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THE OBJECT-GLASS OF THE GREENWICH "GREAT EQUATORIAL TELESCOPE"

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The "Great Equatorial" at the Royal Observatory, Greenwich was completed in 1860 and equipped with a 12.8 inch (325 mm) aperture objective made by G. Merz & Sons of Munich. This article describes the history and work of the objective and presents the results of a recent laboratory examination of its optical properties.

History of the Merz Objective

When G. B. Airy was appointed to the position of Astronomer Royal in 1835 the equatorial telescopes at Greenwich were primitive, consisting of two small and inconvenient refractors mounted in the domes adjacent to the original Wren building now known as "Flamsteed House". The situation was improved in 1838 by the acquisition of an equatorial refractor with a 6.7 inch (170 mm) Cauchoix objective, the gift of the Rev. R. Sheepshanks, FRS.[1] Even in 1852 Airy was satisfied with this modest equipment.[2] But in 1855 (possibly influenced by public dissatisfaction that the 1846 discovery of Neptune had not been made in Britain) he asked for funds to procure a new large equatorial refractor, which were approved in November of that year.[3]

The building and telescope (excluding the objective) were estimated to cost not less than £2000. Airy was careful to stress that the possession of a large equatorial telescope would not be allowed to interfere with the fundamental positional work of the observatory.[4]

Approaches to English manufacturers for the supply of an objective had already been unsuccessful. Good-quality glass blanks were difficult to obtain, particularly (it would appear) those of crown glass. William Simms (of Troughton & Simms) had a 15-inch objective in hand; he wrote to Airy:[5] "We began to work it in 1848 and it does not yet satisfy me. The present crown glass is the fifth we have worked, the material in all the former ones was bad."

In September 1855 Airy approached G. Merz & Sons of Munich for details of their large objectives.[6] The reply quoted prices of from 5000 to 31000 florins (£430 to £2660 approximately) for objectives from 8 to 16 French inches aperture, and stated that a 12-inch objective was available for test at Munich.[7] In October Airy asked for this to be retained for two months as he was not yet in a position to place an order;[8] by mid-November approval for the new telescope had been obtained and Airy wrote to Merz saying that he now had the "authority to treat with you" and asked that the 12-inch objective should be sent to Greenwich for testing.[9] Clearly Merz were reluctant to lose the one objective they had in stock, but they neatly side-stepped the issue by saying that another of the same dimensions was being made and they would supply

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whichever was found to be the better when the second one was finished,[10] an arrangement with which Airy was satisfied.[11]

An enquiry[12] from Airy in February 1856 as to the prospects elicited the reply[13] that better weather was awaited for testing and begged "a little patiency". By mid-August Airy's "patiency" was evidently wearing thin:[14] he wrote to Merz of his anxiety to know the position about the objective and threatened "... that some limit be understood as to the time in which you can supply it". As Merz had originally quoted from 1 to $1\frac{1}{2}$ years for the supply of a 12-inch and the building for the new telescope was hardly started this seems a trifle high-handed.

Merz replied that they were working to make a better objective "than the perfect 12-inch", but if not successful by the end of 1856 they would send the first objective and change it if the second turned out better.[15] Airy was satisfied with this but, to finalize the telescope design, asked for details of the greatest likely aperture and focal length,[16] adding a plaintive postscript: "Have the goodness particularly to specify whether the measure is in English feet and inches or French feet and inches and whether you give the French foot as 1/3 metre." Merz responded with a full-size sectioned drawing of the object cell and stated that the focal length would not exceed 206 inches French measure, a French inch being 0.02707 metre or 1.0658 English inches.[17]

After further enquiries from Airy (including a query about the availability of other large objectives:[18] Merz had a 14-inch on hand at 20800 florins[19]) and complaints from Merz of weather continually too poor for optical tests using star images, the new 12-inch objective was finished "with the utmost exertion" in June 1857 and sent to Greenwich[20] with an account for 13310 florins.[21] The equivalent sterling price (paid in October in bills drawn on the Accountant General of the Navy) was £1144 2s 6d.[22]

By mid-October 1857 Airy had tested the objective, on what he had earlier described in a letter to Simms[23] as an "enormous polar axis, prepared expressly for the trial of 20-foot object glasses...". He wrote to Merz:[24]

> With a bright star there are a few faint rays of which I do not know the origin (I see no veins in the glass) but the central image is small and good and surrounded by well-formed rings. There is a little secondary colour. I have not yet succeeded in separating the small star of γ Andromedae. But on the whole I think it will prove a very fine object-glass.

The separation of γ^2 And in 1857 was 0.59 arc-seconds.[25] The Dawes resolution limit for the objective is 0.36 arc-seconds.[26]

In January 1858 Airy received a letter from Thomas Grubb of Dublin, offering a 12-inch objective for trial and for sale at £500 if approved.[27] Airy, in explaining that the Merz objective was already purchased, regretted that he had not heard of the Grubb lens sooner and lamented the lack of any recognized astronomical advertising medium.[28] The Grubb objective was intended for an equatorial and was interesting in that the inter-lens space was filled with fluid to improve transmission.

The Greenwich telescope, by now known as the "Great Equatorial" or (later, more usually) as the "South East Equatorial" was completed in 1860.[29] Airy had taken great care to ensure a firm mounting, with a braced lattice-work double-

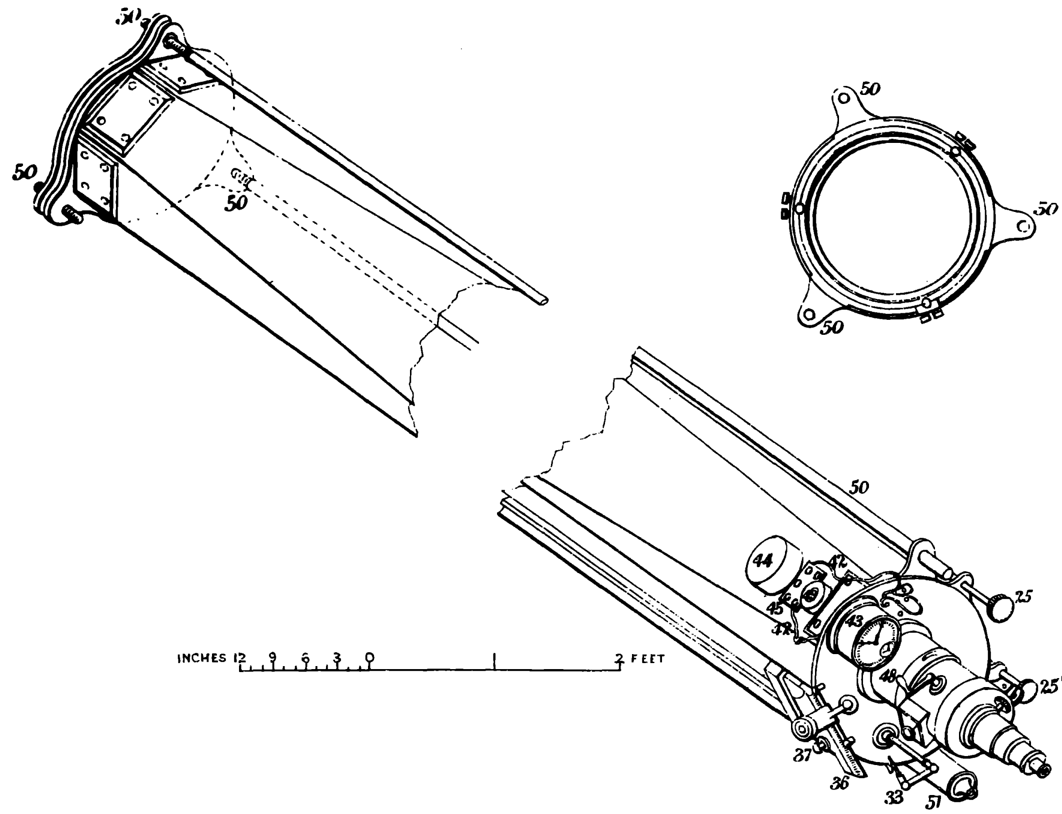

FIG. 1. Drawings of the Merz telescope, from Greenwich Observations 1868.
Key to numbered parts:

25 and 25*	Declination clamp and slow-motion.
33	Naked-flame gas-burner for illumination.
36 and 37	North polar distance indicator.
42 and 45	Electrical connections.
43	Chronometer controlled by seconds impulses from the sidereal clock in the dome, itself under the control of the Transit-clock.
44	Seconds-sounder.
48	Adjustment of illumination reflector.
50	Tilt adjustments of the objective and their extensions back to the eye-end.
51	Finding telescope.

cheeked polar axis of the English form on north and south piers, and provided with finely-graduated circles for the determination of celestial co-ordinates with considerable accuracy. It was not, as he had said,[30] to "... be considered as a mere commodious support for a gazing-telescope". The first recorded observation was an occultation of Jupiter on 1860 May 24.[31]

Elaborate drawings and descriptions of the telescope and its building are given as an appendix to the Greenwich Results for 1868.[32] I reproduce in Figure 1 the drawings relating to the objective and the telescope tube. This was of mahogany, square in the centre but tapered to an octagonal section at the ends. The objective was mounted on a double three-rayed brass structure, the outer member carrying the objective and the inner one fixed to the tube. Screw-adjustments for squaring-on were fitted between the three sets of rays and two of them were extended by long rods back to the eye-end to enable the tilt of the objective to be adjusted by the observers while viewing a star image.

Even before observations with the objective had commenced, a rectilinear pattern of small spots was noticed, forming on one surface of the flint component.[33] On enquiry to Merz these were said to be the marks of the system used to support the lens when working the other surface, and becoming visible because the glass had started to be affected by humidity.[34] Airy's restrained comment was that he "... could wish that the glass furnished had not been so sensitive to the moisture of the atmosphere".[35]

In 1860 Otto Struve visited Greenwich and with Airy subjected the objective to a thorough testing.[36] It was found to be "of the highest order". γ^2 And (evidently a favourite test object) was seen well separated.

The objective continued in use on the Great Equatorial until November 1891, when the whole tube was dismounted in preparation for the installation of a new 28-inch (0.71 m) refractor by Grubb on the same mounting.[37] The strength and rigidity of the mounting was such that the greatly increased weight of the new telescope was taken without trouble. (After being used at Herstmonceux from 1957 to 1971, the 28-inch and mounting were transferred to the care of the National Maritime Museum and returned to Greenwich. Remounted in the original location, the instrument is now on public display.)

In May 1892 the Merz telescope was set on the mounting of the William Lassell telescope.[38] This historic 24-inch reflector, with which Neptune's satellite Triton was discovered in 1846, had been donated to the Observatory in 1883 by the Misses Lassell.[39] Located in a poor situation, it had not seen much productive use and was regrettably later broken up, together with its very early fork mounting, and unceremoniously dumped in a fenced-off area of Greenwich Park known as "the Wilderness".[40] The two speculum-metal mirrors survive.

The Merz objective was again dismounted in 1896, given a new metal tube and remounted as the guiding telescope on the new 26-inch (0.66 m) photographic refractor which had been donated by Sir Henry Thompson.[41] The original three-ray mount was retained but without the facility for adjustments to be made from the eye-end.

During the First World War some limited observations continued, but on the outbreak of war in Europe in 1939 all the large Greenwich objectives and mirrors were dismounted and sent away for safe storage. After the move to Herstmonceux the 26-inch with the Merz as guider was re-erected in 1958 in Dome E of the Equatorial Group of telescopes.

The impending relocation of the Royal Greenwich Observatory at Cambridge and the consequent severance of the connection with the Equatorial Group implies that this note may perhaps be regarded as a valediction after the long career of "the Merz", as the objective is always affectionately known.

The Optical Works of G. Merz & Son

Detailed histories of this firm have been given by Brachner,[42,43] and Chance[44] has provided an account of their glass works, but a short summary may be of interest here. The origin was in a firm of surveying-instrument manufacturers established in Munich in 1802 by Reichenbach and Liebherr, joined in 1804 by Utzschneider. The partners soon found difficulties in the supply of ready-made lenses or of suitable good-quality optical glass from which to make them. The

Swiss glass-maker Pierre Guinand, who had spent 20 years in perfecting the manufacture of optical glass in large sizes, was persuaded by Utzschneider to go to Bavaria, and the old Benedictine monastery at Benediktbeuern, some 30 miles south of Munich, was purchased as a site for glass-works. (The Benediktbeuern monastery is noted for the discovery there in 1803 of the thirteenth-century manuscript of songs now known as *Carmina Burana*, familiar to the modern music audience in the 1937 setting by Carl Orff.[45])

Joseph Fraunhofer joined the firm in 1806 and in 1809 a new partnership (Utzschneider, Reichenbach & Fraunhofer) was formed with workshops at Benediktbeuern, where Fraunhofer was in charge of optical work. Guinand left in 1813, at which time Fraunhofer also had responsibility for glass production. The optical workshop moved back to Munich in 1819, leaving the glass manufacture at Benediktbeuern.

Fraunhofer's achievements in the improvement of glass manufacture, the accurate measurement of refractive index, the design of aplanatic (coma- and spherical aberration-free) objectives, his pioneering experiments with diffraction gratings and his investigation of the solar spectrum are too well known to need further elaboration here. A summary of his life and work has been given by Howard-Duff.[46]

After Fraunhofer's death in 1826 at the age of 39 Georg Merz (who had worked with Fraunhofer since 1808) took over the practical running of the firm with Joseph Mahler. Utzschneider died in 1838: the firm was afterwards owned by Merz and Mahler. By 1845 Merz was sole owner and his two sons entered the firm; Merz died in 1867.

The firm continued in the Merz family, from 1867 to 1883 in the hands of Georg's second son, Sigmund, and then of his cousin, Jakob Merz. The glass works at Benediktbeuern were abandoned in about 1884, but instrument manufacture continued at Munich. The business was sold to Paul Zschokke in 1903.

Large objectives made by the firm include (with diameters rounded to the nearest inch) the 22-inch at Mount Etna observatory, a 20-inch at Manila, 19-inch instruments at Strasbourg and Milan, and the 15-inch group at Brussels, Madrid, Bordeaux, Pulkova, Odessa, Lisbon and Cambridge, Mass.[47] Their catalogue of 1861 lists six equatorial refractors from 6 to 14 inches aperture, smaller undriven equatorials, alt-azimuths and table-mounted refractors, a 7-inch heliometer, comet seekers, numerous marine and terrestrial telescopes, and microscopes.[48] At that time the formal title of the firm was the Optical Institute of Merz, Utzschneider and Fraunhofer.

The Work of the Merz Objective

In the early years after installation, the Great Equatorial was used for mundane observations such as occultations, positions of comets, and planetary drawings and measures using a double-image micrometer.[49] However, the dawn of physical (as distinct from positional) astronomy at Greenwich was at hand. In 1863 a "Prismatic Spectrum-Apparatus" was made and improved in the following year: spectra of bright stars were observed, including the recurrent nova T Coronae in 1866.

In 1869 a "thermo-multiplier" was used to detect radiant heat from bright stars, success being claimed in detecting the radiation from Arcturus and Vega. Some atmospheric dispersion correcting eyepieces[50] were tested in 1871 and used intermittently thereafter.

A new prism spectroscope by Browning was installed in 1873, with provision for the insertion of comparison spectra from discharge-tube sources excited by an induction coil. The instrument was used for daytime observations of the spectra of the Sun and sunspots and for solar prominence observations, as well as stellar work.

In 1875 a programme of observations of star spectral line displacements for radial velocity determinations was started and continued for about fifteen years. The F-line of hydrogen (H_β, 486 nm) and the b_1-line of magnesium (518 nm) were used as comparison lines. These visual observations must have been very difficult, and it is not surprising that towards the end of the programme serious systematic errors were found. Some celestial photography was tried in 1875 using the recently-available gelatine dry plates.

The Browning spectroscope was replaced in 1877 by a new Hilger instrument,[51] based on a design by W. H. M. Christie, then Chief Assistant and later (from 1881) Astronomer Royal. A camera was added in 1880. The telescope continued also to be used for observations and micrometric measures of comets, planets and satellites.

Further photographic experiments were tried in 1887, using an afocal doublet 30 inches within focus, which altered the chromatic aberration to give a minimum focus in the blue region of the spectrum, with a secondary magnifier giving an effective focal length of about 130 feet (40 m).

After installation on the Lassell telescope mounting in 1892, the Merz telescope was used for micrometric measures of double stars, the commencement of the long programme continued by the 28-inch refractor at Greenwich and at Herstmonceux. The Merz observations included several pairs with less than 0.5 arc-sec separation and were nearly all made by one observer, Thomas Lewis.

The Merz objective has been used on the guiding telescope of the 26-inch Thompson photographic refractor since 1896. Major programmes at Greenwich included photography of satellites for position (mainly Neptune's satellite Triton, but those of Mars, Jupiter and Saturn were also studied), contributions to the observations of Eros in 1901 and 1930–31 for the solar parallax determinations, stellar parallaxes, proper motions, and photometry in the Kapteyn Selected Areas. The number of exposures made with the 26-inch at Greenwich is not easy to determine: plates taken with the 30-inch reflector carried on the same mounting were numbered in the same series. Up to the start of the parallax programme in 1911, only about 4000 plates had been obtained with the two telescopes, but by 1939 the total had exceeded 30000 of which probably about 25000 were taken with the 26-inch.

Since re-erection at Herstmonceux the 26-inch has obtained nearly 30000 plates, mainly for parallax and proper motion studies. Other programmes have included the photographic photometry of quasars, and positional work such as the derivation of co-ordinates of secondary reference stars for the determination

FIG. 2. The 12.8 inch Merz objective of the Greenwich "Great Equatorial".

(on other larger telescopes) of accurate positions for radio sources and quasars. For a short time in the 1970s the Merz telescope was fitted with an autoguider.

The focal length of the 26-inch refractor (6.9 m) is decidedly short for parallax work: that of the Merz is shorter still by about 1.5 m and it is only by the most careful attention to manual guiding by the observers that parallax results comparable in accuracy to those from longer-focus telescopes have been obtained.

Laboratory Examination and Tests of the Merz Objective

Figure 2 shows a front view of the objective in its cell, which is made of brass and carries no maker's inscription. The glasses enter from the rear and are held by a retaining ring secured by screws through the outer wall. Side location is provided by two fixed steps and a loose block acting under pressure from two springs, one of which is partly visible in the figure.

The outer glass surface is badly scratched, evidently the result of many cleaning operations over the years. It also shows signs of atmospheric weathering, having in certain areas an "orange-peel" appearance (but without apparent loss of polish). The flint component, despite Airy's concern in 1860, is unaffected apart from some discoloration around the edge where moisture has been allowed to stand between the components. The deterioration of the outer surface causes considerable scattered light: an approximate measure indicates that of the light transmitted by the objective only about 80% goes to form an image.

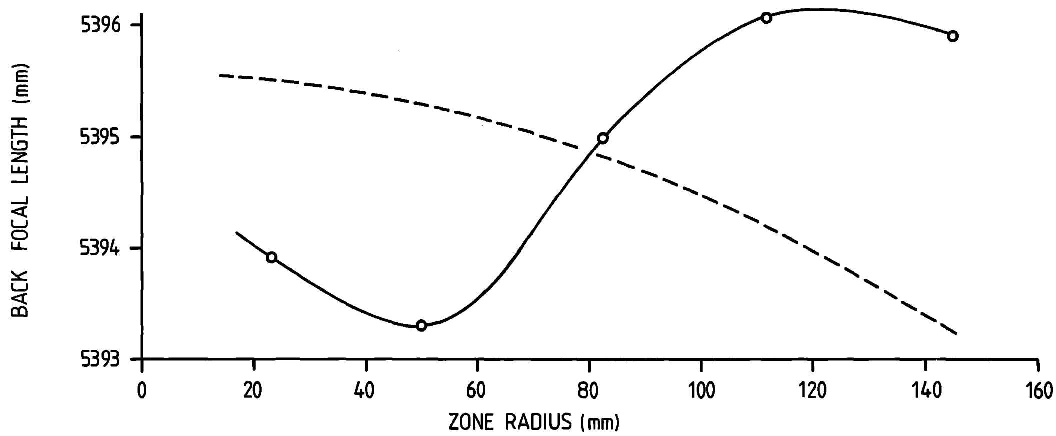

FIG. 3. Zonal focus measures of the Merz objective at $\lambda = 546$ nm. The dashed line represents the focus differences for spherical lens surfaces.

The objective has always been reputed to be of excellent quality but this reputation does not stand up to close scrutiny. Examination under moderately high power of the image formed in the parallel beam of light from a laboratory collimator showed that the objective gives a fairly well-defined Airy diffraction pattern, but with the first bright ring too broad and of too great intensity relative to the central disk. This is indicative of zonal aberrations, and there is also evidence of astigmatism, the pattern being elongated in one direction by about 30%. It is probably fair to add that these image defects, on a scale of one arc-second or less, would not be obvious on a star image under anything but the best seeing conditions.

The off-axis image develops coma at the rate of about 0.13 arc-secs of coma-spread per arc-min of off-axis angle. The coma is noticeable at 10 arc-min and becomes very obtrusive at anything over 20 arc-min off-axis.

The back focal length of the objective is 212.4 inches (5.395 m), giving a focal ratio near f/17.

On the application of a knife-edge test to the on-axis image the zonal errors suspected in the examination of the direct image were immediately obvious. The knife-edge test was used to measure differences of focus from five radial zones in several monochromatic wavelengths. The results at $\lambda = 546$ nm are given in Figure 3 and show zonal focus differentials of nearly 3 mm: results at other wavelengths were similar. The dashed line in Figure 3 represents the calculated longitudinal spherical aberration for truly spherical surfaces conforming to the derived lens parameters which will be described later. Apparently attempts at aspheric figuring were made in manufacture to compensate (not entirely successfully) for the spherical aberration inherent in the design. Of course the objective pre-dates the announcement by Foucault in 1859 of his discovery of the knife-edge test.[52] Evaluation of the direct image was the only criterion available to manufacturers before that time. The longitudinal diffraction-spread of the image, compounded with atmospheric turbulence effects when using a star as a point source, would have made the analysis and correction of zonal errors very difficult.

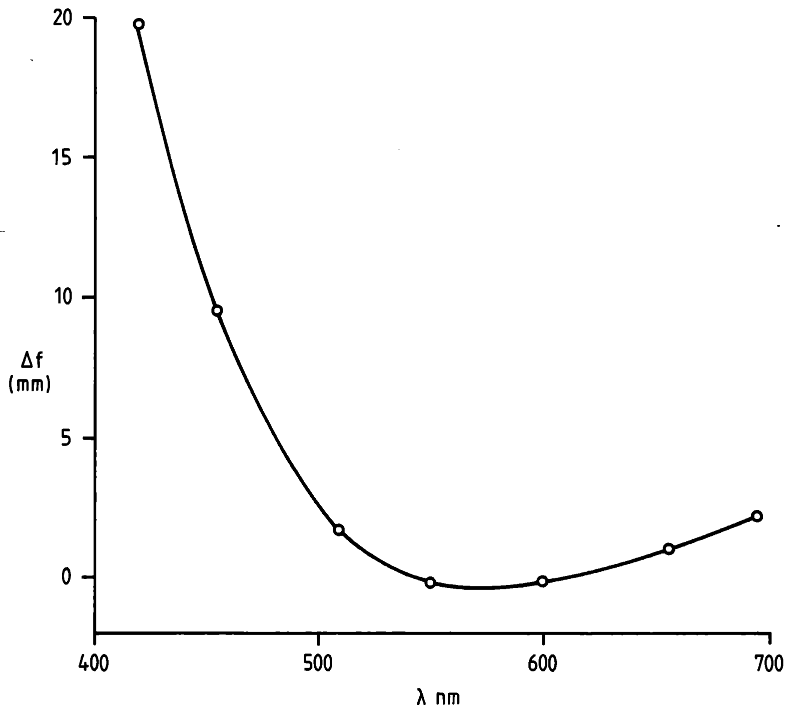

FIG. 4. Colour-focus curve of the Merz objective.

Examination of the reflections formed by the four air-glass surfaces showed that the fourth surface is tilted with respect to the axis defined by the other three. This implies that the flint component has a wedge angle. The apparent tilt of the fourth surface (about 0°.1) is sufficient to account for the astigmatism observed in the direct image.

The colour-focus curve (the "secondary spectrum") is shown in Figure 4. The objective has a quite typical visual chromatic correction with the minimum focus near $\lambda = 560$ nm.

Interferometric testing was carried out using the objective in double-passage with autocollimation from an optical flat. A scatter-plate interferometer[53] was used to produce interferograms at $\lambda = 633$ nm (HeNe laser wavelength). An on-axis example is given in Figure 5. The zonal errors are shown by departure of the interference fringes from straightness, and the astigmatism causes the variable spacing and 'fanning' of the fringes.

Measurement and reduction of the interferogram to remove the tilt between the objective and reference wavefronts and conversion to single-passage produces the contour map of Figure 6, in which the objective wavefront is compared with the best-fit spherical wavefront. The effects of the zonal errors and the astigmatism are apparent: the peak-to-valley wavefront deviation is 0.5 λ.

Figure 7 is from an interferogram taken 20 arc-min off-axis and reduced with removal of the astigmatism and zonal errors to leave only the off-axis aberration. This is clearly principally coma with a peak-to-valley wavefront-error rather less than 0.4 λ at this off-axis angle.

The radii of curvature of the lens surfaces have been measured, using a five-inch spherometer for the first three and by interference against an optical flat for

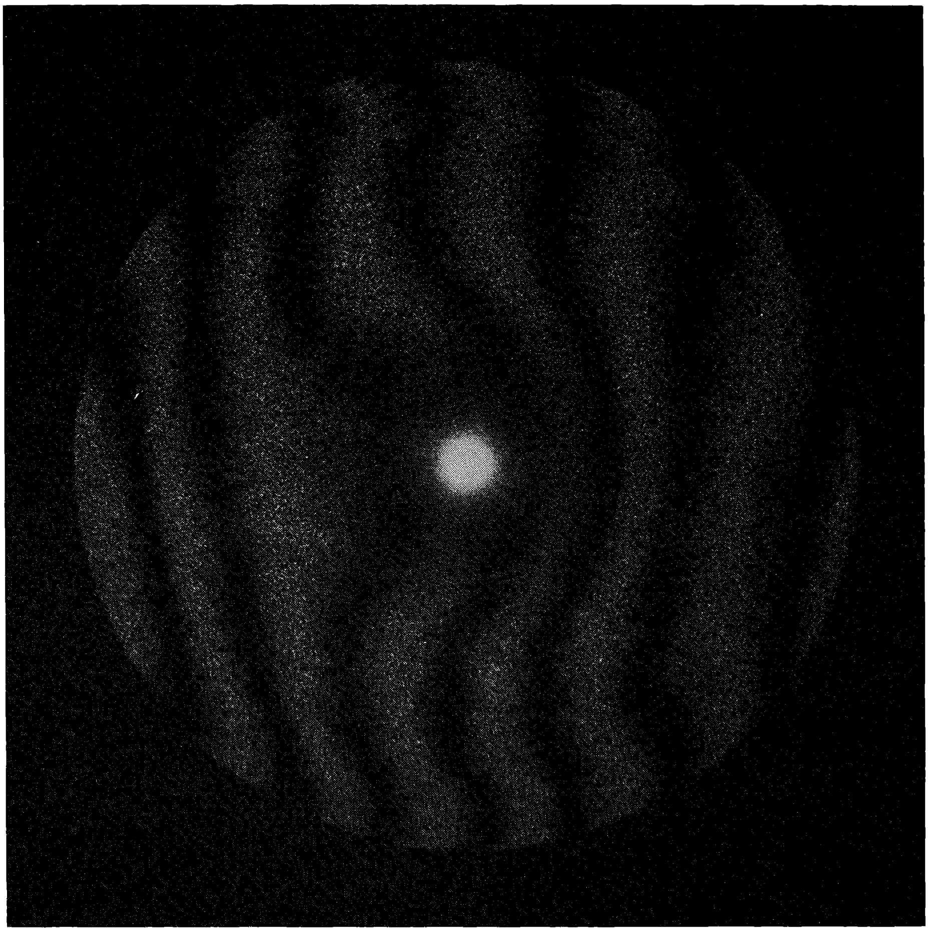

FIG. 5. Double-passage scatter-plate interferogram of the Merz objective. The central bright spot is the returning reference beam.

the nearly-plane fourth surface. The axial separations have also been measured. Using these data and the measured paraxial back focal lengths of the positive crown lens and of the complete objective, the refractive indices of the glasses have been derived by a simple meridional ray-trace.[54] Table 1 gives the radii and separations; Table 2 lists the refractive indices at three wavelengths.

In reassembling the objective after these tests I tried the effect upon the image of relative rotation of the components. No noticeable improvement of the astigmatism occurred. To judge from the many half-obliterated match-marks around the edges of the lenses, this has also been tried in the past and perhaps suggests that the astigmatism had not entirely escaped notice.

Danjon has published details of the history and of some optical tests of the 19-inch (486 mm) Merz objective mounted at Strasbourg in 1880.[55] In its early years the objective gave very poorly defined images. Jakob Merz was consulted in 1896: he deduced that the objective had been incorrectly reassembled after cleaning in 1880 and made a dramatic improvement in the image by face-to-face reversal of the crown lens! The image then suffered from severe astigmatism which in 1923 was much reduced by a 60° relative rotation of the components.

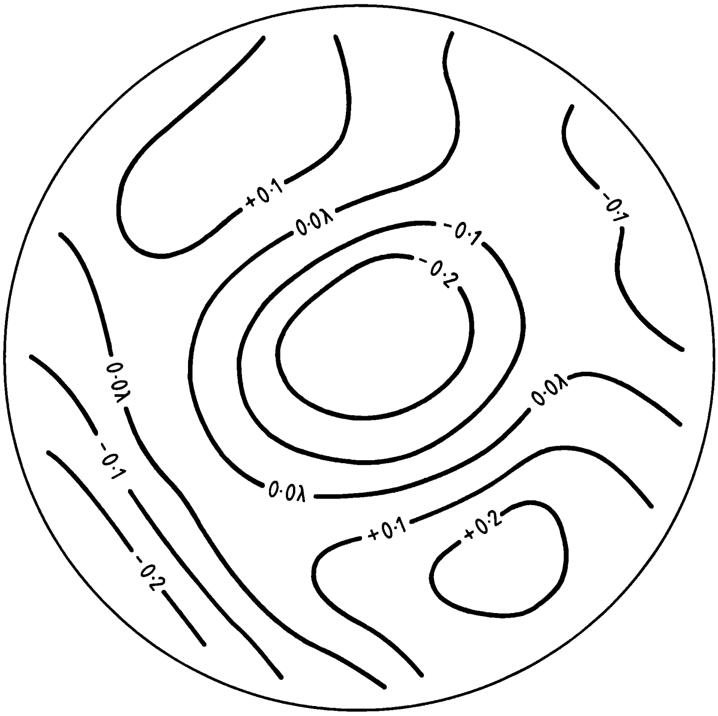

FIG. 6. On-axis wavefront contours of the Merz objective, showing zonal aberrations and astigmatism.

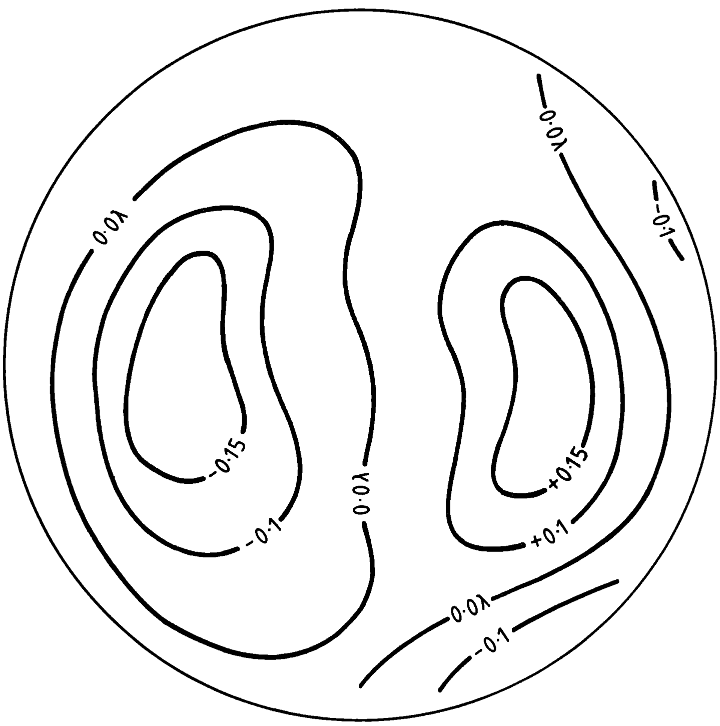

FIG. 7. Off-axis wavefront contours of the Merz objective with zonal aberrations and astigmatism removed to show effect of coma.

TABLE 1. Design of the 12.8-inch Merz objective.

Surface	Radius (mm)	Axial Separation (mm)
Crown lens: 1	2378 convex	
2	2203 convex	22.5
Flint lens: 3	2267 concave	0.3 air space
4	1391000 convex	9.7

TABLE 2. Derived refractive indices of the Merz glasses.

λ (nm)	n Crown	n Flint
656 C	1.5282	1.6303
588 d	1.5308	1.6354
486 F	1.5372	1.6484

TABLE 3. A redesigned "Merz objective".

Surface	Radius (mm)	Axial Separation (mm)
Crown lens: 1	3325 convex	
2	1831 convex	23.2
Flint lens: 3	1865 concave	0.3 air space
4	8393 convex	10.0

TABLE 4. Comparison of relative surface powers.

Surface	Merz Objective	Redesign	Fraunhofer Objective
1	1.20	0.86	0.71
2	1.30	1.57	1.79
3	−1.51	−1.84	−2.12
4	0.00	0.41	0.61

The final image showed longitudinal aberrations which are very like those found for the Greenwich objective. The designs of the two objectives are similar.

A "Redesigned Merz" and a Genuine Fraunhofer Objective

Dr R. G. Bingham has carried out computer ray-tracing that confirms the inherent spherical aberration and off-axis properties of the Merz design. He has also redesigned the objective using the same glasses to give an aplanatic system: details are given in Table 3. Comparison of the redesign with the original objective will show that for aplanatic performance the crown lens needs a much more asymmetrical profile and the flint lens becomes a meniscus. The only feature in common is shown by the internal surfaces, of which the crown lens has a shorter radius than that of the flint.

These characteristics necessary for aplanatism are precisely shown by the objective of the Königsberg heliometer which was made by Fraunhofer, although the lenses were not cut and the instrument not completed until after his death.[56] Details of the objective are given by Ambronn.[57] In Table 4 I compare these properties with those of the Merz objective and the Bingham redesign, in terms of the relative power of each surface $(n-1)/R$ where R is the surface radius scaled to the focal length as unity.

The Fraunhofer objective is clearly quite close to the modern system, in marked contrast to the Merz design. Ray-tracing shows that the Fraunhofer objective was not perfectly aplanatic, with 0.11 mm of longitudinal spherical aberration and a coma-spread of 0.026 arc-secs per arc-min off-axis angle. The spherical aberration would have had a quite insignificant effect upon the image, and even at the 56 arc-min maximum traverse motion of either half-objective[58] the coma amounted to only 1.5 arc-sec. Bessel's comments[59] on the image structure confirm that the objective was essentially diffraction-limited, each image being dominated by the diffraction effects consequent upon being formed by a semi-circular aperture. The high quality of the objective was surely responsible for Bessel's success in deriving the annual parallax of 61 Cygni with the heliometer. His final value of 0.348 arc-secs[60] has an error of less than 20% in comparison with the modern parallax of 0.294 arc-secs.[61]

The evidence provided by the Greenwich Merz objective (and also the later Strasburg example) suggests that the performance criteria and design concepts established by Fraunhofer were no longer heeded by the firm which carried his name in the title.

Acknowledgements

I am grateful to Dr Bingham for his computer ray-tracing of the Merz objective and the redesign to give aplanatic performance. Dr D. H. P. Jones kindly read my draft manuscript and made many valuable suggestions for improvement, as did Dr J. A. Bennett of the Whipple Museum for the History of Science.

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