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THE OPTICS OF THE ESO 3.6 METRE TELESCOPE

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by

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P R E F A C E

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 second of the series and will be followed in the near future by others.

S. Laustsen

Leader of TP Division, ESO

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The Optics of the 3.6 m Telescope

1. Purpose of present report

It is the purpose of this report to give a resumé of the astronomical/technical arguments leading to the choice of the telescope parameters; to discuss in some detail the optical design considerations which fixed the final form of the mirrors; and to give an account of the manufacture and test results with final values of the parameters. No discussion is given here of auxiliary optics for acquisition or guiding: this will be dealt with in a separate report.

2. Basic parameters

Most modern reflecting telescopes have basic parameters laid out more or less according to the recommendations of Bowen [(1)] with prime focus, Cassegrain and coudé observing stations working at relative apertures of about f/3, f/8 and f/30 respectively. The ESO 3.6 m telescope has parameters in close agreement with these recommendations.

An excellent discussion of the considerations involved in fixing the basic parameters has been given by Fehrenbach [(2)]. The main reasons for the decisions will simply be summarized here:

2.1 Aperture

The original aperture of 3 m was upgraded to 3.5 m to allow sufficient space for the prime focus cage. Because the blank as finally cast was somewhat larger, the final free diameter is 3.57 m.

2.2 Relative apertures at the three foci

In the Bowen conception, the most important observing station is the Cassegrain with a relative aperture of the order of f/8. An analysis for the ESO telescope confirmed that the most efficient relative aperture from the point of view of limiting magnitude, sky background and exposure time was about f/6 to f/8. Even at f/6, if this relative aperture were used at the prime focus, the tube length and dome size would have been prohibitive. Thus the Cassegrain form, whose basic and most important feature is its strong telephoto-effect, emerges as the natural solution for providing a short tube length combined with the required relative aperture. For a practical image position behind the primary and an acceptable obstruction ratio of the secondary, the primary mirror would have to be excessively steep to yield a relative aperture at the Cassegrain focus of f/6. With f/8 at the Cassegrain focus, a relative aperture of the primary mirror of about f/3 gives an acceptable obstruction ratio.

The acceptability of an f/3 primary will depend on the feasibility of its manufacture which will depend on its form as well as its relative aperture; also on the astronomical usefulness, which in turn will depend on the field size obtainable with good optical correction and acceptable complexity of correctors. This is discussed in more detail below. Adequate optical solutions exist but it is nevertheless debatable whether a prime focus station is justified in view of the mechanical complications associated with a prime focus cage. However, as with all other telescopes of this size, it was decided to retain the prime focus observing station. Manufacturers were confident that good quality primaries of this relative aperture were technically feasible, although very difficult.

The relative aperture of the coudé was fixed at f/30. The efficiency of a coudé spectrograph, properly dimensioned, only depends on the absolute aperture of the telescope, not on its relative aperture. For a given grating size the longer the focal length of the telescope, the longer will be the spectrograph collimator unless a focal reducer is used. Thus, there is no interest in increasing the focal length of the telescope at the coudé focus further than necessary. A relative aperture of f/30 gives a secondary of comparable size to that of the Cassegrain so that it is conveniently placed in the tube for switching from one system to the other. In the last few years, however, evidence has been accumulating that high-reflectance dielectric mirrors bring such advantage in light gain that they must be seriously considered. Since such coatings are at present only possible on smaller mirrors and only smaller mirrors are suitable for changing with the spectral region, an additional coudé module working at f/150 is now under consideration.

The finished mirrors of the basic f/3, f/8, f/30 layout have, according to Hartmann measurements of the primary and final calculations of the Cassegrain and coudé systems based on them, relative apertures for the free diameter of 3,57 m as follows:

Prime focus without corrector:	f/3.04
Cassegrain focus without corrector:	f/8.09
Cassegrain focus with corrector:	f/8.41
Coudé focus:	f/31.79.

These values have been subsequently confirmed by auxiliary optical tests.

Thus the relative apertures at the prime and Cassegrain foci are very close to those originally prescribed. The reduction of the relative aperture by about 6% in the coudé case is for purely technical reasons in the manufacture of the secondary. This increase in focal length can be accommodated in the present concept of the coudé spectrograph.

2.3 Geometry of coudé system

The geometry of the coudé system is largely dictated by the limited number of telescope mountings feasible for a telescope of this size. The types most frequently considered are the fork type, the horseshoe yoke type (Palomar) and the mixed fork-horseshoe type. The latter was chosen for the ESO telescope. Such a mounting requires three plane mirrors for the coudé system, the last being moveable if different coudé laboratories are to be fed. (A two plane mirror system is in fact possible and has been used in the 2.2 m fork-mounted telescope of the Max-Planck Institute [3]. However, this arrangement has a moveable first plane mirror, leading to some complication of the tube structure, and a vertically mounted spectrograph). Fig. 1 shows schematically the final geometry of the coudé system.

As stated above, a complementary coudé system of the Richardson type, using small dielectric mirrors, is also being studied.

3. Optical design

3.1 Cassegrain focus

This focus being considered astronomically the most important, its requirements fixed the form of all the mirrors. However, the decision has important implications for the other two foci, particularly for the prime focus.

The two mirror Cassegrain arrangement achieves its optimum form as a Ritchey-Chrétien aplanatic telescope. Most other modern telescopes of similar size are strict Ritchey-Chrétiens or minor modifications thereof. The only case against such a solution is that the prime focus is useless without a corrector because of the overcorrection of the R.C. primary, and that the coudé focus has considerably more field coma than the classical telescope, which may be a disadvantage in offset-guiding. Apart from the R.C. and classical (paraboloidal primary) telescopes, the only other candidate of interest is the Dall-Kirkham telescope using a spherical secondary with an ellipsoidal primary. The D.-K. telescope is a very interesting solution if only a single Cassegrain observing station is required and only axial imagery, since it is technically much easier from the point of view of manufacture and testing of the secondary and is normally much less sensitive to decentering. The advantages and disadvantages of the three basic types may be summarized as in the table over-leaf.

Type	Advantages	Disadvantages
Ritchey-Chrêtien or Quasi-Ritchey-Chrêtien	Optimum performance at Cassegrain focus. Simplicity of correctors for residual aberrations of mirror system.	Hyperboloidal primary giving uncorrected axial image at prime focus without corrector. Coma in coudé field. More difficult to manufacture than classical or Dall-Kirkham.
Classical (paraboloidal primary)	Corrected axial image in prime focus without corrector. Coudé field virtually free from coma. Somewhat easier to manufacture than R.C.	Useful field at prime focus extremely small at f/3 without corrector. Field corrector at prime focus more difficult than for R.C. primary. Cassegrain focus suffers from significant coma at f/8. Field corrector is more difficult than for R.C. telescope.
Dall-Kirkham	Ease of manufacture of <u>one</u> secondary. Intensitivity to de-centering.	Large amount of coma in Cassegrain field. Complexity of corrector required which may eliminate the advantage of intensitivity to de-centering. Large amount of coma in coudé field. Ellipsoidal primary giving uncorrected axial image at prime focus without corrector. Undercorrection of primary is unfavourable for the provision of field correctors at prime focus. Only <u>one</u> of the secondaries can be made spherical.

It is clear that the Dall-Kirkham solution is not suited to a general purpose instrument with three observing stations.

The only optical disadvantages of the Ritchey-Chrêtien are its coma in the coudé field and the uncorrected axial image of the primary. There seems to be no clear evidence that the former is serious in practice, particularly if automatic guiders are used which lock on to the centre of gravity of the comatic image. The latter is hardly a practical objection if the primary relative aperture of f/3 is retained, since the field corresponding to 1 arcsec tangential coma is only 96 arcsecs or 5 mm in diameter. If it is accepted that this field is too small to be useful in practice so that a field corrector is anyway necessary, then the overcorrection of the R.C. primary, which facilitates this field correction, means that the R.C. or quasi R.C. solution is optically preferable for both the Cassegrain and Prime Focus observing stations.

It was considered that the manufacture of a R.C. telescope with the above parameters was technically feasible; the decision was therefore taken to assume the R.C. solution as the basis for the detailed design.

A very good account of the basic optical design considerations has been given by Köhler [(4) (5)]. Further discussions were given by Baranne [(6) (7)] and by the present author [(8) (9)].

The problem of correctors for the primary and Cassegrain foci of a telescope of this type has been the subject of extensive research during the last 15 years or so. At the time the basic design of the Cassegrain system of the ESO telescope was decided, hardly any of the currently available solutions had been investigated in detail. The simplest form of corrector, the field-flattening lens, still leaves the astigmatism of the Ritchey-Chrêtien system uncorrected. Köhler (4) (5) discovered that this can be corrected as well if the negative corrector lens is moved a short distance away from the image plane. However, it is very important to make clear that the retention of the coma correction requires some modification of the form of the mirrors. The axial beam width is such that the spherical aberration is hardly affected. Thus, this corrector fulfilled the specification set at the time that correction with the corrector should be achieved over a field of about $\pm$ 0.25° and that axial correction should be maintained when the corrector is removed. This specification permitted a departure from the aplanatic (R.C.) form of the mirror system, which is thus a quasi R.C., not a strict R.C.

The spot-diagrams of Fig. 2 show the performance of the Cassegrain system with and without corrector, in the latter case assuming optimally bent plates. These spot-diagrams are, in fact, calculated for the final system based on measurements of the finished primary. Two points are worthy of special note:

- The departure of the *quasi* R.C. form from the strict aplanatic R.C. form gives a comatic spot-diagram at, say, $\pm$ 0.20° of about one third of that of the equivalent classical telescope. In fact, the strict R.C., because of its uncorrected astigmatism, gives a spot-diagram almost as big at this field but it has the advantage of being symmetrical. Doublet correctors are now well-known [(10)] [(11)] [(9)] which give very good results over the small angular fields required in the Cassegrain foci of such large telescopes - because of limitations of plate size - while retaining the strict R.C. form of the mirrors. Given present day knowledge, it may be that a strict R.C. form would be preferred; however, the spot-diagrams of the ESO telescope *without* corrector in the Cassegrain focus show that the correction must still be rated as good and is much superior to that of a classical telescope with the same geometry (see ref. 9, figs. 6, 7 and 8).

- The size of the individual spot-diagrams with corrector remains extremely small (0.3 arcsec) if optimum focusing is performed for three regions over the range 365 nm to 1014 nm. The most serious error by far of the singlet corrector is its uncorrected chromatic difference of magnification which amounts to about 2 arcsec between 365 nm and 1014 nm at a field of $\pm$ 0.25° and grows linearly with the field. If the spectral region is divided up into three regions by plate-filter combinations, the resolution is thus about 0.7 arcsec over each region. The disadvantage of the lateral colour error of the singlet corrector may be offset by more favourable performance with regard to ghost images: apart from reflexions from the photographic plate, the singlet only yields 1 ghost image whereas a doublet yields 6. A mechanical disadvantage of the singlet corrector is its short back focal distance of 160 mm, whereas doublet correctors tend to have larger back focal distances. However, the problem of fitting in guide probes in the space available in the ESO solution seems soluble.

Fig. 3 shows the final Optical Data Sheet for the quasi Ritchey-Chrêtien focus. This, like the spot-diagrams, was based on available Hartmann measurements of the final form of the primary mirror. The aspheric constants in this Data Sheet are expressed in two different ways, according to the following formulae:

$$x = \frac{y^2}{2r} + \bar{c}_1 y^4 + \bar{c}_2 y^6 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$x = \frac{y^2}{2r} + (1 + \varepsilon_1) \frac{y^4}{8r^3} + (1 + \varepsilon_2) \frac{y^6}{16 r^5} \ldots (2).$$

3.2 Prime focus correctors

The potentialities of two basic types of correctors permitting fields of about 1° diameter were investigated by Glatzel and Köhler (4) (5) at Carl Zeiss, Oberkochen, and by Baranne at Marseille (6) (7). The former work was based on a system of three aspheric plates analysed by Meinel (12) and further developed by Schulte [13]. Baranne's work was based on earlier work of Paul [14] and used 3 lenses of much smaller diameter, one containing an aspheric surface. An exhaustive analysis of prime focus correctors has been carried out by Wynne [10] [11] [15]. Wynne has designed 3-lens correctors for the Kitt Peak and Anglo-Australian telescopes. The above three corrector types - plate type , Paul - Baranne type and Wynne types - were compared by the author [9] for the Max-Planck telescope who came to the conclusion that the Wynne type is the most favourable from the point of view of performance, and ease of manufacture. However, final decisions on a corrector covering this order of field size have not yet been taken.

Apart from the corrector covering about 1° diameter, two others are envisaged covering a more modest field with fewer elements.

A doublet corrector combined with the quasi R.C. is capable of good correction over a field of about $\pm$ 0.3°. The overcorrection of the primary brings its greatest advantage, however, with the third corrector envisaged, namely a Gascoigne plate [16] [17] [18]; for this corrector is not possible with a parabolic primary. The Gascoigne plate can provide good correction of spherical aberration and coma for fields of about $\pm$ 0.14°, a most attractive field for use with electronographic cameras. The ESO telescope is particularly favourable to this solution because its primary is somewhat more eccentric than the strict R.C. form would prescribe. The higher the eccentricity the larger the corresponding Gascoigne plate and the better its optical performance.

A subsequent technical report will give detailed results for the prime focus correctors.

3.3. Coudé focus

Fig. 4 shows the Optical Data Sheet of the coudé system, based on the Hartmann measurements of the parameters of the finished primary.

The uncorrected third order tangential coma is, of course, a linear function of the field. For a field of $\pm$ 0.05°, it amounts to 0.65 arcsec.

4. Manufacture of the optics

4.1 Primary mirror

4.1.1 The Blank

Zero expansion ceramic materials were not available at the time the blanks were ordered. It was decided to use the material of lowest expansion available at that time, namely fused quartz. Fehrenbach [(2)] gives quite a full account of the ordering of the prime mirror blank from the CORNING Glass Works at its reception by REOSC S.A. in May 1967 who had been awarded the contract for working the optical elements.

After the preliminary milling work for the central hole and the production of the necessary radius of about 21.7 m, smoothing was carried out to produce a spherical surface. It was decided to polish this surface provisionally in order to test the material. This revealed that the surface was not suitable for polishing because of some 25 000 to 30 000 bubbles present in or near it. After discussions with representatives of Corning, it was decided that the disc should be returned to the U.S.A. to be remelted and covered with a new layer of quartz. The blank left France in September 1968. In February 1969, CORNING stated that the remelted blank contained 3 holes which would affect the optical surface. Further discussions between the two firms revealed that only one hole would remain after the preliminary roughing and that this could be plugged by REOSC using a special technique. The blank was therefore provisionally accepted by an ESO-Commission and the president of REOSC in June 1969.

Work was recommenced at REOSC in September 1969. The orifice of the hole was milled out and polished to a hemispherical form. A hemispherical plug was similarly prepared from quartz supplied by Corning from the same melt and cemented in with synthetic resin.

4.1.2 Methods of working

The aspheric surface was produced and checked to an accuracy of a tenth of a micron by means of an electro-mechanical test method developed by REOSC [19]. The amount of deformation of a hyperbolic concave mirror from the starting sphere will depend on the form of deformation acceptable to the manufacturer. If a zero point is accepted at an intermediate zone, the amount of deformation can be reduced, but most manufacturers prefer a monotonically increasing deformation function from the centre to the edge even if more material has to be removed. On this basis, the deformation from the vertex curvature sphere is 0.144 mm, so that the relative accuracy of the electro-mechanical measurements was about 0,069%.

An important feature of the technique of working aspheric surfaces at REOSC is the use throughout of full-size tools possessing the necessary flexibility due to their frame construction in wood. This technique had been successfully employed on a number of f/3 mirrors, as well as Schmidt plates. The use of full-size tools clearly has advantages from the point of view of avoiding zonal errors and ripple if the asphericity can still be achieved. The asphericity is produced and controlled by the form and area of the lapping surface.

An account of the working and testing at REOSC is given by Bayle [20].

4.1.3 Testing

The testing of a concave mirror is always much easier than that of a convex mirror, because a concave surface can always be tested in autocollimation at its centre of curvature. Because of its aspheric form, the image has, of course, a large amount of spherical aberration - about 171,5 mm longitudinal aberration or a wavefront aberration for "optimum focusing" of about 2320 λ (λ= 500 nm) for the free aperture of 3.57 m.

Tests were performed using four basic methods:

4.1.3.1 Hartmann tests without a compensation system

This method has the advantage that no auxiliary optics are necessary but the corresponding disadvantage of not being a "null" method: the test must establish that the correct amount (within a defined tolerance) of third order spherical aberration is present apart from the absence of zones. Because of its discontinuous nature with regard to the aperture function, it is less suitable for checking the smoothness of the surface.

Fig. 5 is a reproduction of figures from the REOSC report to ESO on the primary. At the right, the slopes of the surface are given as a function of diameter; at the left, the integration giving the departure in microns from the "best fit" function. According to this curve, the maximum wavefront error (max. to min.) is 0.14 λ (λ = 500 nm).

The Hartmann analysis of an uncompensated primary of this eccentricity is a difficult technical process. Apart from the steepness of the wavefront aberration curve, the problem of centering is considerable. A small amount of decentering introduces coma to an extent which makes precise interpretation of the Hartmann results difficult.

REOSC came to the conclusion that the most probable values for the parameters are:

$$r_1 = 21\ 700 \text{ mm}$$

$$\varepsilon_1 = 1,\ 15175.$$

An independent evaluation of the REOSC Hartmann plates was carried out at ESO by Behr who pointed out that the longitudinal aberration deduced from the Hartmann plates will depend not only on r_1 and ε_1 but also on the distance of the source from the vertex centre of curvature of the mirror. He confirmed this by ray-tracing; results further confirmed by Baranne from ray-tracing and first order theory, and by the author from ray-tracing and by an analytical treatment. It is easy to establish the following general formula, including all orders, for the longitudinal aberration $\Delta s'_2$ resulting from a shifted source (shift = δs) relative to that, $\Delta s'_1$, resulting from a source placed at the centre of curvature.

$$\frac{\Delta s'_2}{\Delta s'_1} = 1 - 2 \left\{\frac{\delta s}{r}\right\} + 4 \left\{\frac{\delta s}{r}\right\}^2 - 8 \left\{\frac{\delta s}{r}\right\}^3 + \ldots \quad (3)$$

This formula gives very good agreement with the ray-tracing results. As an example for $r_1 = 21\ 700$ mm, $\varnothing = 3.66$ m and $\delta s = 100$ mm, $\Delta s'_1 = 178{,}623$ mm and $\Delta s'_1 - \Delta s'_2 = 1{,}624$ mm for the (uncorrected) data supposed at that time. The error is thus almost 1% for $\delta s = 100$ mm.

If we restrict the above formula to the third order term, then by a simple transformation:

$$\frac{\Delta s'_2}{\Delta s'_1} \simeq 1 - 2 \left\{\frac{\delta s}{r}\right\} \simeq \left\{\frac{\sin u_2}{\sin u_1}\right\}^2 \quad \ldots\ldots\ldots\ldots (4)$$

in which u_1 and u_2 are the ray inclinations to the axis. Further, to third order accuracy, for the corresponding wavefront aberrations:

$$\frac{w_2'}{w_1'} = \left\{\frac{u_1}{u_2}\right\}^2 \cdot \frac{\Delta s'_2}{\Delta s'_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Equations (4) and (5) are simply statements of the well-known fact that the wavefront aberration remains unchanged by such a source shift to third order accuracy, but that the longitudinal aberration varies with the square of the aperture angle.

Using the three parameters r_1, ε_1 and δs, it is possible to derive various solutions from the Hartmann results corresponding to a "best fit" to the slope-height function. Figs. 6 and 7 show several such possible solutions set up by Behr. However, without independent knowledge of r_1 or ε_1, it was not possible to decide definitely between these possibilities. Behr suggested as the most probable solution:

$$r_1 = 21\,687{,}5 \text{ mm}$$

$$\varepsilon_1 = -1{,}1550.$$

These values were used in the final calculations of the QRC and coudé systems(Figs. 3 and 4). However, the auxiliary (LYTLE) optical tests (see paragraph 4.1.3.4) indicated a slightly greater value for r_1, in close agreement with the REOSC value of 21 700 mm. Behr's analysis gives as corresponding value

$\varepsilon_1 = - 1{,}1567$, somewhat higher than the REOSC value of $\varepsilon_1 = - 1{,}15175$. This discrepancy can be accounted for by the effect discussed above, of the source position relative to the vertex centre of curvature. This effect changes the REOSC value to $\varepsilon_1 = - 1{,}1583$. Thus the alternative solution of Behr, which seems the most probable in the light of subsequent tests, is:

$$r_1 = 21\ 700 \text{ mm}$$
$$\varepsilon_1 = - 1{,}1567 \pm 0{,}0005.$$

It should be noted that the form of Figs. 6 and 7 (Behr) is in excellent agreement with Fig. 5 (REOSC).

REOSC also used the Hartmann results to analyse the energy contained in a given angular diameter, based on geometrical optics without the effect of diffraction. The contractual requirement was that 75% of the energy should fall within a diameter of 0.4 arcsec (QRC) and 0.5 arcsec (coudé). According to the first REOSC report, 97% of the energy is contained within a diameter of 0.5 arcsec and 77% within 0.25 arcsec. But a subsequent, more refined analysis by REOSC gives 98.6% within 0.4 arcsec and 100% within 0.5 arcsec (Fig. 8). They also give values for the r.m.s. error (λ/33) and the Strehl intensity ratio (96%). The values of this analysis do not take account of residual astigmatic errors, but the evidence is that these are small (see paragraph 4.1.3.4).

4.1.3.2 Null tests with a compensation system

An OFFNER type compensator giving negligible theoretical residual aberration for the combination (lateral aberration only 1.8 μ diameter), was used for a Null-Test examination of the image of a pinhole source 0.3 arcsec diameter. The image of the source was found by REOSC not to exceed 0.4 arcsec diameter from which it was concluded that the transverse aberration for optimum focus and optimum adjustment of the compensator did not exceed 0.1 arcsec.

Fig. 9 shows a FOUCAULTGRAM of the image of a slit of width 0.1 arcsec. This shows that the surface is very smooth. Two zones are observable, the outer one with a diameter of about 2550 mm being the stronger. This corresponds to the maximum change of slope of about 0.35 arcsec detected in the Hartmann measurements. Integration gave $\lambda/36$ as the maximum wavefront error in this region of the mirror.

It should be emphasized that no clear information was drawn from this test regarding the first order (vertex radius) and third order form (Schwarzschild constant) of the primary. In principle, such information can be obtained by tight tolerancing of the radii of the compensator and careful measurement of the position of the principal compensation lens required to achieve optimum correction.

4.1.3.3 Wave Shearing Interferometer (W.S.I.) Tests

W.S.I. tests of the primary were performed by G. Monnet using a He-Ne Laser. These tests were able to confirm the smoothness of the primary mirror surface. The determination of the asphericity was in agreement with that deduced from Hartmann measurements but the accuracy was at least an order of magnitude lower.

4.1.3.4 Auxiliary tests of the telescope optics by the method of LYTLE

The main purpose of these tests was to check the secondary mirrors, but a subsidiary aim was to provide evidence of freedom from astigmatism of the primary and to determine independently its vertex radius.

The results of the LYTLE tests will be given in detail in a future Technical Report. So far as the primary mirror is concerned, the following results emerged:

- The primary is tested in this method in double pass. The zones shown in the Foucaultgram were clearly visible but the very good general smoothness was confirmed.
- In double pass and in combination with the coudé secondary, the astigmatism was less than 0.1 arcsec.
- The value deduced for the vertex radius of curvature was

$$\underline{r_1 = 21\ 705 \text{ mm} \pm 10 \text{ mm.}}$$

4.1.3.5 Conclusions regarding the primary

The tests by diverse methods described above have given very clear information regarding the primary mounted in its cell with vertical axis.

All tests have indicated a very high quality of smoothness.

The information on basic parameters can be summed up as follows:

Method and Evaluation	r_1 (mm)	ε_1
Hartmann - REOSC	21 700	- 1,15175 (ignoring effect of source position)
Hartmann - Behr	21 687,5 or 21 700	- 1,1550 - 1,1567
Lytle - Wilson	21 705	

From this evidence, it is proposed to assume for further calculations on prime focus correctors the following values for the prime mirror parameters as the most probable:

$$r_1 = 21\,700 \text{ mm} \pm 10 \text{ mm}$$

$$\varepsilon_1 = 1{,}1567 \pm 0{,}0005 \text{ (for a given value of } r_1\text{).}$$

The LYTLE tests did not give explicitly a value for ε_1. However, the fact that the aberration was correctly compensated for the correct positions of the compensation lenses in the QRC and coudé cases confirms very well the values given by Behr.

Small errors in the prime focus correctors resulting from errors in the mirror parameters are not in themselves very serious since the correctors can be adjusted in position relative to the focus to correct the spherical aberration; if the shift from the theoretical position is small, the field correction (coma) will not be appreciably affected. Nevertheless, it is highly desirable to have values as accurate as possible for the parameters; for otherwise the mechanical design of the prime focus adapter is complicated by the provision of sufficient reserves for adjustment of the optical elements.

In summary, there is clear evidence that the primary mirror is extremely smooth and that its parameters are very close to those given in the optical data sheets (Figs. 3 and 4). There seems little doubt, so far as its performance in its cell with vertical axis is concerned, that the contractual specification of 75% (geometrical) energy concentration within a diameter of 0.4 arcsec in the QRC focus has been more than fulfilled: the mirror is probably significantly better than this.

Some test material with horizontal axis is available and suggests that the quality is not markedly inferior. However, the technical problems due to air turbulence are so considerable that final judgement of the performance of the mirror and cell with non-vertical axis will have to be reserved until the telescope is in operation.

The primary mirror was formally accepted by ESO in February 1972.

4.2 Secondary mirrors

4.2.1 The blanks

It was decided to use low expansion material also for the secondary mirrors. The blanks are thus also of fused quartz, supplied by HERAEUS.

4.2.2 Methods of working

Similar methods of working were employed at REOSC for the secondaries as for the primary. Although these mirrors are much smaller, the difficulty of manufacture is at least as great, probably greater, than that of the primary. The difficulty is due partly to the much higher eccentricity of the secondaries (Schwarzschild constants ε_1 - 6.91 for the QRC and - 2.18 for the coudé), and partly to the convex form, which is fundamentally both more difficult to test and also to asphérize. A monotonic aspherization function is not possible on a convex hyperbolic surface. The maximum deformation from the sphere of departure is about 22 μ in the QRC case, 16 μ in the coudé case.

4.2.3 Testing

The testing of the convex secondaries is one of the major problems in the manufacture of modern reflecting telescopes. REOSC had proposed and used (21) during manufacture a method of great elegance and offering many advantages, namely the double pentaprism method. The use of a moveable pentaprism for testing a telescope was probably first suggested by Wetthauer and Brodhun in 1920 (22).

Methods for testing convex secondaries will be analysed in a future ESO Technical Report. The advantages of the pentaprism method derive basically from the fact that it is a functional test, simulating the performance of the primary and secondary mirrors in the actual telescope. This is a very important advantage, for it means there are only two mechanical tolerances to be respected and these are easily held: the source position relative to the vertex of the primary and the separation of the mirrors. Any error in the parameters of the primary is automatically compensated by the secondary.

Thus the image, if placed at the source position will automatically be free from spherical aberration. The limits to the mechanical tolerances mentioned above are thus set by the introduction of coma into the QRC image when using the corrector and by the mechanical possibilities for shifting the final image from its theoretical position. The following tolerances were established on this basis:

Source position:	QRC:	− 0 mm
		+ 50 mm
	Coudé:	± 390 mm.

This tolerance is set by spherical aberration introduced by focusing with the secondary mirror to shift the final image. The effect on coma is negligible.

Mirror separation: ± 28.7 mm introduces 0.1 arcsec of coma at ± 0.25° of the QRC field. Since this is technically very easy, a tolerance of ± 10 mm was prescribed.

Although errors in the parameters of the primary will not introduce spherical aberration, they will nevertheless change the coma and, to a lesser extent, the astigmatism, at each of the three foci. This does not matter for the coudé focus (coma fully uncorrected) or the QRC focus without corrector (residual coma small but not negligible), but it will affect the performance of the QRC focus with corrector and the prime focus correctors since these correctors are calculated for assumed mirror parameters.

REOSC presented a complete analysis of the pentaprism test results. Figs. 10 and 11 show the slope-height functions of the wavefront emerging from the QRC combination for field heights 0 mm, 105 mm and 140 mm. Figs. 12 and 13 show the geometrical energy concentrations calculated from these values for a mean of three meridians. These values are well within the contractual requirement of 75% to be included within a diameter of 0.4 arcsec.

In the coudé case the field supplement to the diameter is small. Figs. 14 and 15 show the slope-height function and the geometrical energy concentration. Again the concentration is well within the contractual tolerance of 75% within a diameter of 0.5 arcsec.

Although the double-pentaprism test procedure has real advantages from the point of view of ensuring freedom from spherical aberration in the secondary images, it suffers from certain weaknesses:

- Examination of the whole pupil at one time is not possible, so that detection of errors of high spatial frequency, such as ripple, is very difficult. Furthermore, it is difficult to make measurements corresponding to the edge of the free aperture of the primary.

- Since the measurement over each meridian is normally referred to its own optimum reference sphere, detection of astigmatism is not easy.

- The precision of measurement estimated by Espiard and Favre [21] is about $\pm 10^{-6}$ rad or $\pm$ 0.2 arcsec. While it is not easy to achieve greater precision with other methods, this uncertainty nevertheless makes an independent test desirable.

- The actual position of the coudé focus is many meters behind the primary, a position which is not accessible for the source for tests with a vertical axis. REOSC overcame this difficulty by using a third, concave mirror placed in front of the primary as a focal reducer. This mirror is theoretically a hyperboloid of moderate eccentricity. Although theoretically the use of the third mirror is of no consequence, it nevertheless introduces a third element with inevitable additional sources of error.

- The excess diameter of the QRC secondary necessary for the field can only be tested in conjunction with the QRC corrector using an off-axis source and tilted pentaprism. This complication may also introduce errors; on the other hand, the corrector is tested in function with the mirrors.

For these reasons, it was decided that auxiliary optical tests would be valuable. The method chosen should complement the pentaprism method, its prime aim being to provide a test of smoothness. If possible, it should also give information regarding astigmatism and the parameters of the primary mirror. Following an analysis (to be given in a future technical report), the choice fell on the method proposed by J.D. Lytle [(23)]. A full account of these tests is given in a separate report. Only the principal results will be quoted here. The tests were successful in all three respects:

- The coudé secondary is about as smooth as the primary; the QRC secondary is even better. The principal zone on the primary appeared doubled in height in the LYTLE test and gave an excellent comparison measure. Slight zones could be identified on the secondaries with reference to the slope-height curves of Figs. 11, 12 and 15, also the turned up edge in the QRC case.

- The coudé LYTLE combination indicated a residual astigmatism less than 0.1 arcsec. The QRC LYTLE test was less conclusive in this respect but could detect no astigmatism attributable to the primary or secondary.

- A value for the vertex radius or curvature of the primary of 21 705 ± 10 mm was deduced. This gave excellent confirmation of the value deduced from the Hartmann tests.

In view of this very satisfactory confirmation of the pentaprism test results, the secondary mirrors were formally accepted in December 1973.

4.3 Coudé plane mirrors

The coudé plane mirrors are not yet completely finished. Testing has been performed in the usual way by the Common-Ritchey method of insertion in the beam illuminating a high quality concave spherical mirror from its centre of curvature. Because of turbulence, a horizontal arrangement does not allow a sufficiently accurate assessment of flatness. Hence, the mirrors are being tested in the final stages in the vertical test tower of the primary, the spherical mirror being placed near the side of the tower with axis horizontal and the plane mirror under test deflecting the axis vertically.

It is expected that the plane mirrors will be accepted by the Spring of 1974.

4.4. QRC corrector

This singlet negative corrector of free diameter 310 mm is a relatively simple element to manufacture. The material is UBK7. Being near the image plane, the tolerances regarding form and homogeneity are simple to meet. Acceptance, which will take place shortly, will be based on test plate results, on Foucault tests of the front (concave) surface and on the combined pentaprism test with the primary and secondary mirrors, described above.

4.5 Prime focus correctors

None of these is finally designed at this stage. The manufacture will be the subject of new contracts.

Acknowledgments

The author would like to express his sincere gratitude to the firm of REOSC for their excellent cooperation and generous provision of material; to the CARL ZEISS foundation, where many of the calculations were performed, for the spot diagrams reproduced in this report; and to his colleague, Professor A. Behr, for his collaboration, particularly with regard to the evaluation of the Hartmann tests of the primary.

References

1. I.S. Bowen: Publ. Astron. Soc. Pacific 73, 114 (1961)
2. Ch. Fehrenbach: Proceedings of ESO/CERN Conference on "Large Telescope Design", 1971, p. 99
3. K. Bahner: Sterne u. Weltraum 12 (4), 103 (1973)
4. H. Köhler: ESO-Bulletin No. 2 (1967)
5. H. Köhler: Appl. Opt. 7, 245 (1968)
6. A. Baranne: Publ. de l'Observatoire de Haute Provence 8 (22), 75
7. A. Baranne: In "The Construction of Large Telescopes" Proc. IAU 27, Academic Press, 22 (1966)
8. R.N. Wilson: Appl. Opt. 7, 253 (1968)
9. R.N. Wilson: Proceedings of ESO/CERN Conference on "Large Telescope Design", 1971, p.131
10. C.G. Wynne: Appl. Opt. 4, 1185 (1965)
11. C.G. Wynne: Astrophys. J. 152, 675 (1968)
12. A.B. Meinel: Astrophys. J. 118, 335 (1953)
13. D.H. Schulte: Appl. Opt. 5, 313 (1966)
14. M. Paul: Rev. d'Opt. 14, 169 (1935)
15. C.G. Wynne: "Progress in Optics", Vol. 10, 139 (1972)
16. S.C.B. Gascoigne: Observatory 85, 79 (1965)
17. S.C.B. Gascoigne: Quart. J. Roy, Astron. Soc. 9, 98 (1968)
18. S.C.B. Gascoigne: Appl. Opt. 12, 1419 (1973)

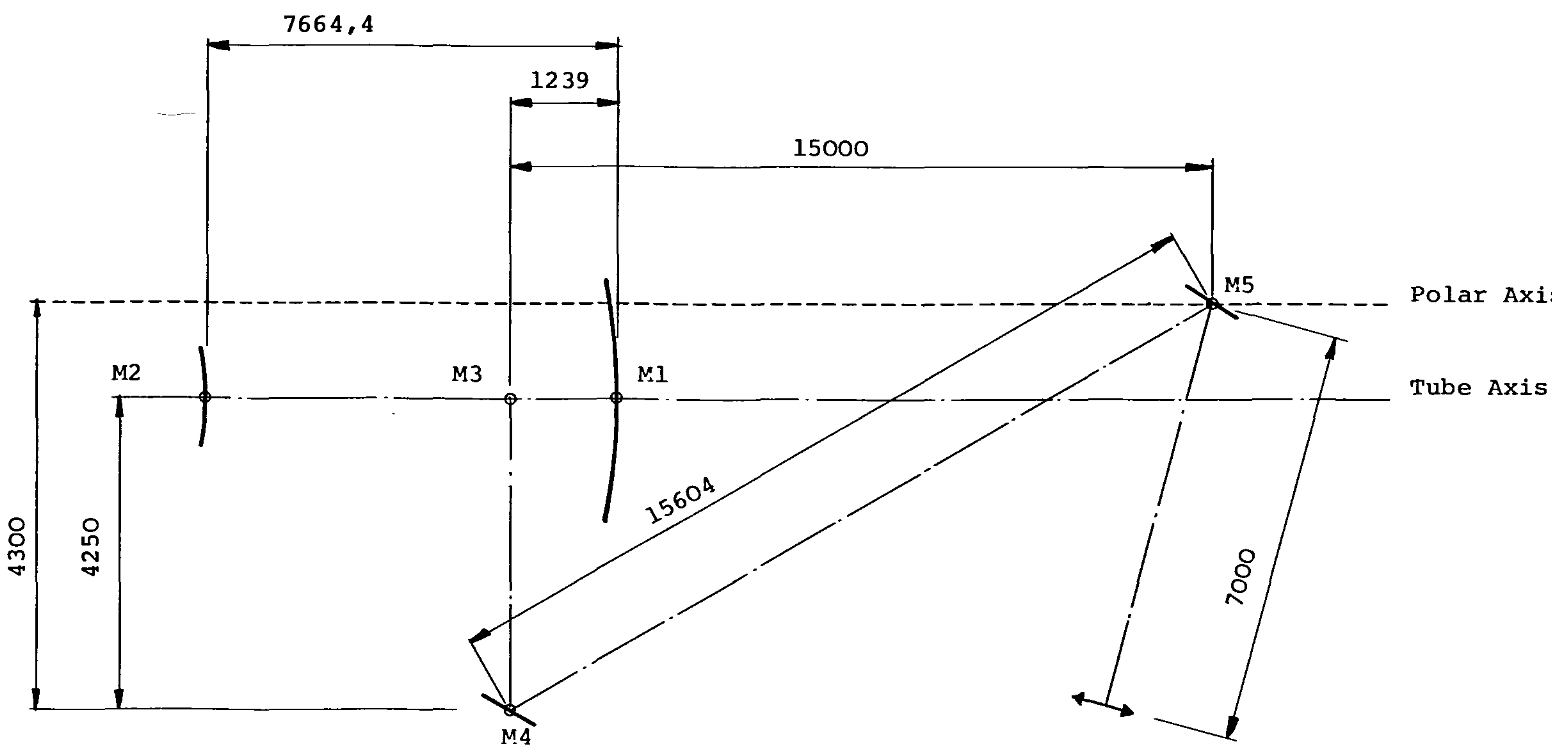
19. J. Espiard: Proceedings of ESO/CERN Conference on "Large Telescope Design", 1971, p. 219

20. A. Bayle: Ref. (19) p. 229

21. J. Espiard and B. Favre: Nouv. Rev. d'Opt. 1, 395 (1970)

22. Wetthauer and Brodhun: Zeitschr. f. Instrumentenkunde 40, 96 (1920)

23. J.D. Lytle: Appl. Opt. 9, 2497 (1970).



$\bar{s}'$ = 4250 + 15604 + 7000 - 1239 = 25615 mm

FIG. 1 : Geometry of Coudé System (schematic)

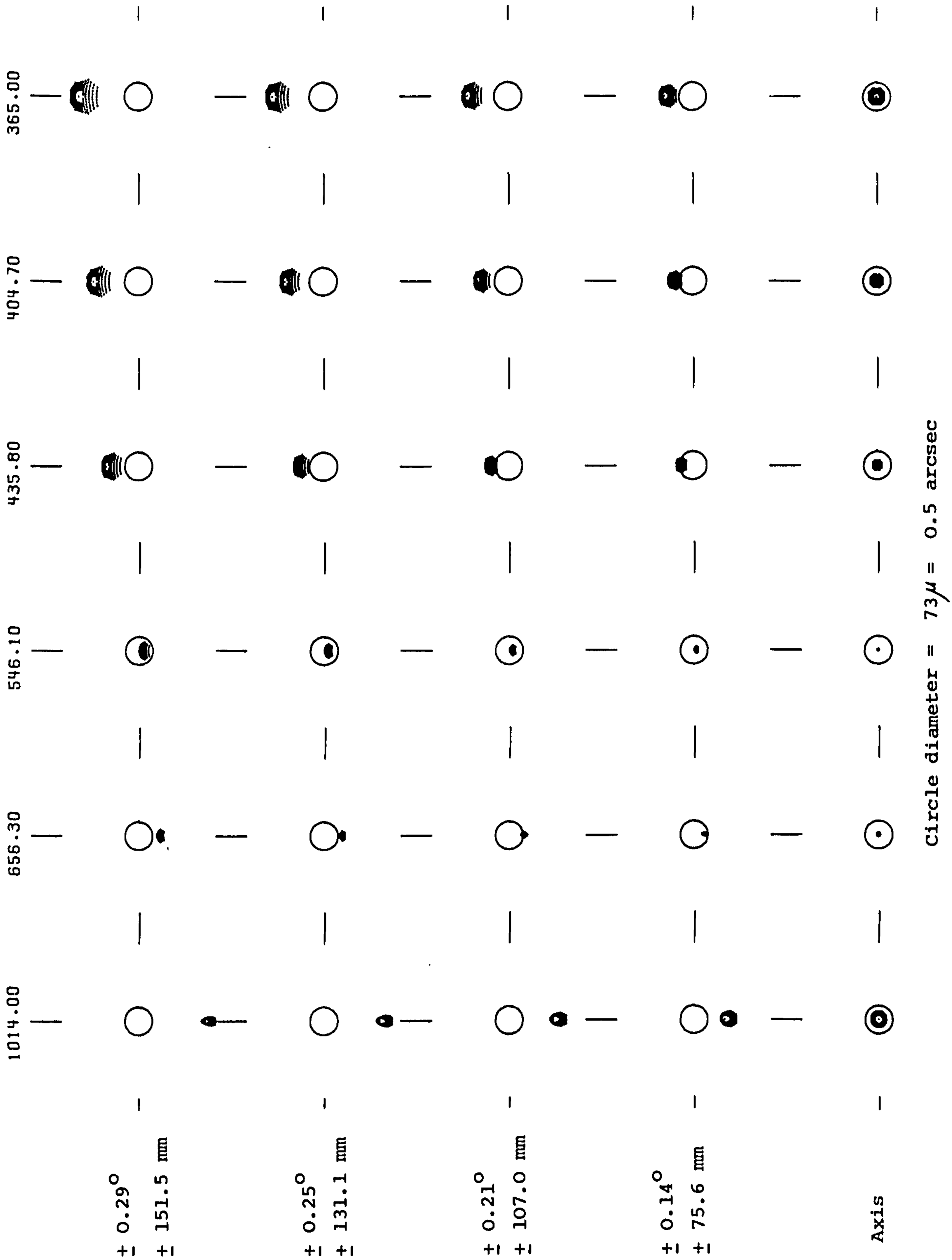


Fig. 2a(i) : Spot diagrams showing the theoretical image quality of the QRC system <u>with</u> corrector (flat field). Optimum focus for green (approx. best mean focus).

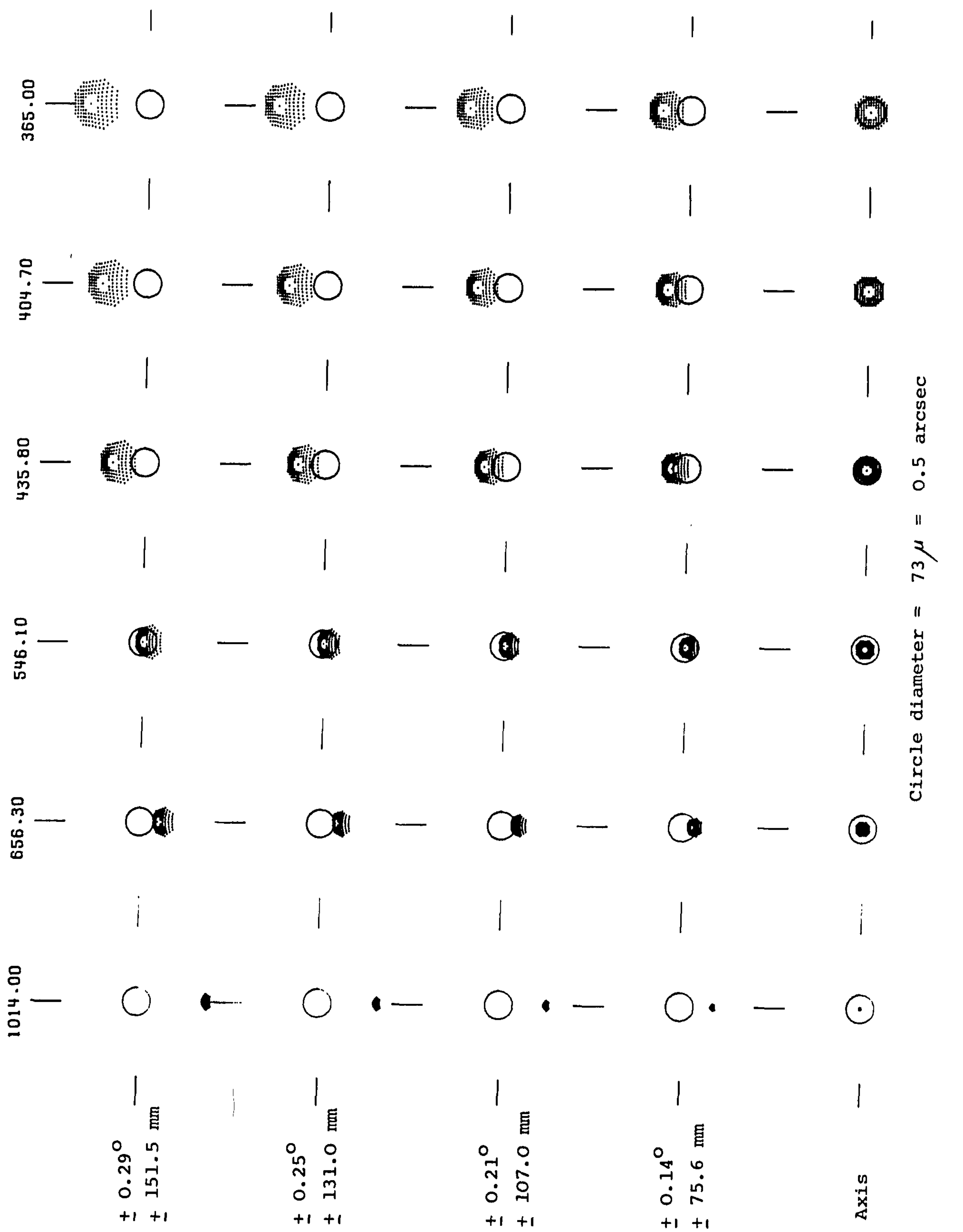


Fig. 2a(ii) : Spot diagrams showing the theoretical image quality of the QRC system <u>with</u> corrector (flat field). Optimum focus for red.

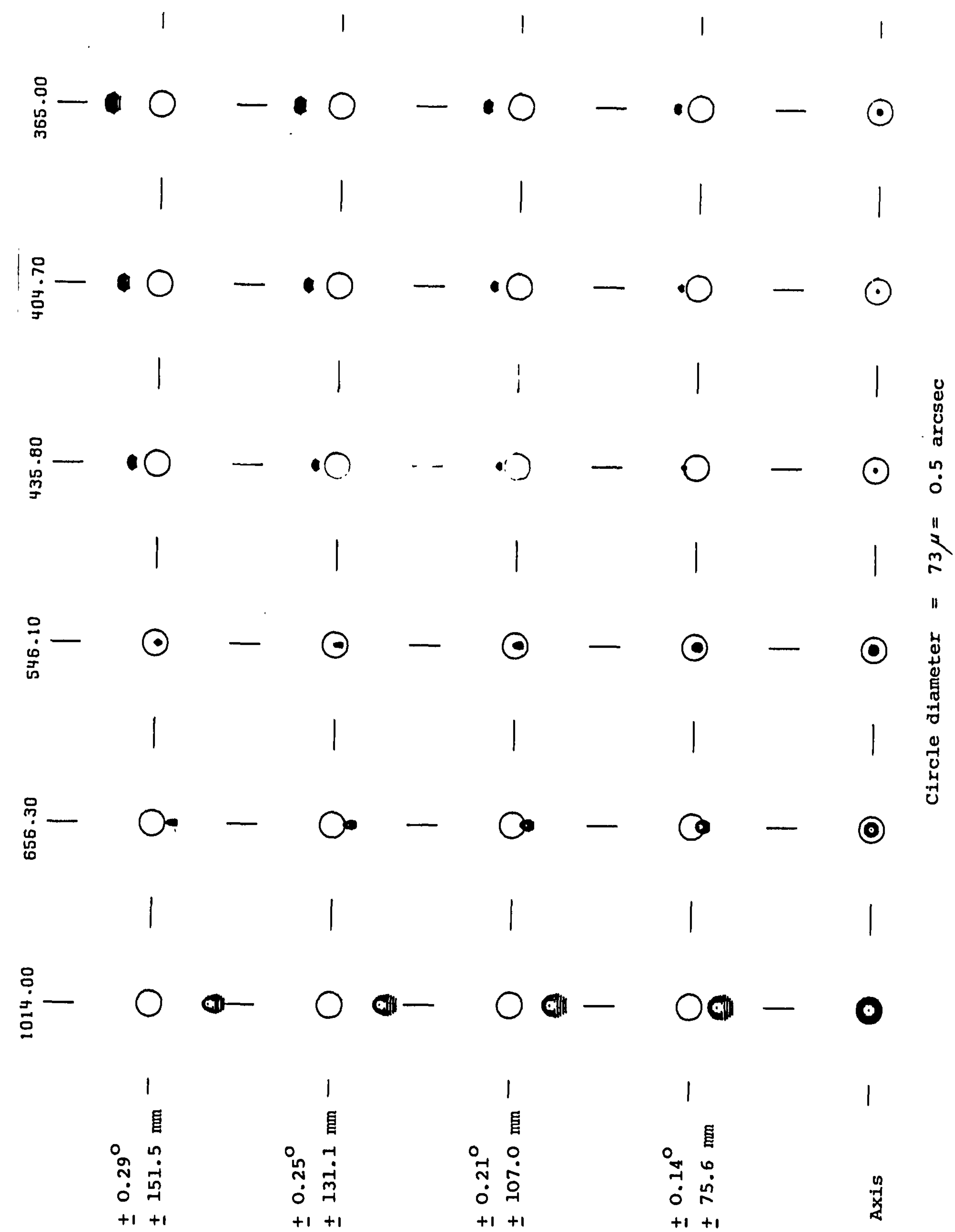


Fig. 2a(iii) : Spot diagrams showing the theoretical image quality of the QRC system <u>with</u> corrector (flat field). Optimum focus for blue.

± 0.29°

± 145.2

± 0.25°

± 125.7 mm

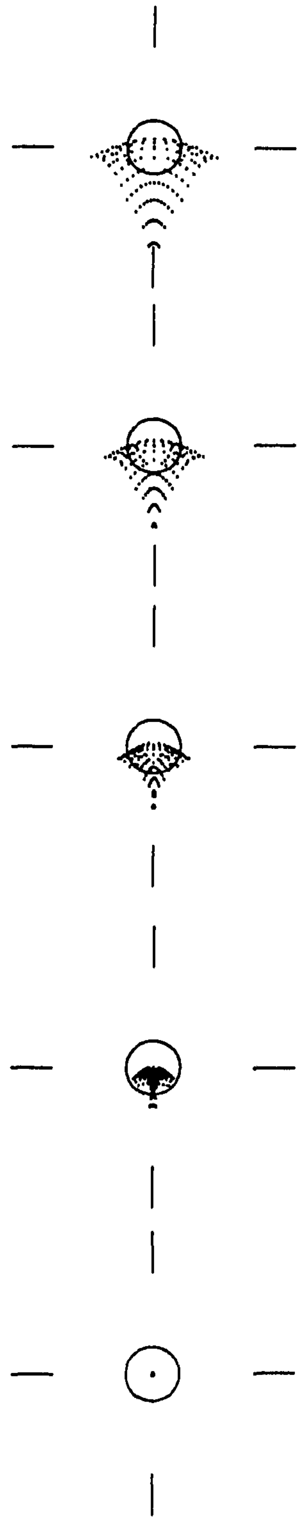
± 0.21°

± 102.7 mm

± 0.14°

± 72.6 mm

Axis

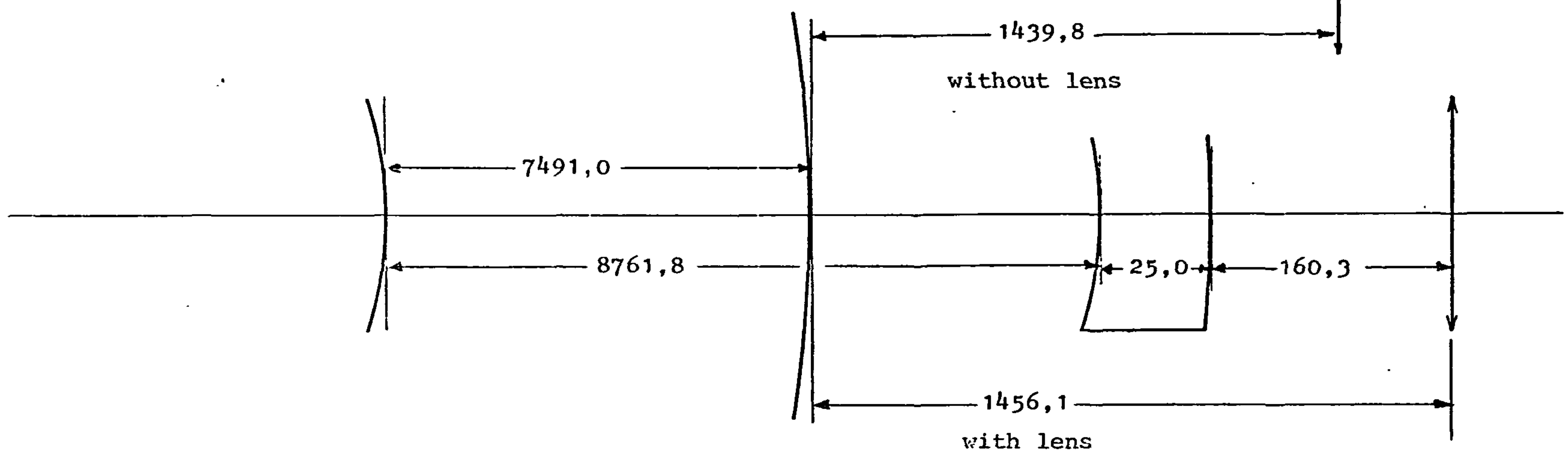


Circle Diameter

= 70μ = 0.50 arcsec

Fig. 2 b : Spot diagrams showing the theoretical image quality of the QRC system without the corrector for plates bent to optimum curvature (r =3384 mm)

Radius of curvature	10 735,9(17)	21 687,5	894,1	1338,8	



Aspheric constants:

$\bar{c}_1 = + 5{,}966423.10^{-13}$ (r = -) $\bar{c}_1 = + 1{,}899386.10^{-15}$ (r = -)

$\bar{c}_2 = - 1{,}41090.10^{-20}$ (r = -) $\bar{c}_2 = 0$ (r = -)

$\varepsilon_1 = - 6{,}906381$ $\varepsilon_1 = - 1{,}15500$

$\varepsilon_2 = + 31{,}197$ $\varepsilon_2 = - 1$

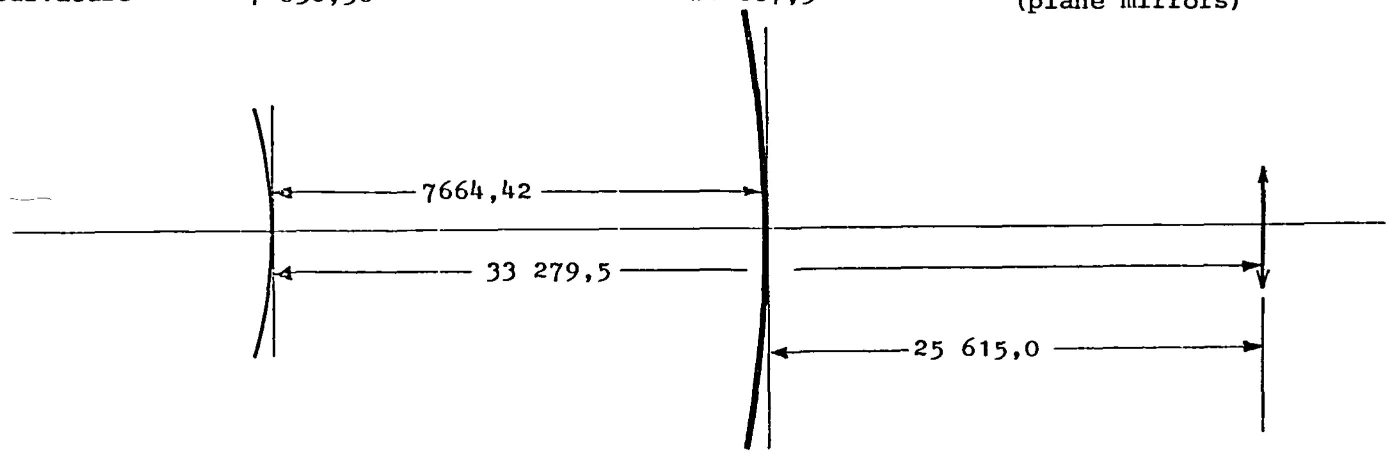
Free diameter : field $\pm$ 0,288°	1184,0	3570,0	307,9	309,5	302,9
Diameter of axial beam :	1107,9	3570,0	20,94	19,10	0

f = 30 035,9 mm <u>with</u> corrector k = 8,413

f = 28 884,8 mm <u>without</u> corrector k = 8,091

FIG. 3 : Optical Data Sheet for the QRC focus

Radius of curvature	7 030,30	21 687,5	(plane mirrors)



Aspheric constants:	$\bar{c}_1 = + 4,250695.10^{-13}$ (r = -)	$\bar{c}_1 = + 1,899386.10^{-15}$ (r = -)	
	$\bar{c}_2 = - 5,4867.10^{-21}$ (r = -)	$\bar{c}_2 = 0$ (r = -)	
	$\varepsilon_1 = - 2,181603$	$\varepsilon_1 = - 1,15500$	
	$\varepsilon_2 = + 0,508$	$\varepsilon_2 = - 1$	
Free diameter field $\pm$ 3 arcmin.:	1062,2	3570,0	198,1
Diameter of axial beam:	1048,7	3570,0	0

f = 113 506 mm   k = 31,794

FIG. 4 : Optical Data Sheet for the Coudé focus

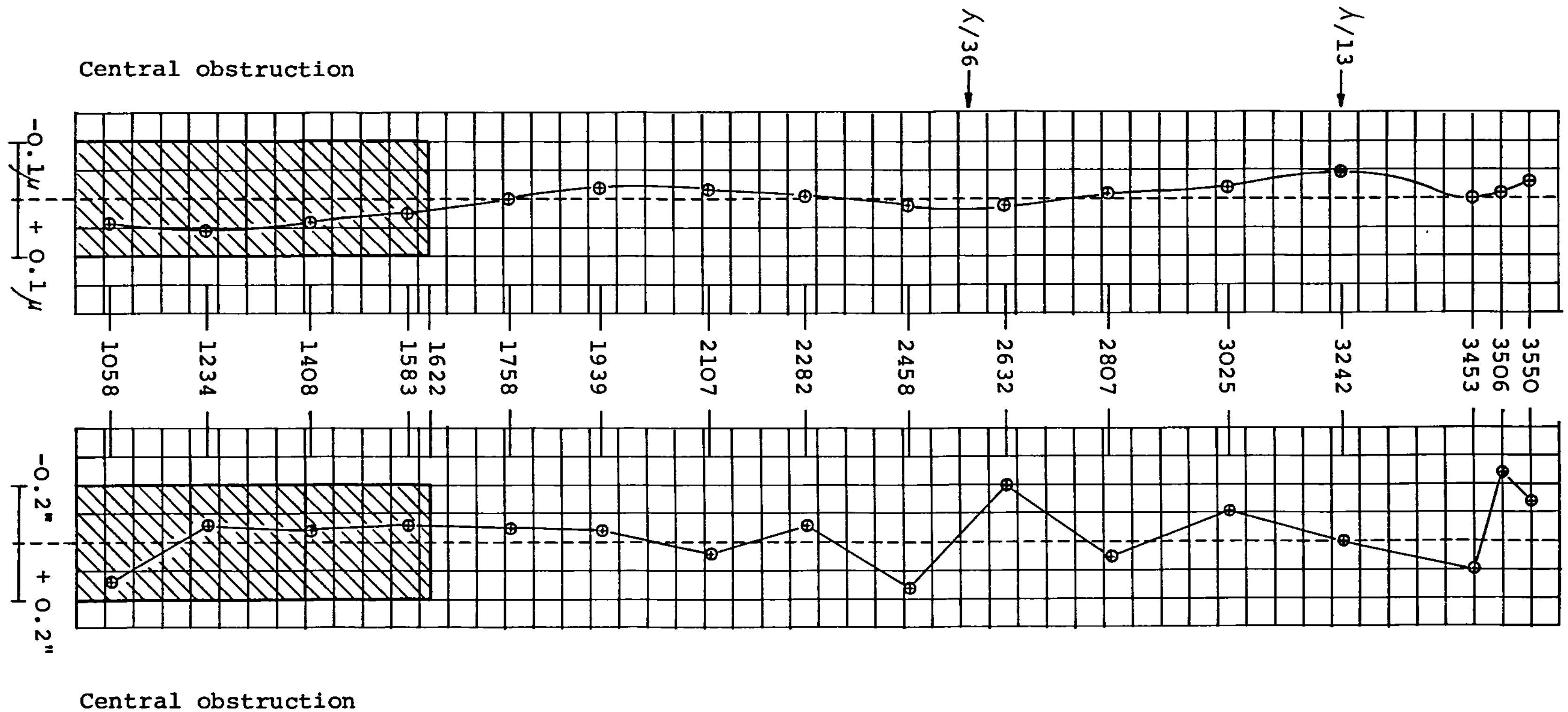


Fig. 5 : At the right - error of finished primary as a slope - height function
At the left - error of finished primary as a wavefront error - height function with reference to the "best fit" aspheric surface.

(Figures reproduced from REOSC report).

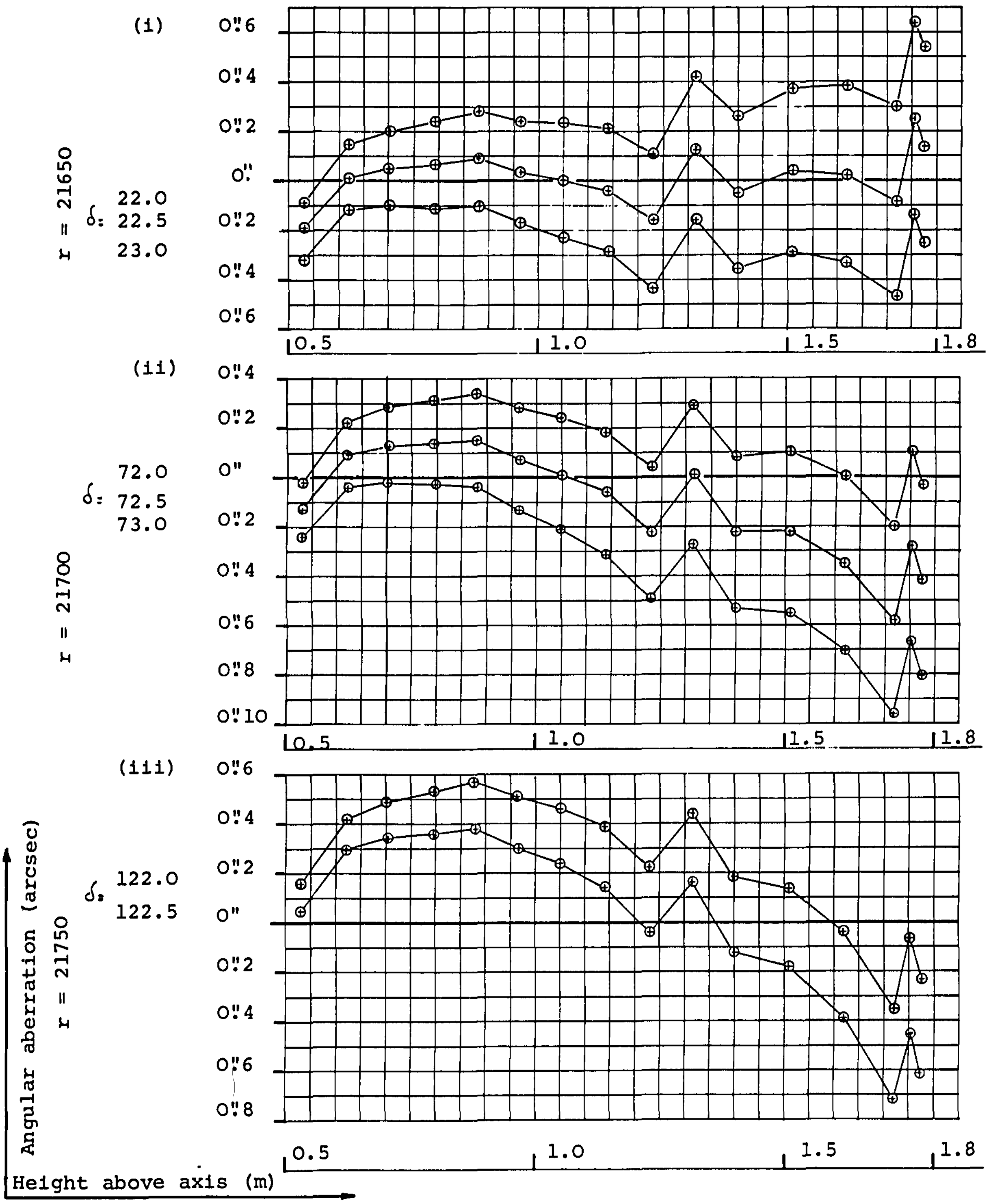


Fig. 6 (a) : Behr's analysis of Hartmann plates of primary with mirror axis vertical. Solutions for $\mathcal{E}_1 = -1.15175$.

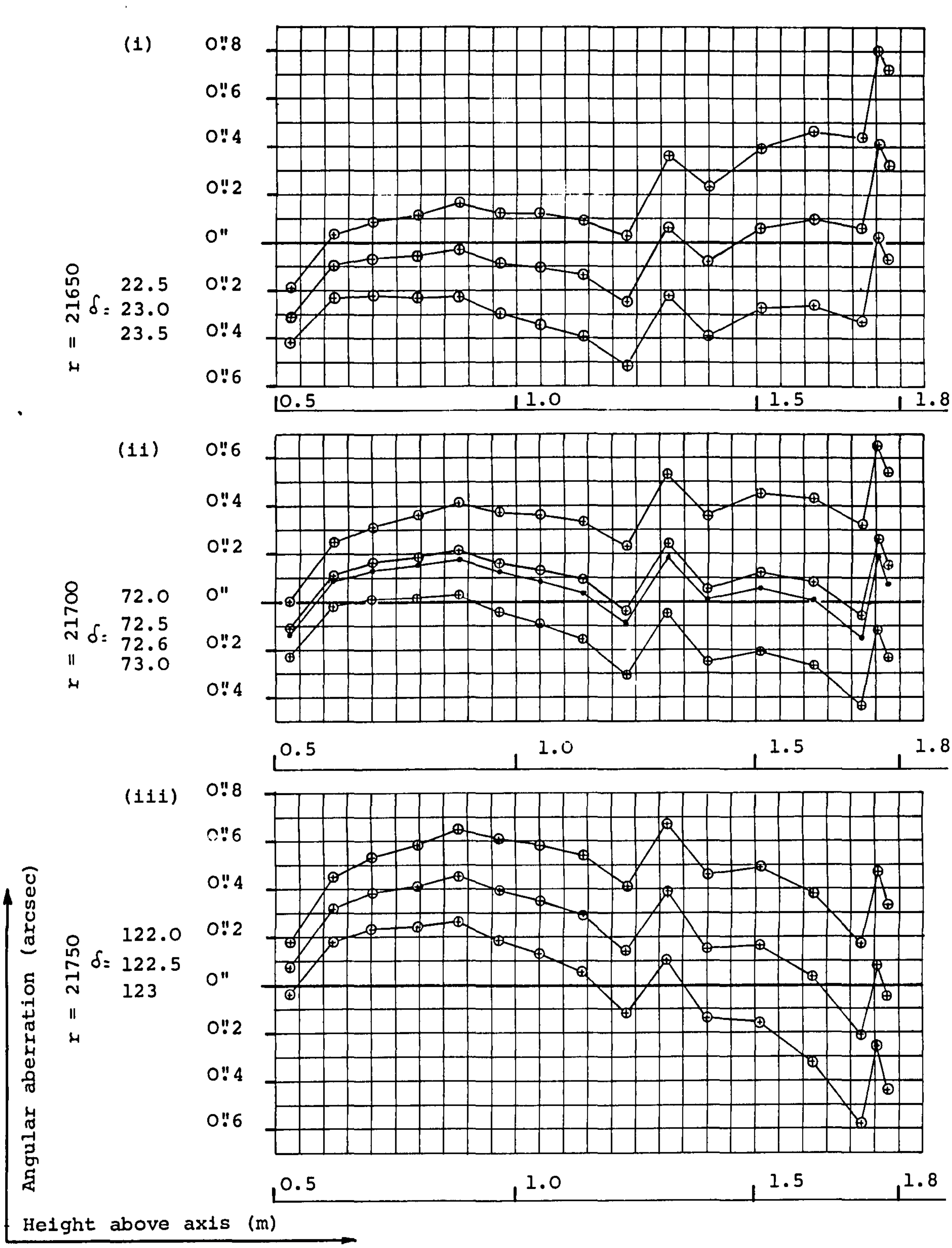


Fig. 6 (b) : Behr's analysis of Hartmann plates of primary with mirror axis vertical. Solutions for $\mathcal{E}_1 = -1.15675$. (Fig. 6 (b)(ii) is considered the most probable solution).

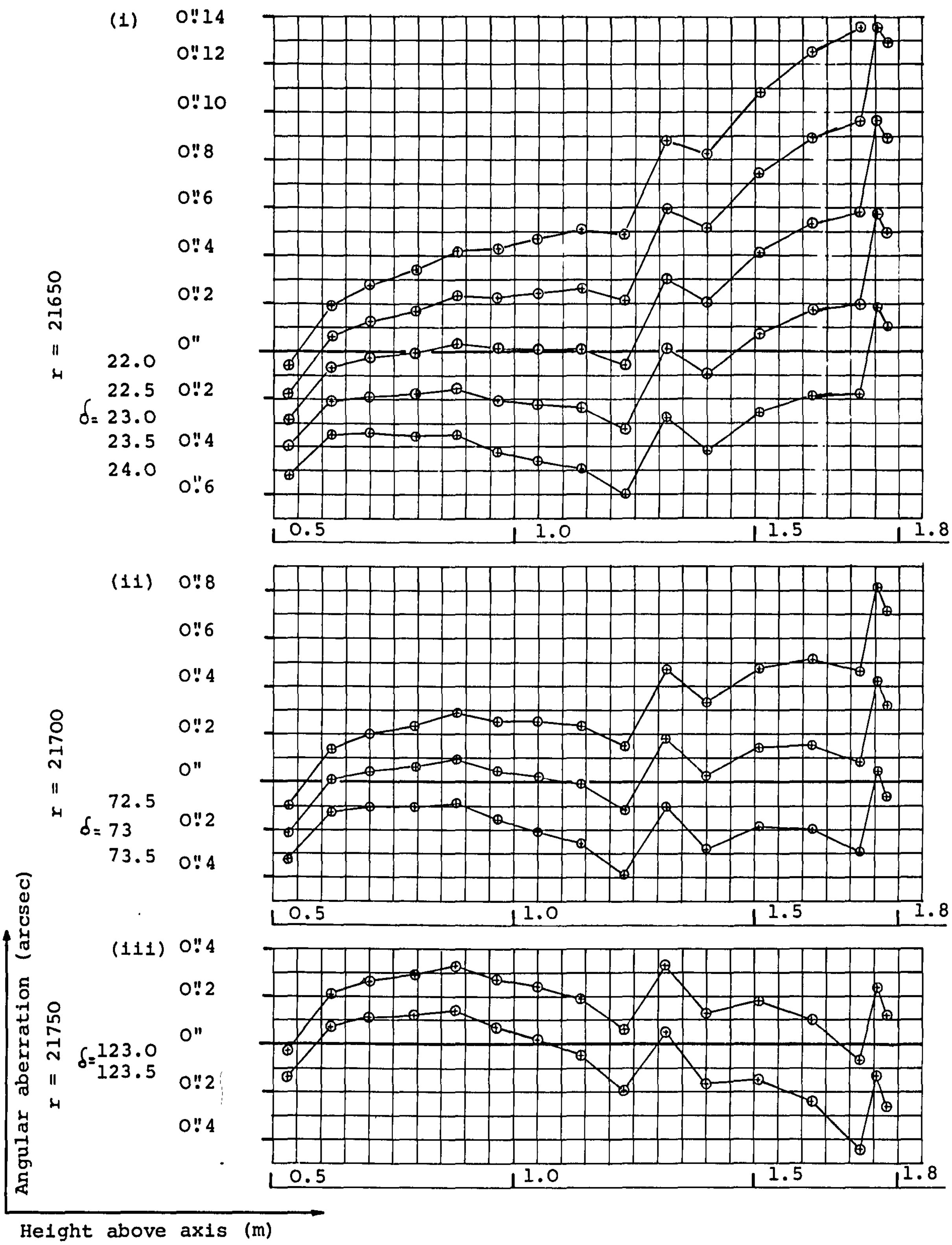


Fig. 6 (c) : Behr's analysis of Hartmann plates of primary with mirror axis vertical. Solutions for $\varepsilon_1 = -1.16175$.

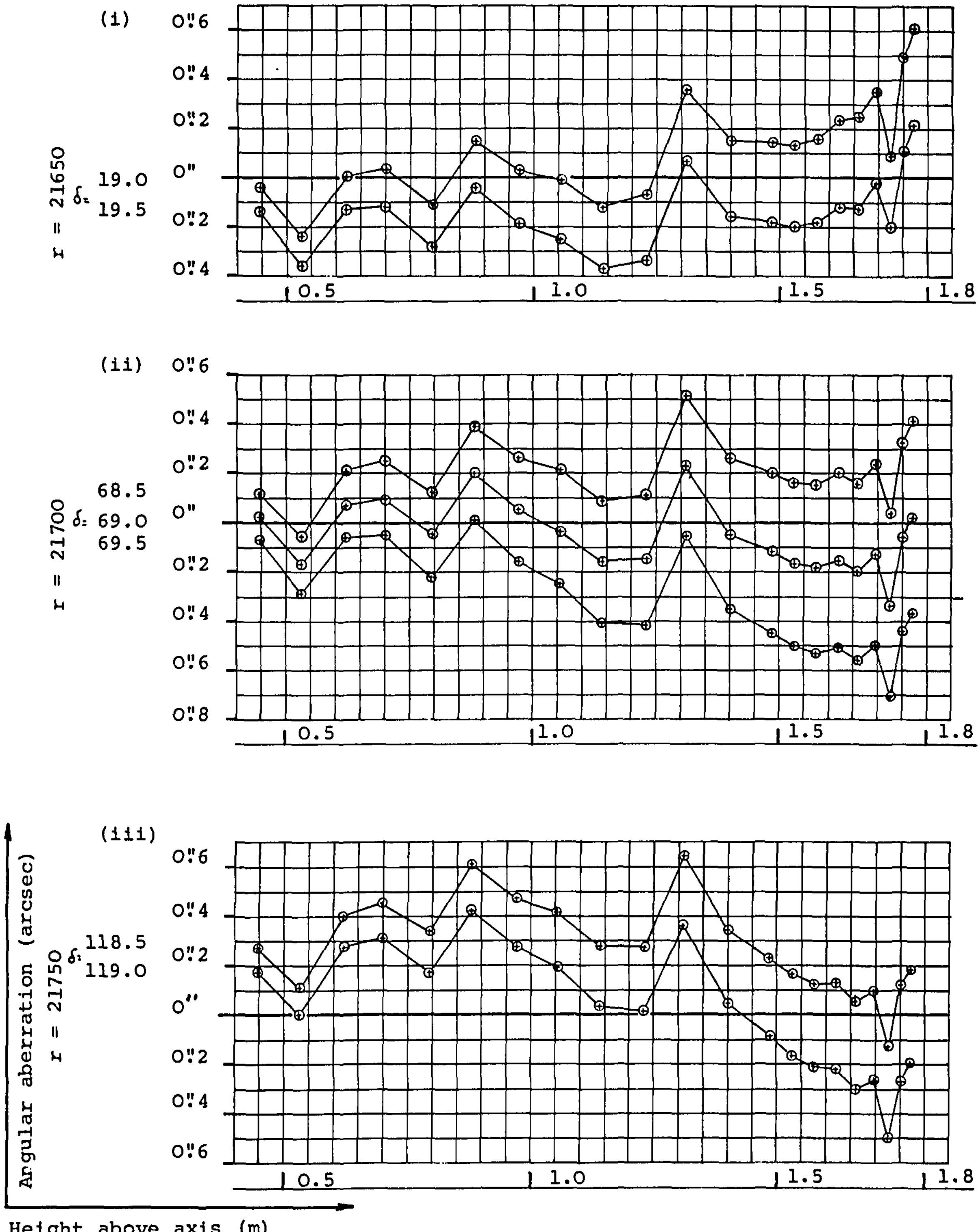


Fig. 7 : Behr's analysis of Hartmann plates of primary with mirror axis horizontal. Solutions for $\varepsilon_1 = -1.15675$. (Fig. 7 (ii) is considered the most probable solution).

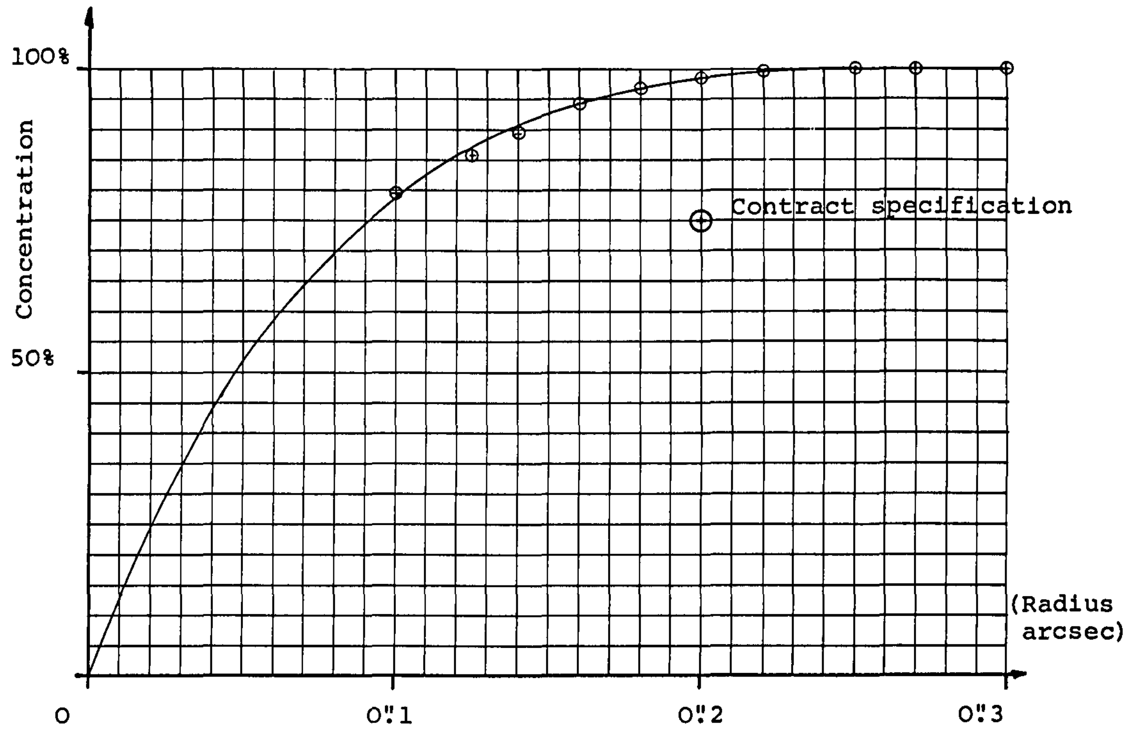


Fig. 8 : Finished primary - geometrical energy concentration (Figure reporduced from REOSC report.

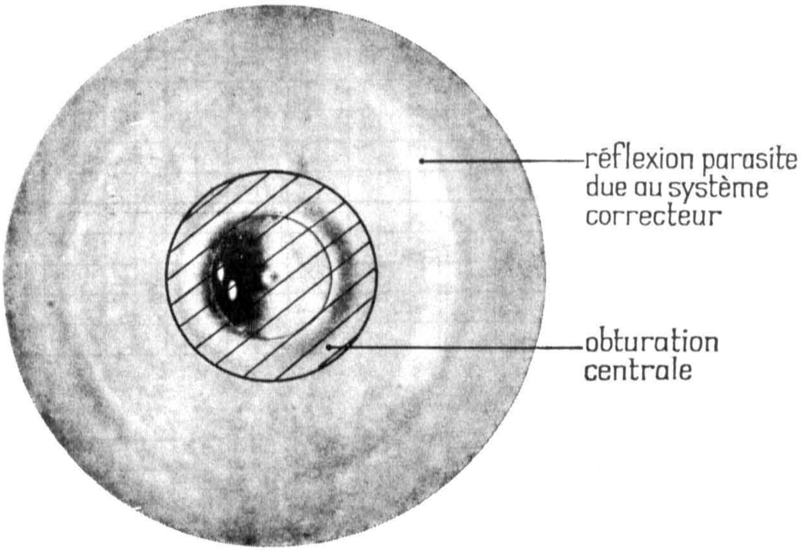

réflexion parasite
due au système
correcteur
obturation
centrale

Fig. 9

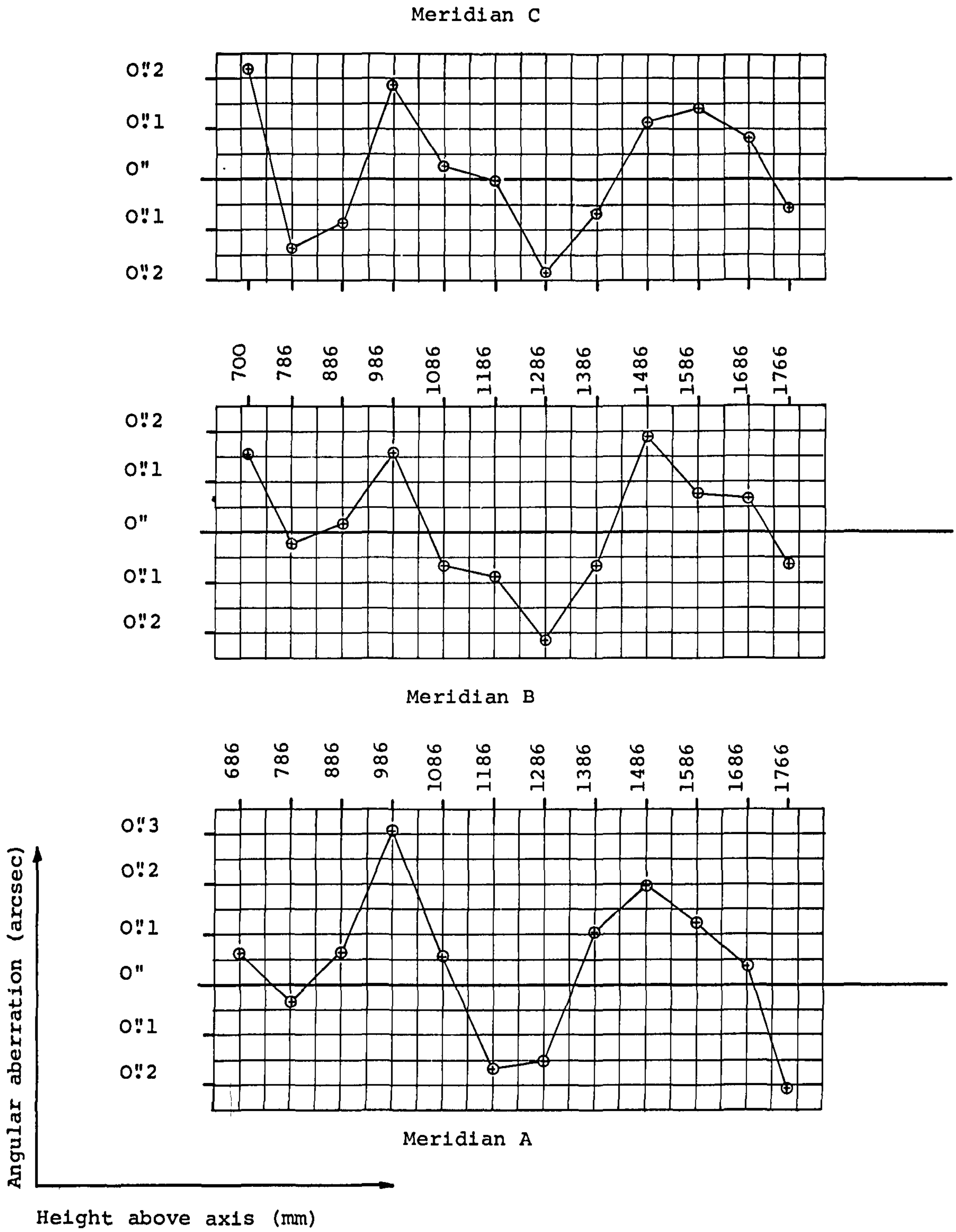


Fig. 10 : QRC Secondary - Slope - height error function of the test wavefront - Axis (Reproduced from REOSC report).

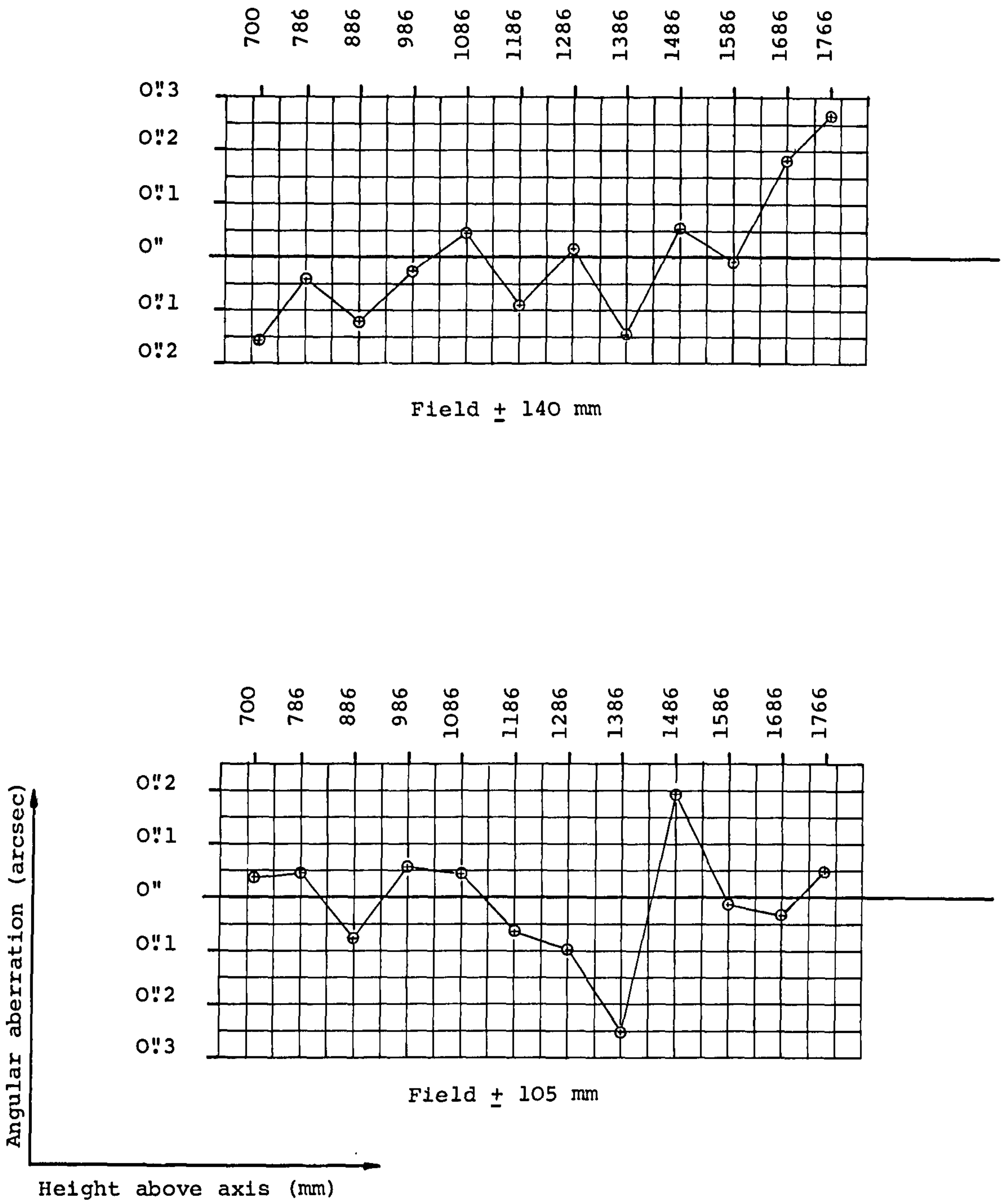


Fig. 11 : QRC Secondary - Slope - height error function of the test wavefront. - Meridian C - (Reproduced from REOSC report).

Radius in arcsec	Concentrations		
0".05	$\frac{18,88 + 11,88 + 16,66}{3}$	= 15,51 %	Average for three meridians
0".10	$\frac{35,93 + 69,15 + 52,13}{3}$	= 52,40 %	
0".15	$\frac{57,57 + 69,15 + 80,05}{3}$	= 68,92 %	
0".19	$\frac{96,72 + 90,57 + 75,57}{3}$	= 87,62 %	
0".20	$\frac{96,72 + 90,57 + 86,40}{3}$	= 91,23 %	
0".208	$\frac{96,72 + 90,57 + 92,81}{3}$	= 93,37 %	
0".215	$\frac{96,72 + 100 + 92,81}{3}$	= 96,51 %	
0".305	-------------------	100 %	

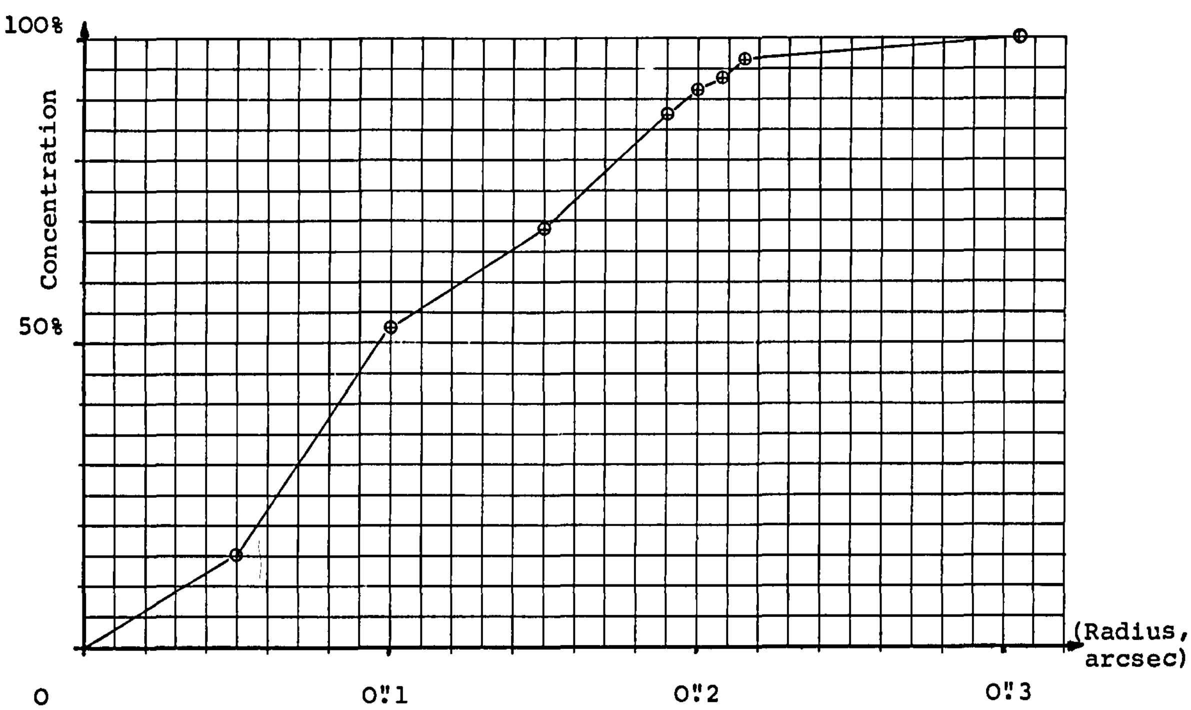


Fig. 12 : QRC Secondary - Geometrical energy concentration in axial image of QRC combination. (Reproduced from REOSC report)

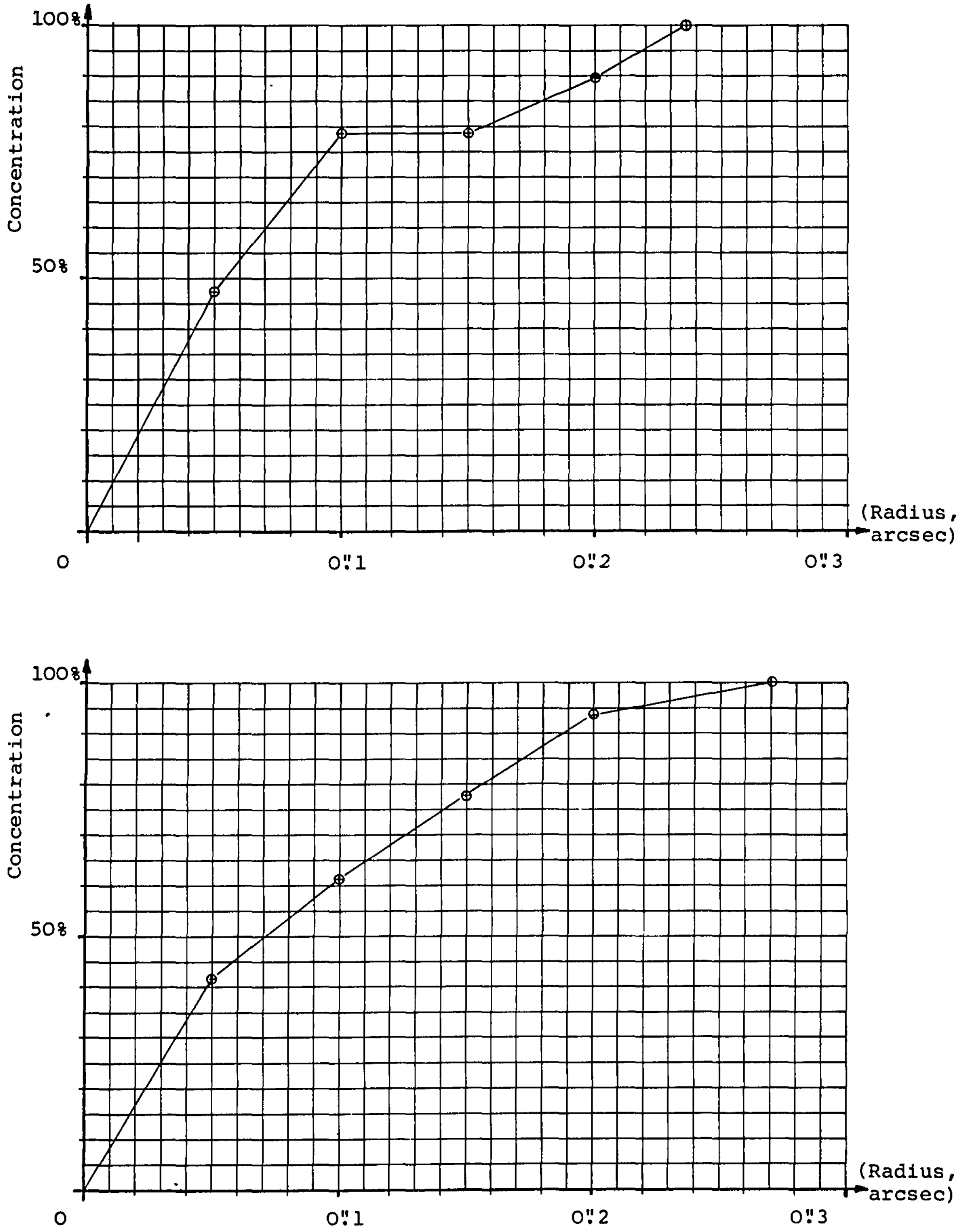


Fig. 13 : QRC Secondary - Geometrical energy concentration at field ± 105 mm (above) and ± 140 mm (below) of QRC combination (Reproduced from REOSC report).

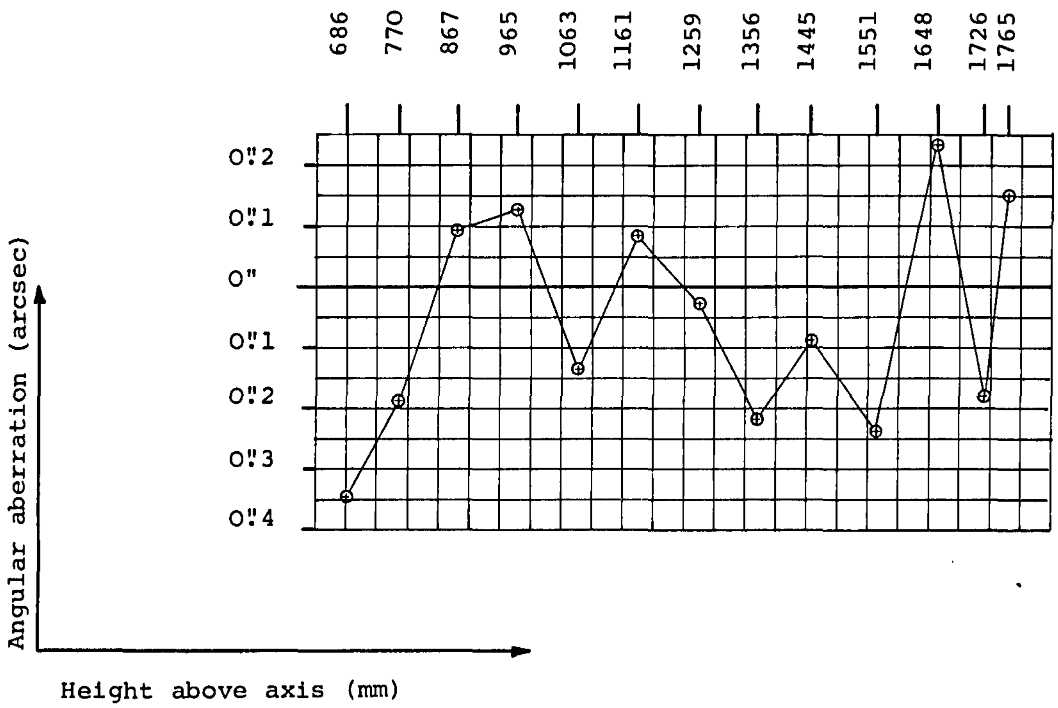


Fig. 14 : Coudé Secondary - Slope - height error of the test wavefront (Reproduced from REOSC report)

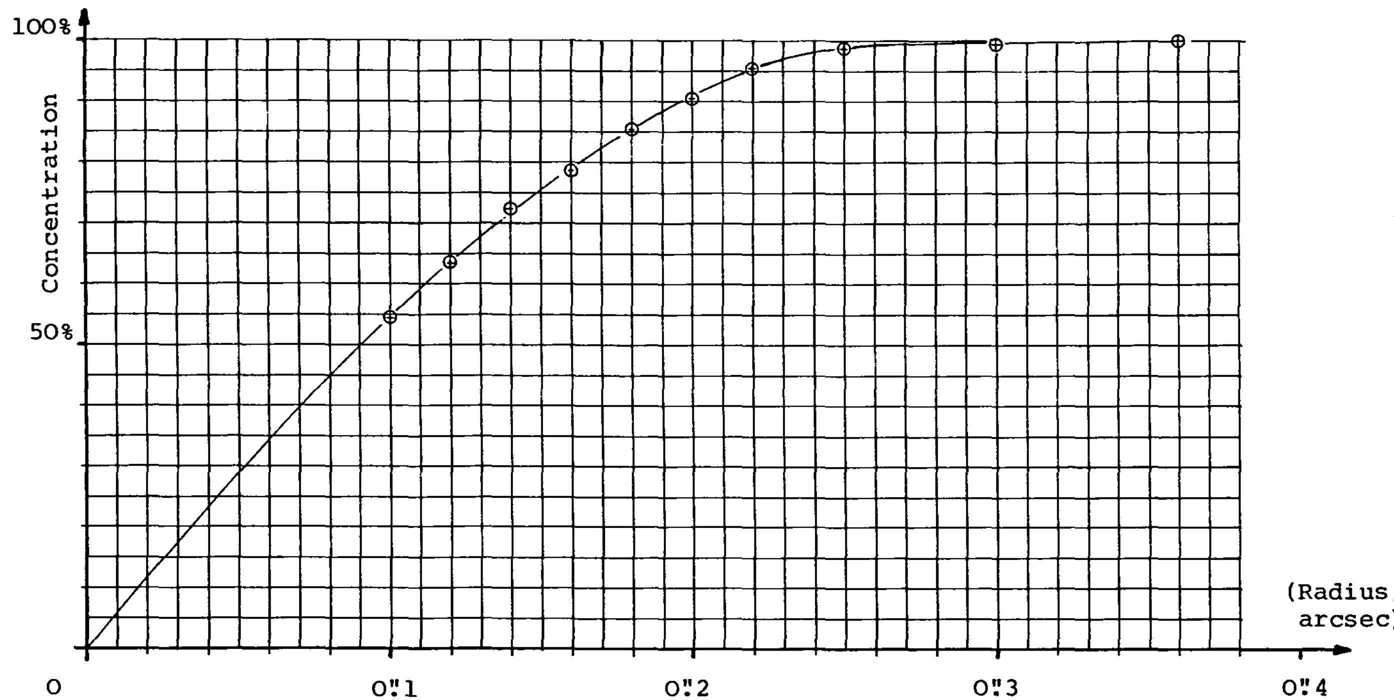


Fig. 15 : Coudé Secondary - Geometrical energy concentration in axial image of Coudé combination (Reproduced from REOSC report).