THE ESO OFF-LINE TELESCOPE TESTING TECHNIQUE ILLUSTRATED WITH RESULTS FOR THE MPIA 2.2 m TELESCOPE II

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1. Method used in ESO for testing the optical quality of telescopes

The ESO test device is based on the proposal of Shack[1].

Fig. 1 shows the principle of this method, which we call the SHACK-HARTMANN (S-H) method as it is derived from the well-known conventional Hartmann technique. The beam from the telescope focus (6) is transmitted by a beam-splitting cube (2) of high quality to a collimating (Fabry) doublet objective (3). This images the exit pupil of the telescope to the plane (4) where a special SHACK lenticular raster is inserted. Each lens of this raster then forms a point image of that part of the parallel beam incident upon it on to a photographic plate (5) placed at the focal distance of the raster lenses from (4). The angular aberration in the telescope image is thus transferred through the system and shows as a transverse displacement of the spots. However, errors of the Fabry objective and the lenticular raster are superimposed on the basic telescope errors. To eliminate these supplementary errors, a "reference beam" is introduced from the pinhole source (1). A slight offset from the axis produces separation of the two sets of raster spots. The telescope aberrations are then derived from the differences between the small separations of spot-pairs (Fig. 2) produced by each raster lens. The reference beam is fundamental to the method and presupposes, because of the angular shift between the two beams, isoplanatism of the aberrations over the small angle concerned. This is self-evident for the collimator, but is a point to which attention must be paid for the raster lenses because - depending on the manufacturing technique - they may have very high spatial frequency errors which, in the Fourier transform process of imagery, may cause failure in isoplanatism over even quite small angles.

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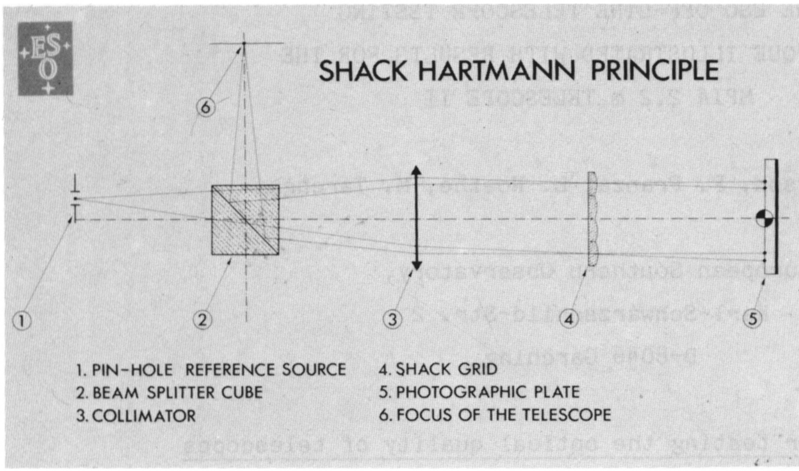

Figure 1: Principle of the SHACK-HARTMANN method.

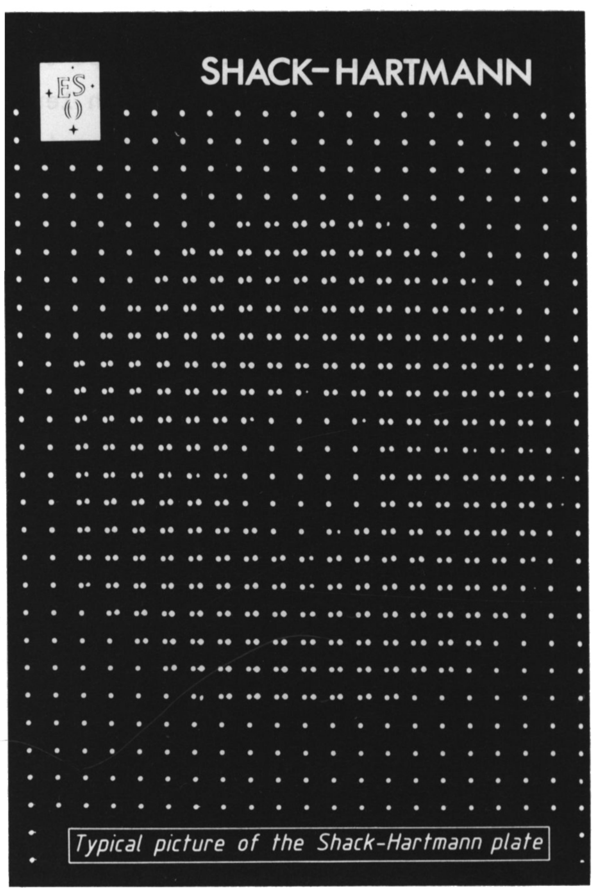

Figure 2: Typical SHACK test plate showing the double raster of points. The raster corresponding to the telescope image shows the form of pupil of the telescope.

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The type of raster screen is less fundamental to the method than the existence of the reference beam. For example, it is quite possible to insert at (4) a miniature Hartmann screen of conventional sort instead of the SHACK screen, and we in ESO have also done tests with such a screen. The same method using such a conventional screen has also been used and published by Bahner and Loibl(2).

In ESO we have preferred to use the lenticular raster screen originally proposed by Shack because of the following advantages:

- Higher sampling. The spot concentration compared with the patch corresponding to a Hartmann screen hole permits much higher sampling without overlapping. Our present screens have 40 x 40 lens elements and can be largely utilised by varying the collimator focal length according to the relative aperture of the telescope. We commonly use sampling of 500-900 points over annular telescope pupils.

- The reference and star image rasters are on the same plate and only <u>differential</u> measurements over small ranges are required. This gives very high measuring precision and freedom from such errors as emulsion distortion.

- There is a gain of ca. 5^m in light efficiency due to spot concentration. Since the telescope image light is spread over about 35 mm diameter, this advantage is probably the most important since stars of about 6^m can be used instead of about 1^m. This is fundamental for testing telescopes in different azimuths and zenith distances.

A disadvantage of the SHACK screen is the problem of procurement. Dr. Shack kindly gave the first author a perspex screen, mechanically made on a milling machine producing crossed cylindrical lenses whose departure from the sphere with the weak individual lenses (1 mm square, f/170) was below the diffraction limit. Although this production technique is very elegant, it is laborious unless a negative master could be made leading to easily made positive copies. Fortunately, a method of manufacturing fine lens arrays by laser beam writing on photoresist film came to our attention, developed by the RCA Laboratories in Zürich.(3) Through the help of Dr. M.T. Gale of RCA, which we gratefully acknowledge here, we have been able to obtain master negatives of high quality from which copies can readily be made.

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After considerable experience both with conventional Hartmann testing previously reported[4] and over several years and on many telescopes with the SHACK-HARTMANN device, it is our conviction that the latter is certainly one of the best, most reliable and convenient methods available for the optical testing of telescopes in situ on natural stars. In comparison, conventional Hartmann testing seems old-fashioned: the big screens are expensive, because of the high precision required, inconvenient in use (balance problems) and, furthermore, a serious source of thermal and convective effects in the telescope beam. By contrast, the ESO S-H device has dimensions 450 mm x 300 mm x 200 mm and is attached to a flange of 340 mm diameter. The total weight is 12 kg. It can simply be bolted on to any telescope instrument flange or mounted at the image in a fixed focus station.

2. Technique of image analysis

An image analysis procedure was developed in 1976 for the Hartmann testing of the ESO 3.6 m telescope.[4] This was based on a test polynomial and conventional least squares analysis which we have since used continuously, with minor modifications, for the last 8 years.[5] (With addition of one term for technical reasons, it is also the polynomial for our on-line active optics image analysis in the NTT). Since reference to this polynomial is essential for understanding the test results, we reproduce it here:

ESO Quasi-Zernike Test Polynomial

Wavefront aberration $w = k.\rho^m \cos(n\phi + q\theta)$ using:

$w = a$ - constant

$+ b.\rho \cos(\phi + \theta_0)$ - wavefront tilt (= lateral focus = pointing)

$+ c.\rho^2$ - longitudinal focus

$+ d.\rho^3 \cos(\phi + \theta_1)$ - decentering coma (3rd order Seidel) C

$+ e.\rho^4$ - 3rd order (Seidel) spherical aberration S

[$+ f.\rho^6$ - 5th order spherical aberration]

$+ g.\rho^2 \cos(2\phi + \theta_2)$ - 3rd order (Seidel) astigmatism A

$+ h.\rho^3 \cos(3\phi + \theta_3)$ - "triangular coma" Δ

$+ i.\rho^4 \cos(4\phi + \theta_4)$ - "quadratic astigmatism" $\square$

[$+ j.\rho^4 \cos(2\phi + \theta_5)$ - 5th order astigmatism]

[$+ k.\rho^5 \cos(\phi + \theta_6)$ - 5th order coma (NTT only)]

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The terms in brackets are not normally used but are available if their presence is suspected on the basis of normal test results.

3. Test results for the MPIA 2.2 m Telescope II (RC focus)

This telescope, on lease to ESO from MPIA, was erected at La Silla and became available for the first optical tests in October 1983. Before final centering it revealed under excellent seeing conditions very beautiful visual images of Saturn and Jupiter even with the magnification of about 2300 x necessary to get the whole pupil into the eye. Centering was done afterwards using our usual "pupil plate" technique (seeing integrated plates of star images sufficiently defocused to be well outside the caustic and reveal the pupil geometry distorted by aberrations). Unfortunately the seeing was extremely bad at that time and the telescope tracking did not permit fully adequate integration, as it had not yet been optimised. The precision of the centering measurement was therefore less good than can normally be achieved. It revealed an initial decentering coma of only about 0.6 arcsec from the absolute mechanical adjustment by Zeiss, a remarkable achievement without any optical tests. It was estimated that the adjustment with pupil plates had reduced this to 0.1 ± 0.2 arcsec, the significant margin of error being due to the inferior quality of the pupil plates for the reasons given above. In fact, the S-H test gave a tangential coma value (C) of 0.31 arcsec, so the centering actually achieved was less good than had been expected.

Table 1 gives a résumé of the test results in the zenith and at a zenith distance of 45°N.

All figures refer to a purely geometrical optical analysis from which the geometrical angular energy concentration diameters are deduced for 80% encircled energy. The polynomial analysis gives the aberration coefficients (not shown in Table 1) of the test polynomial in nm. In order to understand the causes of image degradation, the aberrations can be mathematically removed from the total aberration function and the resulting theoretical energy concentration recalculated. Thus column 2 shows the result for the telescope as it actually performed including the decentering coma mentioned above. Column 3 is the most important result since it gives the geom. opt. performance of the whole optical train including support systems without decentering coma: it is the figure to be compared with a geom. opt. specification. Columns 4 to 10 show the theoretical effect of the removal of other terms or combinations thereof. Column 10 shows

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1	2	3	4	5	6	7	8	9	10
Basis	Telescope Performance incl. decentering coma C (arcsec)	Minus C ≡ Telescope actual geom. opt. quality	Minus C+S	Minus C+A	Minus C+Δ	Minus C+□	Minus C +S+A	Minus C+S +A+Δ	Minus C+S+A +Δ+□ ≡ Telescope intrinsic geom. opt. quality
ZENITH									
Bad SHACK spots removed	0,490	0,431	0,398	0,399	0,424	0,431	0,371	0,370	0,368
Bad + doubtful spots removed	0,446	0,401	0,370	0,370	0,396	0,398	0,337	0,332	0,330
Mean	0,47	0,42							0,35
ZENITH DISTANCE ca. 45° N									
Bad SHACK spots removed	0,628	0,610	0,560	0,490	0,603	0,601	0,434	0,427	0,411
Bad + doubtful spots removed	0,604	0,592	0,538	0,464	0,586	0,583	0,416	0,408	0,393
Mean	0,62	0,60							0,40

KEY C = 3rd order coma, S = 3rd order spherical aberration,
A = 3rd order astigmatism, Δ = "triangular coma" (trifoil),
□ = "quadratic astigmatism" (quadrifoil)

Table 1: SHACK-HARTMANN test results of the MPIA 2,2 m Telescope II (RC focus) in October 1983 (after erection and centering). All figures are in arcsec and are the mean diameters corresponding to 80% of geometrical energy obtained from 4 S-H plates.

what we term the intrinsic quality, that geom. opt. quality remaining if all terms that can be influenced at all by the mirror supports were removed. Residual errors in column 10 are therefore high spatial frequency effects and can only have originated in the polishing process, e.g. zones, ripple, azimuth dependent bumps or holes in the wavefront.

Inspection of the zenith results, columns 2 and 3, shows immediately that the residual decentering coma C (0,31 arcsec of t-coma) is easily the worst error, in spite of the care taken (under poor conditions) to correct it. Columns 4 and 5 show that S and A have similar effects and are quite small. Columns 6 and 7 show that Δ and □ are negligible. There is thus no detectable over- or underloading of the axial fixed points. Column 10 shows that higher spatial frequency errors are the most important source of image degradation from the optical system. Foucaultgrams confirm that residual ripple is the main source. Even very small amplitude ripple has flank slopes giving spreads of 0,3 arcsec diameter.

At 45° N zenith distance, the decentering coma is slightly improved by Serrurier compensation error which would have the opposite effect on the south side. But the total telescope performance is significantly worse (columns 2 and 3).Column 3 shows a mean value of 0,60 arcsec compared with 0,42 arcsec in the zenith. The spherical aberration is slightly worse, but the cause of virtually the whole deterioration is the astigmatism A whose coefficient is 2.5 times worse. Since support errors usually lead above all to astigmatism, an error in the primary pneumatic support occurring in this azimuthal sector of the sky seems the most probable cause. But exhaustive further tests would be necessary to establish this, since other possible sources - in whole or in part - such as the primary radial support, the secondary mirror supports or even a dome turbulence effect would have to be eliminated.

The ESO S-H tests must be seen as critical compared with other tests of telescopes known to the authors, since we use systematic 2-dimensional analysis of the pupil at unusually high sampling. Table 2 shows the effects of different levels of sampling. Each second row and column of the S-H spot pattern was suppressed to reduce the sampling from about 510 points to about 125. A similar further reduction brought the sampling figure down to about 25. The table gives the results for two S-H plates in the zenith. Sampling of ca. 125 gives a mean reduction in 80% energy concentration diameter of the order of 7% from the ca. 510 sampling values, whereas sampling ca. 25 leads to reductions of the order of

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PLATE No.	SAMPLING POINTS	TEL. AS FOUND	WITHOUT COMA	INTRINSIC QUALITY
3	567*	0,489	0,437	0,372
	525	0,445	0,397	0,329
	127	0,390	0,359	0,311
	24	0,303	0,269	0,240
4	549*	0,517	0,475	0,378
	505	0,461	0,438	0,326
	122	0,441	0,428	0,297
	25	0,367	0,300	0,200

* includes disturbed points of doubtful validity

Table 2: SHACK-HARTMANN test results of the MPIA 2,2 m Telescope II (RC focus) in October 1983. 80% geom. opt. energy concentrations in arcsec showing effect of reduced sampling. From 2 plates in zenith position.

30% from the ca. 510 sampling values. Further sampling reduction would lead to a rapid fall in diameters since the minimum information necessary even for low order aberrations would no longer be present. Conversely one can conclude that doubling the sampling to ca. 1050 points would only increase the ca. 525 sampling diameters by 1 or 2 per cent at most. In other words, the high frequency ripple is sampled at least adequately with ca. 525 points.

Fig. 3 shows for one S-H plate the image profile for the zenith position plotted as geom. opt. encircled energy percentage against diameter in arcsec. Three cases are shown: the telescope as tested including decentering coma; removal of coma only, and the intrinsic quality with removal of all the aberrations. The filled circles indicate the telescope specification.[6][7] Ref. 7 gives a careful analysis of the workshop test results for the MPIA 2,2 m Telescope I. We presume that Telescope II had similar quality. These workshop test results predicted a geom. opt. energy concentration of 95.7% in 0,30 arcsec diameter and 100% in 0,60 arcsec. The curve 2 in Fig. 3 for the telescope after removal of coma gives 64% (spec. = 70%) in 0,30 arcsec dia. and 98% (spec. = 90%) in 0,60 arcsec dia. As predicted in Ref. 7, therefore, the concentration in 0,6 arcsec dia. was met by a considerable margin, while the specified concentration for 0,30 arcsec dia. has not quite been met. However, from Table 1, zenith, column 5 indicates that correction of the small residual astigmatism would bring also this point up to the specification. This might be feasible by a

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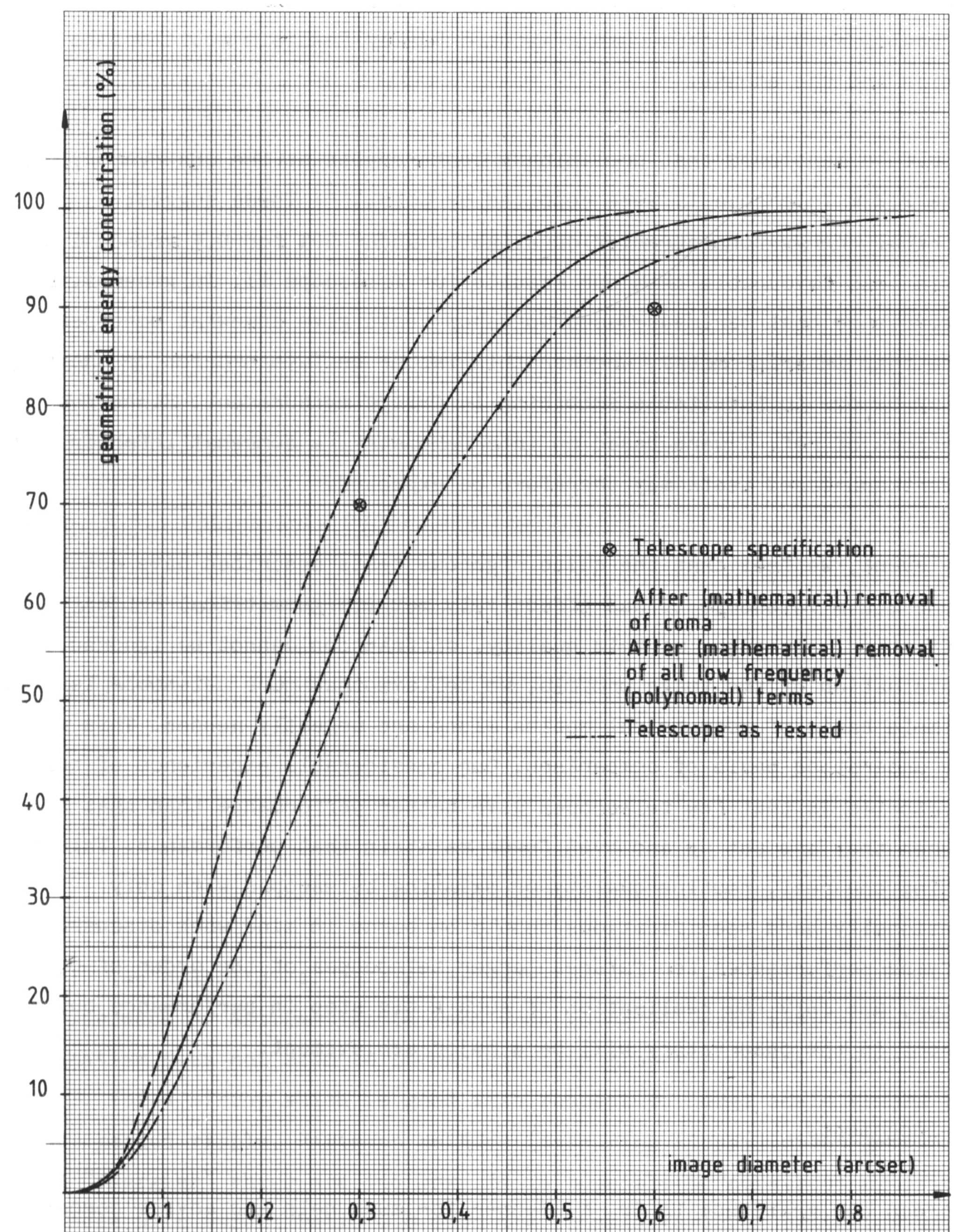

Figure 3: MPIA 2,2m Telescope II :Geometrical optical image profile deduced from one S-H plate taken in the zenith in October 1983

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minor support correction. Alternatively, a modest shift of the final focus could remove the residual spherical aberration as shown in Table 1, column 4, with the same result. Whether such a change is technically feasible would depend on the direction and the amount.

It should be mentioned that preliminary test results at the observatory, also for the 2,2 m Telescope I, were reported by Loibl.[2] These suggest a geometrical energy concentration of slightly under 50% for 0,3 arcsec diameter which is less favourable than our results for Telescope II. In general, it is our experience that Hartmann-based workshop tests give somewhat more pessimistic results than interferometry, whether this latter be Twyman-Green or shearing. This may be due to inevitable smoothing in fringe measurement. Since the predictions of ref. 7 were based on interferometry, a somewhat inferior result from Hartmann-based tests may therefore be expected.

In any event, we feel that the quite rigorous tests described have established that the 2,2 m Telescope II has effectively met its geometrical optical specification. Although, at this quality, diffraction cannot be ignored in a true evaluation of the image profile, we believe that more telescope tests on the simple basis of geometrical optics alone are urgently needed. This gives an easily understood basis of comparison. Our considerable experience of tests in observatories is that few telescopes give better performance than that reported here when they are set up and even fewer maintain that performance. This reality regarding the real, routine quality of existing telescopes with only conventionally hard specifications should be borne in mind when discussing or specifying performances for future, larger telescopes of the order of 0,1 arcsec diameter. Not only the realisation of such a big step in performance but also its proof in the observatory will be a major achievement.

Acknowledgements

We express our gratitude to Dr. K. Bahner for much help and advice concerning the optics and other aspects of the MPIA Telescope II, and to the firms Carl Zeiss and M.A.N for their careful and highly successful erection of the telescope at La Silla. We also acknowledge the major contribution of our colleague, B. Delabre, to software development and in many discussions. Last but by no means least, we are grateful to Dr. Roland Shack for drawing the attention of the first author in 1976 to the SHACK method and for kindly supplying our first screen.

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DISCUSSION

K. Bahner: Two comments: 1. In similar tests of our 2.2m telescope at Calar Alto, no increase of astigmatism is seen when going to large zenith distances. The astigmatism does not seem to be an intrinsic property of the support system. 2. For a mirror which is good with respect to large scale errors but has some short period ripple, Hartmann methods (measuring slopes) might give encircled "energies" which are too low. It is possible to construct artificial wave surfaces with Strehl ratio 0.8 from the Väisälä-Maréchal criterion which do not look good from Hartmann tests.

R. Wilson: To question 1: This is an interesting comparison. Of course, it does not follow that, for some technical reason, an astigmatism effect due to a support defect could not occur in Telescope II even if an identical support did not produce it in Telescope I. However, it would require much more exhaustive investigations to prove the precise origin of this astigmatism. The primary

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support seems the most likely cause, but an air turbulence effect cannot be excluded at this stage.

To question 2: It is quite true that Hartmann-based tests give only an approxmation to a geometrical optical result, depending on the sampling, which in its nature does not agree well with the precise physical optical nature of the image with Strehl ratios approaching 0.8, particularly in the presence of ripple. This discrepancy would be particularly true of the "intrinsic quality" curve where the low frequency terms are absent. For the other curves (telescope as tested and telescope with zero decentering coma), the other residual observation coefficients are sufficiently large (coma ca. 550mm, sph. ab. ca. 1000mm, ast. ca. 240mm) that the Strehl ratio must be quite low. One should also bear in mind that the superimposed atmospheric turbulence also pushes the total wavefront error into a range where geometrical optics is more valid.

In my view, even in the region where the Strehl ratio exceeds 0.5, telescope tests giving geometrical optical energy concentrations are of value for comparative purposes between telescopes and with workshop test data. It is much better to have this than nothing.

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