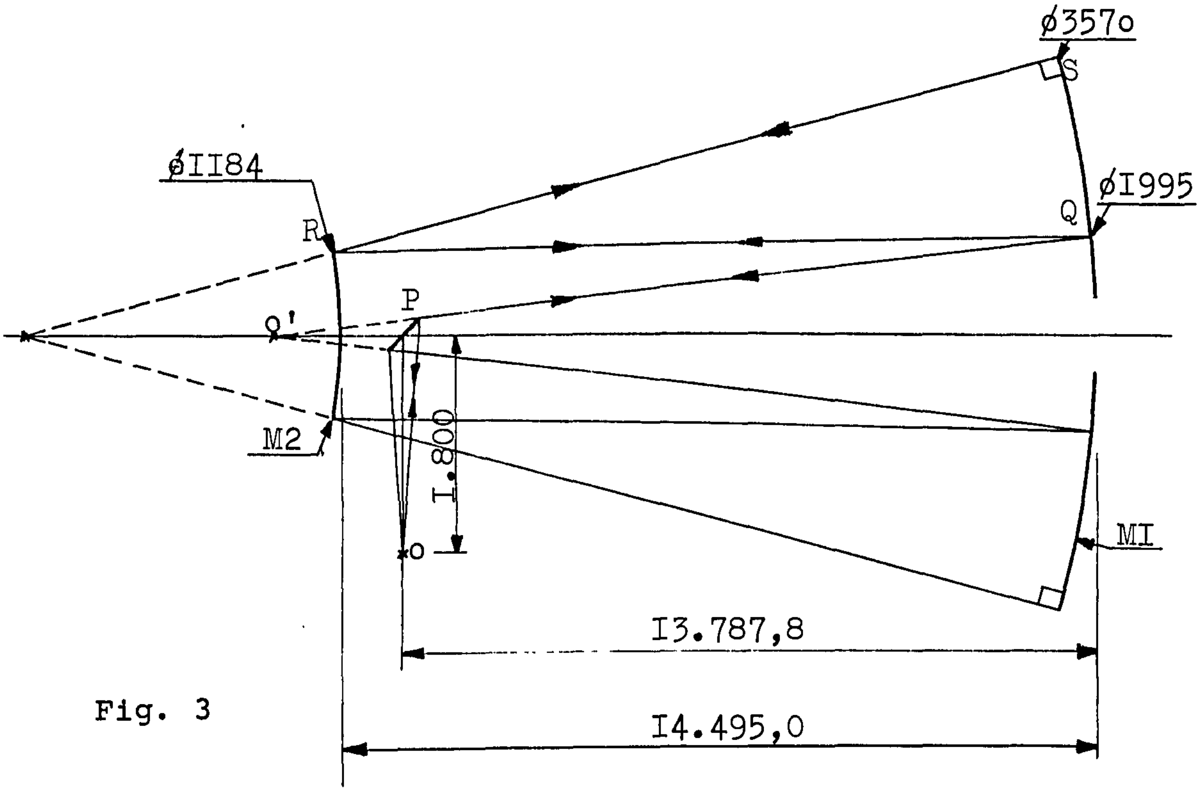

Fig. 3

point source O - placed at the side of the system so that there is no obstruction - is deflected at right-angles by the small plane mirror P to the primary. The marginal ray is reflected from the primary at Q and strikes the secondary at the edge R of its free aperture, so that it is fully illuminated. After reflection at R, the marginal ray strikes the primary at the edge of its free aperture S normally whereafter it retraces its path giving autocollimation.

Whether the method is in principle applicable or not depends on the distance of the final image O' behind the secondary M2 if the point R is at the edge of the free aperture of the secondary and S is not higher than the edge of the free aperture of the primary. If O' is too far behind M2, it is impossible to get the beam out to O without an unacceptable obstruction. This is the case with the ESO coudé secondary. With the QRC secondary, on the other hand, the geometry (Fig. 3) is very favourable, the obstruction ratio of the plane mirror being only 0.188.

If the primary has no central hole and the whole surface has been worked to good quality, the height of point P is unimportant. Since most primaries do have central holes and because "dead zones" are not always worked to good figure to the edge of the hole, the height of point Q is, in practice, also important. On the ESO 3.6 m primary, for example, Hartmann measurements have been made down to a diameter of 889 mm, to which minimum diameter the surface may also be considered good. The beam diameter for point Q (1995 mm) relative to this minimum useable diameter of 889 mm gives an obstruction ratio of 0.446. This is slightly less than the obstruction ratio of the telescope in function, so would be acceptable. In fact, by lowering the point S the point Q can be raised, thus improving the obstruction ratio at the primary. However, the obstruction ratio due to the plane mirror becomes rapidly worse, so that an obstruction ratio at the primary due to a minimum diameter of 889 mm of about 0.41 is about the optimum in the case of the ESO 3.6 m QRC system. However, this gain would be useful in shifting the test beams away from limiting zones of the primary mirror where the figuring quality is less certain.

Apart from the additional plane mirror, the only change required from the functional set-up is that the separation between the primary and secondary mirrors is increased from 7491 mm to 14495 mm. Since the tower for manufacturing the primary must provide for tests at its centre of curvature (i.e. 21 700 mm above the primary), this mirror separation can cause no difficulties.

The method is classification A2, the final image having spherical aberration. Elementary considerations show that the aberration will be of the same sign (over-correction) as that of the primary at its centre of curvature and of the same order of magnitude. It could thus be readily compensated, apart from zonal error, with a single positive lens. This would be sufficient to give a check on the smoothness of the secondary.

An important feature of autocollimation in this method is that the double reflection at the secondary occurs at unchanged height. This is necessary for the interpretation of the test results. If it were not the case (i.e. if the incidence angle at S were not normal), then it would be difficult to identify observed errors in the final image with the zones causing them on the secondary.

c) Advantages: Classification B1 including edge zone of secondary for field. Cheapness - only a relatively small flat and a compensation system are needed. Can be carried out in manufacturer's test tower with minimum of change. High sensitivity because of double reflection at secondary.

Disadvantages: Classification A2 due to non-functional ray path. Requires high quality of figure of the primary.

d) Because of the advantages given, the method seems to be of great interest for the ESO 3.6 m telescope. In particular, its advantages and disadvantages complement the pentaprism test extremely well in that it provides cheap and efficient means of checking the smoothness of the secondary.

2.4.2 As paragraph 2.4.1 but with an auxiliary mirror in front of central hole

a) Classification A2 and B1 (including edge zone of secondary required for field).

b) This variation is of interest for cases where the point Q in fig. 3 is so low that the obstruction ratio caused through the minimum useable diameter at the primary is unacceptable. In this case, the diameter required for an auxiliary concave mirror placed directly in front of the central hole of the primary becomes feasible. Since the obstruction ratio due to the plane mirror will always be favourable in such cases if this mirror has the same radius as the primary, it will have a relative aperture at its focus of the order of f/8 to f/10. Its form can be spherical, since the method has anyway classification A2 and its aberration is therefore of no consequence.

c) <u>Advantages:</u> Classification B1. Quality of inner zones of primary no longer necessary as compared with paragraph 2.4.1. Auxiliary mirror is shallow and spherical.

<u>Disadvantages:</u> Classification A2. Auxiliary mirror required of comparable diameter to secondaries, and this must be centred.

d) The ESO 3.6 m telescope probably does not require this variation on paragraph 2.4.1 anyway. If this variation is used in such limiting cases, the size of the auxiliary mirror required makes it an expensive item. Furthermore, the size required would be such that the obstruction ratio set by the auxiliary mirror for the reflexion at S of the primary would anyway be unacceptable.

2.4.3 <u>As paragraph 2.4.1 but using refracting optics in front of the secondary</u>

a) Classification A2 or possibly quasi A1 and B1.

b) In this modification, additional refracting power is used in front of the secondary to produce a convenient final image position. It may be possible

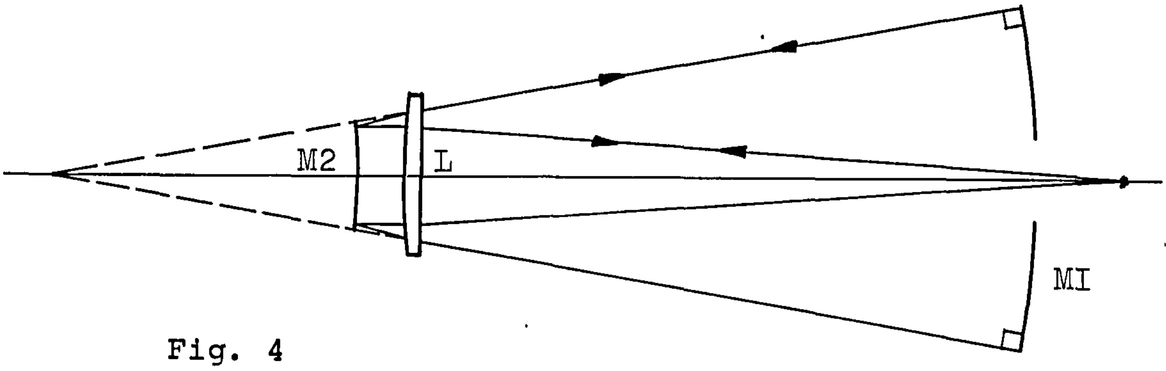

Fig. 4

to locate it behind the central hole as in Fig. 4. This requires a lens with a relative aperture of the order of f/10. Because of the classification A2, the lens aberration is immaterial; in any event it tends to compensate that of the mirror system so that a third order compensation may be possible giving the method a quasi A1 classification. The method is limited to telescope sizes for which the material of the lens L can have the necessary homogeneity. The testing of its convex spherical surface can be performed by treating it as a concave mirror through the plane back surface using a compensation system.

c) Advantages: Classification B1. Flexibility of final image position. Possibility of quasi auto-compensation - A1 classification. Auxiliary lens weak compared with paragraph 2.6.2 below.
Disadvantages: Large additional refracting element. Accompanying homogeneity problems.

d) The method can be discounted for a telescope of the size of the ESO 3.6 m because of the homogeneity problems of the auxiliary lens.

2.4.4 Lytle test

a) Classification A2 and B1.

b) This method was suggested by Lytle (11). The principle of the method is shown in Fig. 5. The point source O

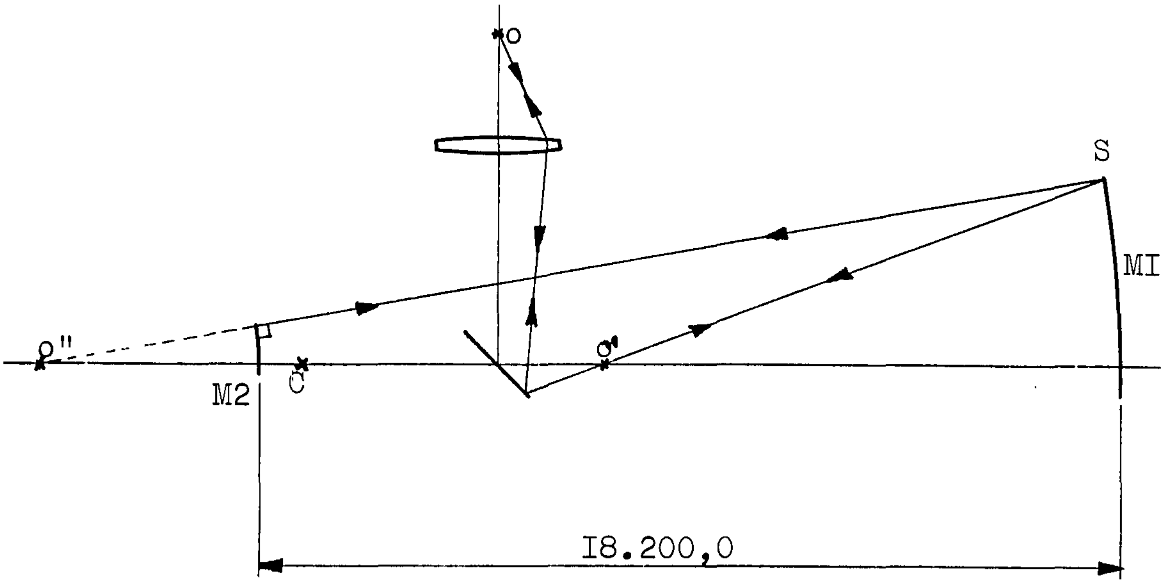

Fig. 5

is imaged by a lens compensation system in O' via a small plane mirror. Point O' is somewhat nearer the primary than its centre of curvature C. The marginal ray O'S is reflected from the edge of the primary S so that it would pass through the point O". The secondary mirror M2 is set up near C such that its centre of curvature is at O", giving autocollimation. Thus autocollimation is established by normal reflection at the secondary, whereas method paragraph 2.4.1 achieves this by normal reflection at the primary. The method is applicable to any secondary mirror whose relative aperture at its centre of curvature is somewhat less than that of the primary at its centre of curvature.

This is the case for both the QRC secondary and the coudé secondary of the ESO 3.6 m telescope, so the method is more universal than that of paragraph 2.4.1. Its only disadvantage compared with that method seems to be the greater test length required. An analysis of the obstruction problems in detail shows that the method is perfectly feasible for the parameters of the ESO 3.6 m telescope, although the illumination of the coudé secondary right to its edge is not possible.

c) Advantages: Classification B1 including the edge zone of the secondary required for the field. Cheap method requiring only small additional flat to obtain real image. Double reflection at primary covers whole surface each time and thus does not place special demands on zones of the primary near the centre as does method 2.4.1. Applicable to wide variety of secondary mirrors - in ESO 3.6 m telescope both QRC and coudé secondaries.

Disadvantages: Classification A2. The only apparent significant disadvantage of the method is the relatively large separation of the two mirrors requiring a vertical test height of about 18½ m (and a total ray path of about 80 m) in the case of the ESO 3.6 m telescope compared with about 15 m in the case of method 2.4.1.

d) Since sufficient test height was available in the REOSC tower, the Lytle method provided a cheap and unproblematic way of getting a classification B1 test of smoothness. In addition - and unlike method 2.4.1 - it enabled not only the QRC secondary but also the coudé secondary to be tested.

2.5 Test methods of secondary alone without primary and without large auxiliary optics

2.5.1 Test through back surface

a) Classification A2 and B1.

b) This method overcomes the basic difficulty of the convex nature of the secondary by treating it as a concave mirror which can be tested through its back surface in autocollimation. The technical problem of testing the secondary is then, in principle, the same as the primary and is in practice much easier because of the shorter test length. There are, however, two basic requirements. First, the back surface must be plane (or concave spherical) and of high quality. This rarely presents serious difficulties. Secondly, the homogeneity with double pass must be sufficiently good that the wavefront is not significantly deformed. This condition is very difficult to meet for larger size mirrors, particularly for materials which may be required for thermal properties and which are not usually intended to meet high requirements of homogeneity. Fused quartz is the best candidate, but it is doubtful whether this method is applicable to telescopes of more than 1 m aperture (secondaries about 350 mm Ø). For small telescopes the method is excellent.

c) Advantages: Classification B1 including edge zone for field. Directness. Ease of interpretation. Disadvantages: Classification A2. Back surface must be worked to high quality. Homogeneity requirement can only be fulfilled for smaller telescopes.

d) The ESO 3.6 m telescope is certainly too large for this method to be feasible. No high homogeneity requirement was set for the secondary mirror blanks.

2.5.2 Refraction through mirror as Cartesian lens

a) Classification A1 and B1.

b) This is undoubtedly the most elegant solution, in principle, to the problem. A Cassegrain convex secondary mirror is a <u>divergent</u> optical element as a mirror, but as a lens surface in transmission it is <u>convergent</u>. Thus, a convex mirror with, say, a plane back functioning as a lens automatically produces the real image required for testing. If the back surface is plane and a collimated beam is incident on the lens, then the "Cartesian surface" (12) required to produce an aberration-free image is a hyperboloid whose eccentricity is dependent on the refractive index of the mirror material and its magnification from one focus of the hyperboloid to the other. The relationship is given by:

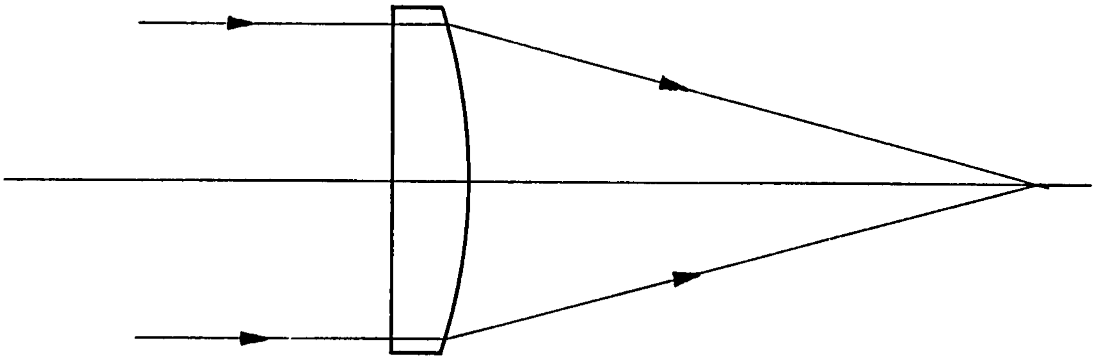

Fig. 6

$$\frac{n'}{n} = \varepsilon = \frac{\beta + 1}{\beta - 1}$$

in which n and n' are the refractive indices of the surrounding medium and the lens respectively, ε is the eccentricity of the hyperboloid and β is the magnification of the hyperboloid from focus to focus. (β is only the same as the magnification of the secondary <u>in the telescope</u> if the latter is a <u>classical</u> telescope). For a test wavelength of 632 nm (Laser), quartz requires a value of β from the above formula of 5.376. Smaller telescopes can often be adapted to this value and the method is extremely interesting in such cases. By changing the conjugates or making use of the back surface, it is also possible to retain autocompensation, or at least, third-order autocompensation, of the image while departing somewhat from the strict conditions of the above equation. For the ESO 3.6 m telescope, β has the values of about 2.2 for the QRC secondary and 5.1 for the coudé secondary. The method would thus, in principle, be difficult to apply to the former but feasible for the latter. The major problem, however, is again the homogeneity requirement, which rules it out for large telescopes.

The method has been suggested independently by various workers but its specific use on a small telescope has been given by Norman(13).

c) <u>Advantages:</u> Classification A1 and B1 including edge zone of secondary used for field. No auxiliary optical surfaces necessary except the back surface of the mirror.

Disadvantages: Homogeneity requirement of material of secondary. Sensitivity of double-pass refraction only half that of a reflection. Necessary refractive index linked to magnification β of the hyperboloid, but this limitation can be obviated by abandoning the classification A1 and autocompensation.

d) The method is unsuitable for the ESO 3.6 m telescope because the homogeneity requirement cannot be met for a telescope of this size. The magnification of the QRC secondary would anyway not permit autocompensation (classification A1) in this case.

2.6 Test methods of secondary alone without primary but with large auxiliary optics

2.6.1 Hindle Sphere

a) Classification A1 and B1.

b) The Hindle-Sphere is a well-known and widely used method first suggested by Hindle in 1931 (14) (15). The method provides a true null-test (classification A1) for any hyperboloid. The departure of RC or QRC secondaries from exact hyperboloids is negligible: calculations on the ESO 3.6 m telescope QRC secondary have shown that the systematic wavefront error involved in manufacturing the surface with a Hindle-Sphere as a Null-Test is only 0.0092 λ, corresponding to an angular aberration at optimum focus of only 0.08 arcsecs.

The basic parameters of a Hindle-Sphere are its relative aperture and its diameter. A detailed analysis with particular reference to the ESO 3.6 m telescope has shown that QRC secondaries represent extreme cases with regard to the necessary relative aperture whereas coudé secondaries are more demanding on the diameter because of central obstruction in the test set-up. Allowing for a slight reserve, minimum parameters of about 1/2.4 at its centre of curvature for the relative aperture and 2300 mm for the diameter have been estimated for the testing of the secondaries of the ESO 3.6 m telescope. Such a Hindle-Sphere is a powerful general tool permitting the testing of the secondaries of all telescopes up to about 2.5 m diameter and of most other larger telescopes. The only secondaries which might require a larger Hindle-Sphere would be the coudés of larger classical telescopes which hardly depart from paraboloids.

c) Advantages: From the point of view of the classification (A1 and B1) and universality, the Hindle-sphere is undoubtedly the best method in existence. Apart from its use for secondary mirrors, it is useful for testing large plane mirrors in the Ritchey-Common (16) (17) (18) arrangement and can also be converted into a large collimator by means of a compensation system.

Disadvantages: The high cost of a high quality mirror of this relative aperture and diameter.

d) The advantages of the Hindle-Sphere for testing the ESO 3.6 m telescope must be weighed against its high cost compared with other methods. The Hindle-Sphere can best justify its high cost if its advantage of universality is made use of by applying it to the secondaries of a number of telescopes.

2.6.2 Meniscus Hindle Sphere used in transmission

a) Classification A2 und B1.

b) This method resolves the obstruction problem associated with a small Hindle Sphere by using it in transmission (Fig. 7). Thus the Meniscus Hindle Sphere need not be much larger than the secondary mirror itself, although some latitude is required to take account of the different positions of the focus S' of different secondary mirrors if the Meniscus Hindle Sphere is not to be confined to one secondary.

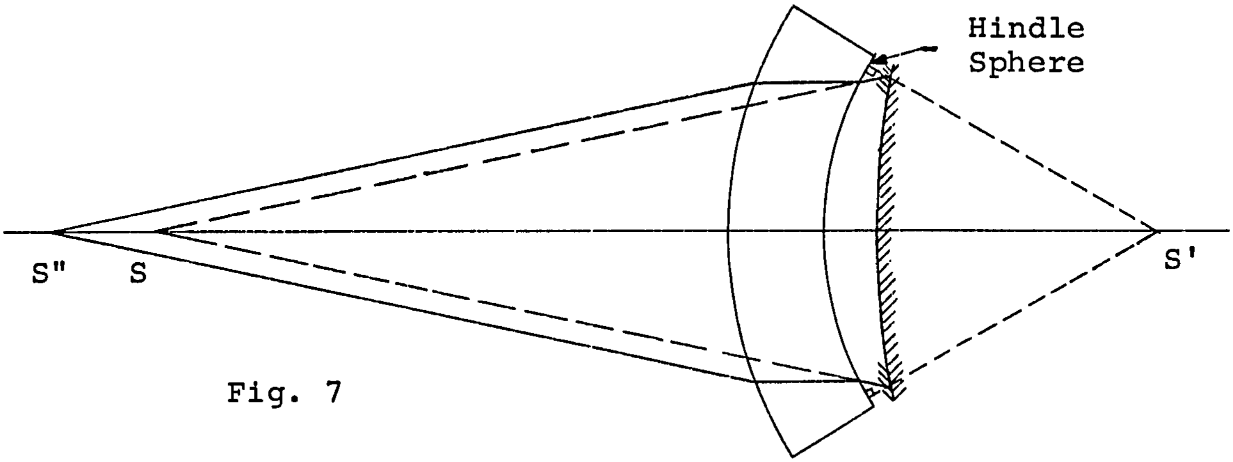

Fig. 7

This very interesting method was proposed by Grubb-Parsons (19) and has been used successfully in the manufacture of the secondary mirrors for the Anglo-Australian 3.9 m telescope.

It should be noted that the method, unlike the normal Hindle Sphere, has the classification A2 because the passage through the meniscus introduces aberration. Theoretically, the amount of this aberration can be calculated, but a considerable weakness remains in the test in the above simple form because inhomogeneity of the meniscus material will impress the traversing wavefront with errors which may be systematically worked into the mirror surfaces. One method used by Grubb-Parsons to perform an independent check on the homogeneity is by turning the meniscus round and testing it in a concentric arrangement against a concave spherical mirror (Fig. 8). This is an elegant way of checking the homogeneity and the only objection that may be raised is that the light path through the meniscus is not identical in the two tests because the meniscus has been turned round.

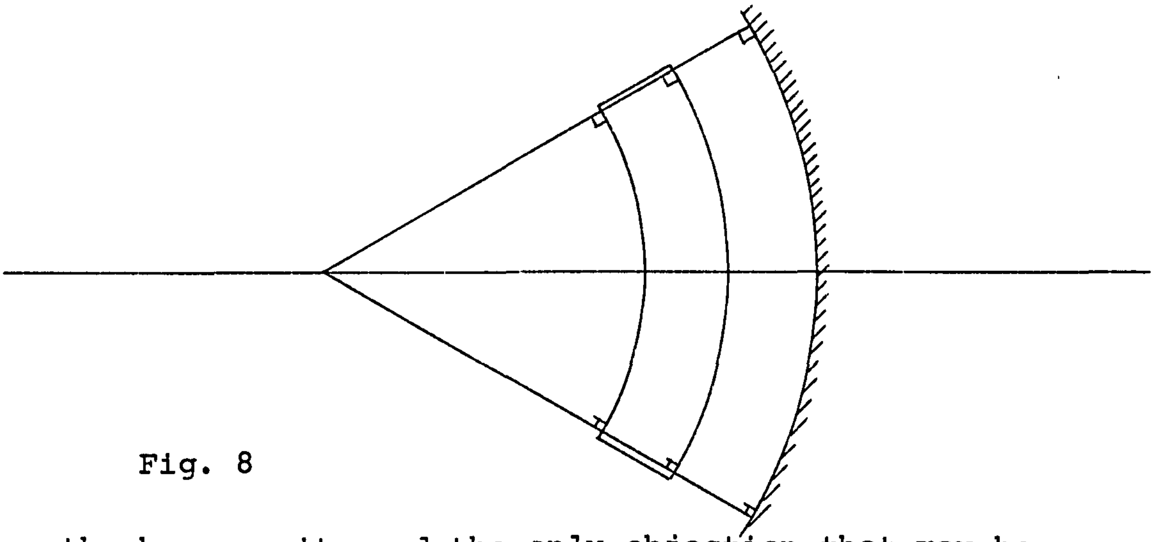
Fig. 8

While discussing the method with the author, S.C.B. Gascoigne made the suggestion that the meniscus could be tested against a concave mirror without turning it round. Gascoigne envisaged at first a non-null method in which the inhomogeneity of the meniscus would show up as irregularities of the interference fringes corresponding to the theoretical aberration of the meniscus used as in Fig. 7. A more certain check would be provided if the theoretical aberration is compensated by a single weak, positive lens which could even be retouched on one face to correct wavefront errors due to inhomogeneity (Fig. 9). (Alternatively, the compensation could be achieved by aspherising the convex face of the meniscus).

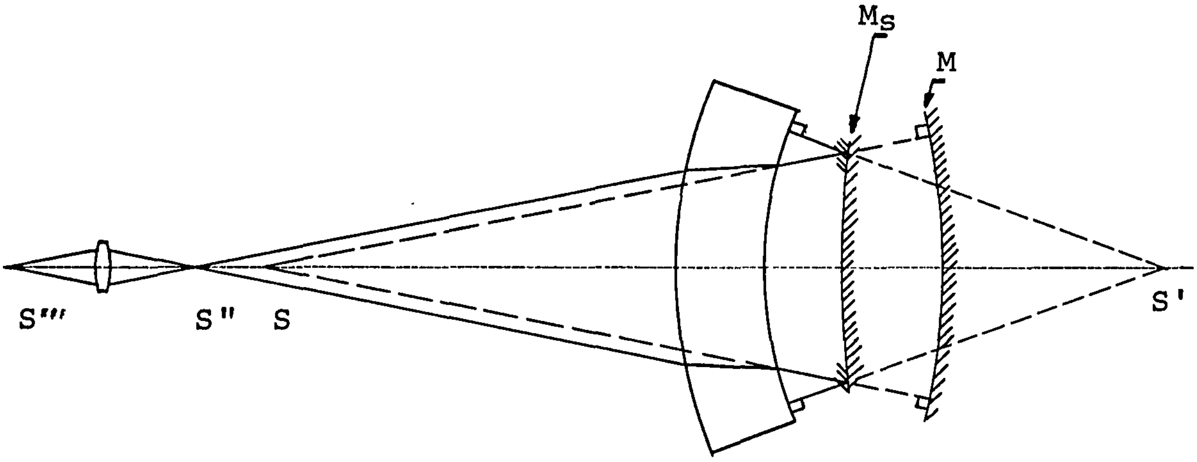

Fig. 9

In this way, it is possible to check directly in the actual test set-up of the meniscus that the wavefront emerging and impinging on the concave spherical mirror M is spherical within a prescribed tolerance. M is then removed and the secondary mirror Ms, which is to be tested, moved into place. The compensation of the small amount of aberration introduced by the meniscus is a simple problem: by this device, the combination of Meniscus H-S with simple lens becomes the full practical equivalent of a larger classical H-S, but without the necessity for such a large diameter. Such possibilities have already been envisaged and tried out by Grubb-Parsons (19).

c) Advantages: Classification B1. Considered as a unit, the combination of Meniscus H-S and compensation lens assumes the Classification A1. The method is compacter and certainly cheaper than classical H-S.

Disadvantages: For large telescopes, the size of meniscus blank required may be difficult to obtain with good homogeneity particularly if some reserve of diameter is provided to extend the use to several secondaries. However, if the wavefront is checked as in Fig. 9 with the concave mirror M and retouching of the compensation lens is performed, this objection has very little weight. The method is, however, less flexible in its application to different secondaries than a large Hindle Sphere.

d) This method, particularly if the quality of the spherical wavefront is established as in Fig. 9, is unquestionably one of the most interesting for telescopes like the ESO 3.6 m.

2.6.3 Auxiliary lens in front of secondary

2.6.3.1 With spherical surface

a) Classification A2 and B1.

b) This method is analogous to 2.4.3 except that the additional lens is the only additional element in the ray path (Fig. 10). The necessary refracting power is stronger than that needed in 2.4.3 and it may be considered as a condensor overcoming the negative refracting power of the convex mirror. A plane-spherical lens introduces considerable undercorrected aberration in addition to that given by the mirror. Undercorrected spherical aberration is more difficult to compensate than overcorrected aberration (see ref. 3). The method also implies the manufacture and testing of a convex spherical surface and high

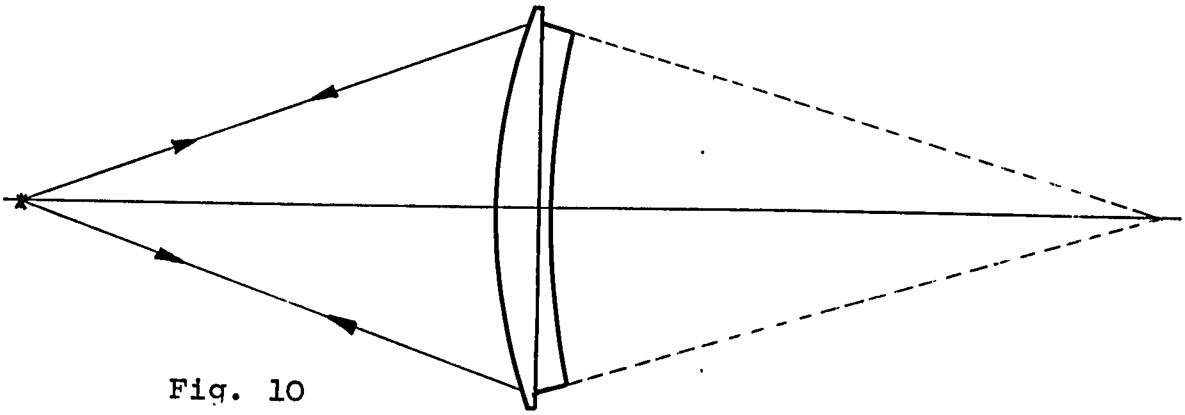

Fig. 10

homogeneity of the lens. Since the lens material can be chosen from the point of view of good homogeneity, the problem is less serious than getting good homogeneity in the mirror blank. Nevertheless, the method is not feasible for telescopes of the size of the ESO 3.6 m instrument.

c) <u>Advantages:</u> Classification B1. Directness and compactness.

<u>Disadvantages:</u> Classification A2 with awkward compensation requirements. Manufacture and particularly homogeneity problems of the lens.

d) Not feasible for telescopes as large as the ESO 3.6 m instrument.

2.6.3.2 <u>With aspheric surface</u>

a) Classification A1 and B1.

b) The convex surface of the lens in Fig. 10 is aspherised to give a Null-System in the test set-up, the aspherising being performed by testing the convex surface as a concave mirror from the back. This method has advantages over method 2.5.1 if lens material is available with the necessary homogeneity but the mirror material is inadequate in this respect. The method is analysed in ref. 3. For the same reasons as for method 2.6.3.1, it is not feasible for large telescopes. The production of the lens may be performed using methods 2.5.1 or 2.5.2.

c) <u>Advantages:</u> Classification A1 and B1, but the production of the lens may involve an A2 method. Directness and compactness. Compensation problem for lens surface solvable.

Disadvantages: Use of auxiliary aspheric surface. Homogeneity requirement of lens.

d) Not feasible for telescopes as large as the ESO 3.6 m instrument.

2.6.4 Concave matrix mirror - interference test

a) Classification A2 and B1.

b) Together with the Hindle-Sphere, this is one of the most widely used test methods and has produced good telescopes. The convex secondary is tested against a concave aspheric matrix glass as a Null-Interference Test. For tests of the mirror without its cell, it is quite feasible to observe the interference through the back of the mirror. The homogeneity requirements for observing interference effects are very modest: in fact, any normal mirror material is acceptable. If a test in the mirror cell is required, the observation of the interference fringes must be done from the front. This requires a condenser lens with an aspheric surface of fairly low quality.

The aspheric matrix glass is concave and is tested at its centre of curvature in a conventional manner. Since it delivers overcorrected spherical aberration, the design of a compensation system is no more difficult than that of the primary mirror.

Some workshops (see, for example, ref. 9) use a spherical matrix glass for test purposes. However, although this can give a useful guide to the general form and smoothness of the figure, the relatively large number of interference fringes precludes the high accuracy necessary for the final assessment.

c) Advantages: Classification A1 and B1, including edge zone of secondary for field. Directness of interpretation of test results. Compactness of test set-up.

Disadvantages: Cost and technical difficulty of aspheric matrix glass, where production is classification A2. Inflexibility of method - matrix glasses cannot be used for other projects without re-working.

d) This method is already in use for telescope projects of comparable size and its technical feasibility is well established for smaller projects. If the cost of aspheric matrix glasses - bearing in mind the existence of spherical ones - is low compared with that of a Hindle-Sphere, the method could certainly be considered for the ESO 3.6 m telescope. Since the method has classification B1, it is well suited to complement the pentaprism test 2.2.4.

2.6.5 Richardson test

a) Classification A2 and B1.

b) This method, proposed by Richardson (20) resembles the Lytle test (paragraph 2.4.4) in its basic philosophy, but uses an auxiliary spherical mirror instead of the primary mirror as the element producing the real image (Fig. 11). The concave spherical mirror is not much larger than the secondary because it is much closer to it than the primary mirror in the Lytle test. As in the Lytle test, it images the point O' at O" such that O" is the c. of c. of the secondary. It thus works with a magnification very different from unity, whereas the primary mirror in the Lytle test departs

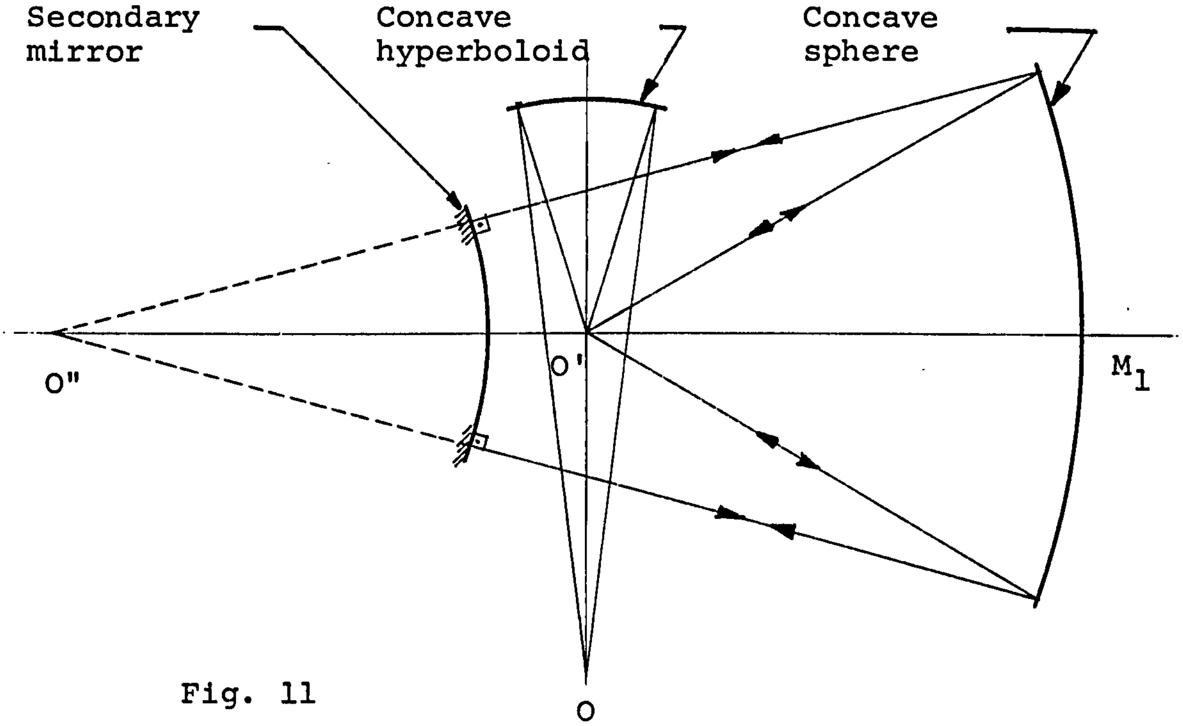

Fig. 11

relatively little from unit magnification. Used in this way, the concave spherical mirror working in double-pass introduces strong undercorrected spherical aberration, exactly the opposite of that introduced by a paraboloidal or hyperboloidal primary used in the Lytle test. As in the Lytle test, the secondary contributes undercorrected spherical aberration, but in that test the overcorrection from the primary in double-pass produces a balance of overcorrection. In the Richardson test, the image O' is strongly undercorrected. This is the validation of the imagery of O' in O by a concave hyperboloid rather than a positive lens system. The hyperboloid produces strong overcorrection, thus giving a Null-Test at O.

Because of the sign of the aberration, the design of a lens compensator is probably difficult (3), as a negative lens is required which forms a virtual image. The auxiliary concave hyperboloid could be tested at its c. of c. by conventional methods. In this sense, the method has analogies with paragraph 2.6.3.2.

c) Advantages: Classification B1. Much shorter total ray path than the Lytle method. Relatively small size of auxiliary optics. Auxiliary spherical mirror may be used as a coudé spectrograph camera mirror.

Disadvantages: Classification A2 with awkward compensation requirements for a lens system. Compensation with a concave hyperboloid means manufacture of an auxiliary aspheric surface with consequent additional source of error.

d) A method of great interest for large telescopes.

3. Resumé of suitability for secondaries of ESO 3.6 m telescope

In view of the current use of the pentaprism method 2.2.4, it is important that any auxiliary method should be complementary from the point of view of its advantages and disadvantages. Thus, only methods with classification B1 appear interesting, preferably covering the edge of the secondaries required for field coverage in the telescope.

Only a few of the methods fulfilling the classification B1 requirement are feasible for a telescope of this size. The most interesting seem to be methods 2.4.1 (double reflection at primary), 2.4.4 (Lytle test), 2.6.1 (Hindle-Sphere), 2.6.2 (Meniscus Hindle Sphere), 2.6.4 (concave matrix mirror), and 2.6.5 (Richardson test). The major advantages and disadvantages of these methods are tabulated here (they all have the advantage of B1 classification):

Method	Title	Major Advantages	Major Disadvantages
2.4.1	Double reflection at primary	Cheapness. Short test length compared with 2.4.4. High sensitivity because of double pass.	Demands on inner zones of primary. Only applicable to QRC secondary. Classification A2.
2.4.4	Lytle test	Cheapness. Places fewer demands on primary than 2.4.1. Applicable to both QRC and coudé secondaries.	Relatively long test length. Single pass. Classification A2.
2.6.1	Hindle-Sphere	Flexibility. High sensitivity because of double pass. Classification A1.	High cost.
2.6.2	Meniscus Hindle Sphere	Moderately flexible and compact. High sensitivity because of double pass. Reduced size and cost compared with classical Hindle-Sphere. Simple compensation to produce classification A1.	Classification A2 in basic form. Reduced flexibility compared with 2.6.1. Reasonable homogeneity required for meniscus.
2.6.4	Concave matrix glass	Compactness. Cheaper than 2.6.1. Classification A1 in test set-up.	Intermediate in cost. Indirectness because of auxiliary aspheric surface. Inflexibility compared with 2.6.1 (no subsequent use for matrix glass).

2.6.5	Richardson test	Compactness compared with Lytle test - reduced total ray path. Relatively small size of auxiliary optics. Aux. concave sphere may be used for a coudé spectrograph camera. Flexibility in application of this mirror to testing different secondaries.	Classification A2 with awkward compensation requirements for a lens system. Concave hyperboloid implies additional aspheric surface with consequent source of error; the hyperboloid may only be useable with one secondary.

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