MICROSCOPE OPTICS

and J.J. Lister's Influence
on the Development
of the Achromatic Objective
1750–1850

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J.C. Deiman: *Microscope Optics 1750–1850*
and J.J. Lister's Influence on the Development of the Achromatic Objective

A thesis submitted for the degree of Doctor of Philosophy of the University of London and for the Diploma of Membership of the Imperial College.

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Dedicated to my beloved parents
C. Deiman (1921–2007) en T. Deiman-Visser (1921–2015)

Dr. J. van Zuylen (1906–1995)

Prof. Dr. G. L'E Turner (1926–2012)
Helen Turner (1930–2004)

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FOREWORD

This is the fifth revision of the thesis I originally submitted in February 1992. A second version of 30 copies was published in September 1992, on the occasion of a festive meeting in the Senate Hall of the university of Utrecht. Later another 60 copies of this second version were printed and sold. A fourth version on CD-ROM was published by Savona Books in 2008.

All these revisions differ slightly from the original one and of each other, every time I found some small errors that were corrected in these subsequent editions.

This fifth edition differs from the other ones in one important aspect, it was composed in LaTex, which generates an output PDF file. Apart from this there were again small textual changes, more illustrations could be added, and indexes and cross-references could be added fairly easy in LaTex.

ABSTRACT

A number of microscopes were selected for study from the Utrecht University Museum, the Science Museum and the Wellcome Collection in London, and the Museum of the History of Science in Oxford. On these instruments, optical parameters were measured, namely the focal length of eyepieces and objectives, and the magnification, numerical aperture, and resolving power of objectives.

Eighteenth-century English compound microscopes were selected on the criterion that two or more examples by a particular maker were available. Nineteenth-century achromatic objectives were chosen on the basis that they would stand comparison with those improved during the period 1825–1850 by J.J. Lister. For this reason, only objectives by Ross, Smith & Beck, Powell, and Powell & Lealand were studied. As far as possible, the internal construction of these objectives was also examined.

The data on eighteenth-century objectives and eyepieces was used to show that spherical and chromatic aberration were not the main limiting factors in their quality.

The work of J.J. Lister was elucidated by a thorough examination and analysis of the Lister Archive that belongs with the collection of the Royal Microscopical Society. This archive consists of plans, drawings, and letters to makers, together with Lister's lenses, fabricated partly by himself. As a result of this study, it proved possible to answer the question why the achromatic microscope developed so much later, and more slowly, than the achromatic telescope. The sheer complexity, both technological and theoretical, of the compound achromatic objective was found to be the main cause of this slow development.

The objectives of Ross, Smith, and Powell were examined to trace Lister's influence on their development. His direct influence did not last long, but his methods of design–a combination of qualitative reasoning and trial and error–were used until they were superseded by Abbe's rigorous calculations in the last quarter of the nineteenth century.

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To my supervisor, Professor Dr. G. L'Estrange Turner (†2012) and his wife Helen Turner (†2004), who taught me *the art of being English*. They both stimulated me during the discussions we had in Islip, be it before, during or after meals which I will never forget. Apart from this they both made this project possible, helped me when I was in difficulty and encouraged me to continue when I despaired.

To my parents, modestly in the background as always. They stimulated my curiosity by never refusing to answer all my questions.

To my friends, who had to endure my temper and my bad moods: Peter van der Salm and Heleen Griffioen, Jan Teeuwisse and Alice Weve, Hans Rooseboom, Wim Thomas, Leon Dennett, and Chris Frewin Howse–this thesis would not have been possible without their support. Jan Teeuwisse's laserprinter was a welcome guest for some weeks. Hans Rooseboom found many spelling mistakes and inconsistencies, which he seemed to enjoy greatly. Peter van der Salm brought the design of this book to perfection. Wim Thomas gave me hospitality during my stays in London. Leon Dennett helped me in deciphering Lister's handwriting and improved the general quality of my English.

To my Director drs. S.W.G. de Clercq, my fellow curator drs. J. Schuller tot Peursum-Meijer and my other colleagues from the Utrecht University Museum for allowing me to spend so much time in England during the last three years.

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Dr. ir. J.C. Deiman DIC, Amsterdam–Bali, 1989–2020.

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INTRODUCTION

1.1 THE STUDY OF SCIENTIFIC INSTRUMENTS

The development of the microscope is characterized by periods of feverish activity and periods of gradual development or stagnation. After its invention at the beginning of the seventeenth century, probably shortly after that of the telescope, it took some fifty or sixty years before people started using microscopes for systematic research.

A first period of energetic activity, which lasted from 1660 to ca. 1720 is described by Fournier in her recent thesis.[1] During and after this period many improvements were made, which turned the microscope into a useful tool for research in the life sciences in general. The microscope became a very popular instrument for the eighteenth-century lettered public as well.

When at the end of the 1750s the optical quality of the telescope was greatly improved by the use of achromatic object glasses, it took some sixty years before this principle became of equal importance for the microscope. In the period 1825–1850, when the compound achromatic object glass was developed, using achromatic doublets, triplets and combinations of these, the resolving power of the compound microscope increased to nearly tenfold, from ca. 3μm to 0.3μm.

Various authors have studied this period from different points of view. Van Cittert, one of my predecessors at the Utrecht University Museum, systematically measured in 1934 the resolving power of all the historical microscopes available to him.[2] Using the data he obtained in this way he was able to show the dramatic increase in resolving power in the period referred to.[3] Similar surveys, though on a smaller scale, have been conducted by Frison, who investigated the microscopes of the Van Heurck Collection in the Antwerp Zoo; Otto, using the microscopes in the historical collection of Carl Zeiss in Jena, and Bradbury who investigated a number of different types of eighteenth-century microscopes.[4] The study by Hughes is valuable, though he heavily relies on secondary sources as far as his instrumental data is concerned.[5]

Notably the catalogue of Van Cittert contains a number of mistakes which were discovered by Van Zuylen and myself. Turner investigated a number of aspects, some of which were rather unconventional but proved to be very valuable.[6] Nuttall's articles can serve as an introduction, but I did not find many new or original points of view in them.[7]

1 Fournier [47]
2 van Cittert [111]
3 van Cittert [112], 51-62; van Cittert [113] 182; van Cittert and van Cittert-Eymers [114], 73–80.
4 Frison [50], Frison [51]; Otto [87], 189–195; Bradbury [19], 151–173.
5 Hughes [65], 1–22; Hughes [66], 47–60.
6 Turner [103], 175–199, Turner [105], Turner [106]
7 Nuttall [85], 71–88; Nuttall [86], 590–604.

Social aspects of microscopy were emphasized by Butler, Nuttall and Brown in their monograph written on the occasion of an exhibition on this theme in the Whipple Museum, Cambridge.[8] One chapter is devoted to the 'amateur microscopist', the two others discuss the relation of the microscope to the medical profession. In 1989, on the occasion of the 150th anniversary of the Royal Microscopical Society, Bennett also contributed to this theme.[9] In his article he emphasizes the influence of the user on the development of the instrument. In early Victorian England wealthy amateur scientists wanted a different type of microscope than the professional scientist on the Continent. Especially the most expensive English microscopes were highly specialized instruments where resolving power was more important than cost or ease of use, while Continental instruments were made for the daily work in research laboratories, where ease of use and a low price are much more important factors. In chapter 6 of this thesis, where I compare English and Continental objectives, this is shown by the higher resolving power of the English objectives compared to most Continental ones.

The importance of the microscope for the medical profession in the nineteenth century is also stressed by a number of Dutch authors in 'Medische Microscopie in de Negentiende Eeuw'.[10] The university of Utrecht was, in the 1840s and 1850s, an especially important centre where professors such as Schroeder van der Kolk, Mulder, Harting and Donders greatly added to the use of the microscope in biology, medicine and physiology. The microscope and its role in the education of the working classes in Victorian England is discussed by Gooday in a recent article.[11]

Though a number of authors hint at some technical problems which might have caused some delay in the development of the achromatic microscope, the one more than the other, they do not emphasize these technical problems very much, or even tend to reduce and neglect them.

It is a sad fact that in history of science many professionals tend to be more interested in the philosophical, social, psychological and economic aspects of science, and much less in the technological and instrumental aspects. The study of historical scientific artefacts has for this reason often more in common with archaeology and history of art (where objects are a primary source of knowledge too) than with history of science.

An important common trait with archaeology and history of art is the importance of collections of artefacts with a good provenance. As in archaeology where a pot without a provenance is just a pot, which can be studied in its own right, for the historian of scientific instruments a microscope without a provenance is just a microscope: it can be studied and certain aspects can be discussed, but the environment in which it has functioned is lost.

Extensive collections of scientific artefacts, for my own research on microscopes, in the Utrecht University Museum, the Science Museum and the Wellcome Collection in London, the Museum of the History of Science and the Royal Microscopical Society Collection in Oxford are an absolute prerequisite for serious research. Unfortunately science museums tend to spend most of their

8 Butler et al. [22]
9 Bennett [10], 267–280.
10 Fournier [48], 59–114.
11 Gooday [53], 307–341.

resources and effort in making temporary exhibitions for a general public, neglecting their more important task of preserving, cataloguing, and studying their collections so that they can be used for scientific research. Exceptions are the museum in Utrecht where Van Zuylen and I could work on the preparation of an extensive catalogue raisonné of the collection of about 300 microscopes and measure data of some 800 objectives; the Whipple Museum in Cambridge which has published an astonishing number of catalogues, and the Royal Museums of Scotland where much work is done in this field.

In archaeology and history of art connoisseurship has always played an important role, especially when these branches of the arts were establishing themselves. In the second half of this century it became apparent that connoisseurship alone is not always sufficient to ascertain the authenticity of objects and that modern methods of scientific research can form a valuable addition to it. The enormously inflated prices of works of art may well have stimulated this trend. In this connection it is perhaps good to point out that a triplet lens by Tulley is much rarer than a painting by Rembrandt or Van Gogh.

1.2 SCIENTIFIC INSTRUMENTS

A crude subdivision of the sciences, useful for the period from roughly 1600–1800 could be the following:

mathematical sciences	natural philosophy	natural history
astronomy	gasses	biology
navigation	heat	zoology
surveying	electricity	geology
mechanics	physical optics	pharmacology
geometrical optics	chemistry	medicine
mathematics		

Scientific instruments, which were used in the mathematical sciences and in natural philosophy especially, can also be divided along the lines set above, so we have mathematical instruments and philosophical instruments.

Mathematical instruments are generally characterized by some kind of division, a linear scale or a divided circle. Examples are measuring rods, compasses, sextants, theodolites.

Philosophical instruments form a heterogeneous group. Their construction is mainly based upon empirical knowledge, they were used by natural philosophers for lecture demonstrations or to demonstrate a particular theorem. Examples of such instruments are air-pumps, electrical machines, and mechanical models.

There are also instruments which do not completely belong to one of both groups–for instance the barometer and the thermometer. Both have the scale which is so characteristic for mathematical instruments but as long as this scale is empirical and not based upon an exact mathematical theory they can be considered as philosophical instruments.

Other instruments which do not belong to one or other group are optical instruments, like the telescope and the microscope. Another argument to define a separate subclass for these instruments is that instrument makers called themselves 'mathematical, optical and philosophical instrument maker'.[12] Mathematical instruments could not be made without an elementary knowledge of mathematics. For the construction of optical instruments knowledge of both geometrical optics and physical optics was needed, together with a lot of technological knowledge. Optical instruments were used for observations, not for measurements.

For telescopes this changed when astronomers and geometers started using telescopes as sights on mathematical instruments, with micrometer eyepieces or cross-wires. And also when astronomers used them to determine the exact position of heavenly bodies, using the same techniques. Microscopes were simply observation instruments; though micrometer eyepieces were used on them, the purpose of these was mainly to determine the dimensions of objects.

Microscopes were instruments based upon theories from the mathematical sciences and natural philosophy. They were used by people who mainly fall in the third category, of natural historians. As a consequence the instrument was interdisciplinary, which slowed its development considerably.

Though telescopes and microscopes were generally made by the same instrument makers, they were used by different groups of people, which strongly influenced their development. New optical inventions, like the achromatic objective, were incorporated in telescopes much earlier than in microscopes. A reason for this time lag in the development of the microscope compared to the telescope is that astronomy was a mathematical science. It was practised by a professional body of people, who were well versed in mathematics and in geometrical optics. Astronomers which contributed to optics were Kepler, Huygens, and Herschel. They solved many of the practical and theoretical problems associated with their telescopes.

In contrast, microscopes were not used by a well defined professional group. Natural history was to a great extent practised by amateurs. They were in general not mathematicians who could improve the optical part of their microscopes. As a result the improvements were mainly mechanical; after all these people knew how to use a microscope. Optical improvement depended on the initiative of instrument makers. Eighteenth-century users of microscopes must have been content with their instruments, I will analyse in chapter 3 the large number of 243 single objective lenses and some 35 eyepieces of microscopes made between 1750 and 1820. I found them to be of reasonable quality, though their useful magnification was limited to a 100–150 diameters. Especially the three-lens eyepiece which came into use in the second half of the century formed a good compromise between complexity and quality. Their distortion is higher than we would accept, especially in the outer zone of the field, but it is small enough for normal visual observation. Also their chromatic difference of magnification is not extremely large.

As long as the use of the microscope did not change, this rather static development of small changes did not give rise to problems. However, when the difference between what people expected of a microscope and what instrument makers could produce became too large–which was what happened in the 1820s–

12 Bennett [9]

a revolution rather than an evolution was required. This revolution started in a number of countries–an obvious proof for a need universally felt–and was characterized by a number of centres of revolutionary activity.

The achromatic doublets made by Van Deijl in Amsterdam in 1807, the ones made by Marzoli from Brescia in 1811 and those made by Fraunhofer from 1812 onwards were a first attempt to improve the microscope in a revolutionary way. They did not find massive support; it is not unlikely that the troubled times and the isolated position of their makers were responsible for this. Also the high cost of those early achromats was prohibitive, the difference when using the single lens was not striking enough to justify producing achromats on a large scale.

A second start in the 1820s in Paris was more successful, the combination of two and more achromatic doublets by Selligue and Chevalier was the real breaking point. Both Lister in England, who was fiddling with Tulley's clumsy triplets and Amici in Italy, who got stuck in the construction of equally clumsy elliptical mirrors, were stimulated by Chevalier to investigate the combinations of doublets and triplets which were to dominate the rest of the period. That this development was so successful was not only caused by the genius of Lister and Amici, the rapid growth of science in Europe in the second quarter of the nineteenth century was at least equally important. The end of this period coincides approximately with the Great Exhibition of 1851 in London. Around this year the classical dry objective reached the zenith of its possibilities–a further increase of its numerical aperture and hence its resolving power was impossible.

The emergence of water- and later oil-immersion objectives and objectives with a better chromatic correction and a flatter field falls beyond the scope of this thesis, together with the theoretical progress in understanding the forming of microscopical images, which made these developments possible.

1.3 PURPOSE

The purpose of this thesis is twofold. Firstly, to investigate whether there were independent technological reasons why the development of the microscope was much slower and occurred much later than that of the telescope. And secondly, to introduce methods of modern scientific research as an addition to connoisseurship in the history of scientific instruments.

This is worked out in two case studies; in the first one the optical properties of the eighteenth-century chromatic microscope are investigated. In the second one the topic is the development of the compound achromatic objective by Lister in the period 1825–1850.

It was considered to be very important for both case studies to investigate as many instruments as possible within a reasonable length of time, rather than to concentrate on a few instruments in great depth.

The pilot project in Utrecht, where some 800 objectives (ca. 150 single lenses and 650 achromats) belonging to the 300 microscopes of the collection were investigated, showed that until ca. 1880–when the Germans started producing great numbers of objectives within close tolerances–the differences between the individual objectives were too large to neglect.

From the Science Museum, the Wellcome Collection, the collection of the Royal Microscopical Society and the Museum of the History of Science in Oxford I selected another 440 objectives, which comprised 100 single lens objectives and 340 achromats. Of these 340 achromats, 220 were made by Ross, Powell/Powell & Lealand and Smith/Smith & Beck, the others were by various Continental makers. It was also possible for the first time to investigate fully the lenses and objectives from the Lister Legacy in the collection of the Royal Microscopical Society.

It became clear that the development of the achromatic objective was also slowed down because the non-achromatic microscope–if properly used–was not as bad as many authors suggested. In Utrecht, with its well equipped laboratory, the professors mentioned on an inquiry form of 1848/1849 not only the microscopes made by Amici and Oberhäuser but also the old ones made by Martin, Dellebarre, Jones, Adams and Van Deijl.

The investigation of Lister's lenses and his papers revealed many of the problems which had to be overcome before achromatic objectives could be manufactured on a commercial scale.

2

METHODOLOGY

2.1 INTRODUCTION

Like astronomy, geometrical optics is one of the oldest mathematical sciences, much older than Newtonian mechanics. A reason for this is that the straight line of Euclidean geometry and the ray of light of geometrical optics are essentially the same thing. The laws of reflection could be defined as simple theorems from Euclidean geometry.

The subdivision into geometrical optics–a very mathematical science–and physical optics, which was much more speculative, proved to be of use. Geometrical optics could be developed as a mathematical model, refined enough to solve the first problems encountered by people who wanted to make telescopes and microscopes. There was always interaction with physical optics.

One characteristic of a mathematical science is that it deals not primarily with reality but with a much simplified model of reality. The assumptions on which the model is based are the ties of the model with the physical reality. In this way the model can be developed independently of metaphysical problems and also independently of physical problems which are not yet clearly understood. Gradually, the mathematical model becomes so refined that it starts predicting phenomena which do not agree with common sense experiences or with the physical reality on which the mathematical model is based. Then the axioms of the mathematical model have to be adapted to the new situation and a new or more refined model has to be developed. This process is described by Kuhn as a scientific revolution, though in general it evolves much more slowly and gradually, both the old and the new paradigm coexisting for a long period of time.[1]

An example of such a period of change is the seventeenth century when Kepler, who investigated the human eye, definitively proved we see objects because they radiate light to the eye, instead of the other way round. Later in the century Huygens had to rewrite part of his optical work in which he took account only of spherical aberration and not of chromatic aberration as a cause for the deterioration of the image, when he learned about Newton's publications in 1672 about the colours ofwhite light. And in the second quarter of the nineteenth century the discoveries of Young, Fresnel and Airy lead to an undulatory theory of light which clearly showed the limitations of the geometrical model used by their predecessors.[2]

Alongside geometrical optics and physical optics optical technology had to be developed. The progress here was slow, it was no academic discipline, it needed contributions from many different fields of knowledge and experience. Also

1 Kuhn [74]
2 Hakfoort [58]

instrument makers were secretive about their methods, the accumulation and diffusion of knowledge was not much boosted by this secrecy.

2.2 THE LENS AND ITS ABERRATIONS

2.2.1 *Refraction*

When light travels from one optical medium into another, from air into glass for instance, the directions of the rays are changed. The law governing this is called after its discoverer, Willebrord Snel van Royen (1580–1626), who apparently formulated it in 1621. Snell's law states:

$$N = \frac{\sin i}{\sin u} \tag{1}$$

with i the angle between an entering ray and the perpendicular and u the angle between the corresponding refracted ray and the perpendicular.

Snell never published his sine law. Lohne states in his article in Sudhoff's Archiv that Descartes knew about Snell's unpublished sine law since 1627, it was published by Descartes in 1636.[3] It took until the second half of the seventeenth century before the sine law was universally accepted.

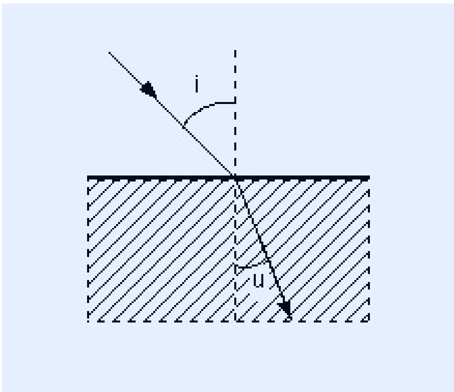


Figure 1: refraction

The refractive index N is not independent of the wavelength of light. In this thesis I have assumed, when measuring optical parameters, that the refractive index found corresponds with the refractive index for the yellow-green helium d-line, with a wavelength of 587.6nm. The refractive index for this wavelength is denoted as N_d. The dispersion ΔN is given as the difference between the refractive indices of the green-blue hydrogen F-line at 486.1nm and the red-yellow hydrogen C-line at 656.3nm, with refractive indices N_F and N_C respectively.

2.2.2 *The Lens*

A lens is characterised by its two radii r_1 and r_2, its thickness d and the physical properties of its material, usually glass. In optical drawings and calculations it is

3 Lohne [76]

common usage to assume that rays from an object enter the optical system from the left and go to the right. The direction from left to right is taken as positive. A radius is counted positive when its center of curvature is to the right of the surface and negative when the centre is to the left of the surface.

The focal length f of a lens is then given by the formula:[4]

$$f = \frac{N r_1 r_2}{(N-1)\left((r_2 - r_1)\,N - d\,(1-N)\right)} \tag{2}$$

The distance between the focal point F and the surface of the lens is the back focus bkf:

$$bkf = f - \frac{r_2 d}{N\,(r_2 - r_1) + d\,(N-1)} \tag{3}$$

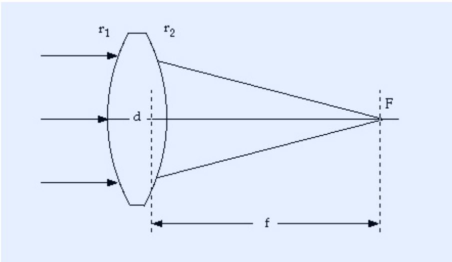


Figure 2: the backfocus of a thin lens

When the thickness d of the lens is small compared to its radii, thin-lens approximations can be used. The focal length f of a thin lens is:

$$\frac{1}{f} = (N-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{4}$$

The focal length f of a system of thin lenses, close to each other is:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} + \quad etc. \tag{5}$$

These thin-lens formulæ were generally used in the seventeenth, eighteenth and early nineteenth century to design optical systems.

The behaviour of lenses departs in many ways from the ideal. Notably spherical and chromatic aberration, which are shortly treated in the following paragraphs, can cause a lot of problems. Other aberrations, which are not treated extensively are astigmatism and coma. Astigmatism is the phenomenon that a point is depicted as a short line. Coma shows itself in the form of a tail like a comet around the stars in an artificial star test. An extensive treatment of the theory of aberrations is found in Welford.[5]

4 Lummer [78]
5 Welford [120]

2.2.3 *Spherical aberration*

The focus of the lens defined above is its paraxial focus, the focus for a very narrow pencil close to the optical axis of the lens. For a wider pencil the position of F depends upon the distance of the rays from the axis. This phenomenon is called spherical aberration. For a positive lens the focus for rays farther from the axis is closer to the lens, this is called spherical under-correction. In a negative lens this is just reversed, as a result a positive lens and a negative lens can form a combination which is (nearly) free from spherical aberration.

All the various authors, Huygens, Clairaut, Euler, Herschel, Barlow who deal with spherical aberration of lenses express the longitudinal amount of aberration of a marginal axial ray in the form of a formula.

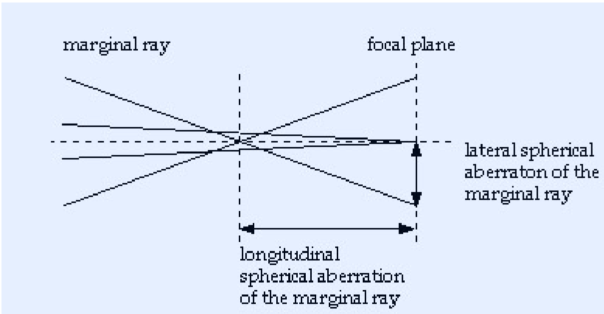


Figure 3: the backfocus of a thin lens

Such a formula becomes very complex and impractical, for a system of two or three lenses a length of one page quarto is quite normal. To get formulæ which were more useful, third order approximations were used and the thickness of the lenses was often neglected. For optical systems with a small aperture, like telescopes, these methods led to acceptable results. As we will see in later chapters this did not work for microscopes where the aperture has to be high because of its relation to resolving power. As a result it was not possible until the second half of the nineteenth century to design an objective for a microscope which was sufficiently free from spherical aberration. Trial-and-error methods based upon third order approximations and experiments with lots of lenses were the only way to make an objective of an acceptable quality. When optical designers started using the technique of tracing a ray through an optical system, an exact geometrical analysis of systems became possible. Ray tracing does not produce a formula but gives a series of mathematical prescriptions which have to be repeated for every surface and every ray. In this thesis spherical aberration is expressed as lateral spherical aberration.

2.2.4 *Chromatic aberration*

Chromatic aberration is caused by the interdependence of the refractive index and the wavelength of light. Unlike spherical aberration, which can be analysed as a purely mathematical problem, chromatic aberration is a physical phenomenon. It took some 140 years between Newton's publications in 1672 about the colours of white light, and Fraunhofer's publication in 1814 about the fixed lines in the solar spectrum, and the way to use them as reference points for exactly measuring the refractive index, before chromatic aberration could be analysed in a rigorous way. The main problem was that while the refractive index could be measured with some precision, it was not possible to indicate exactly at which wavelength this was done. The colours were described as red or violet, which gives an indication but which is after all vague and therefore inaccurate.

In this thesis chromatic aberration was estimated, since a direct and accurate measurement of the refractive index for different wavelengths was impossible. The usual refractometer cannot be used because of the curved surfaces of the lenses. The other available method of immersing the lenses in a liquid of the same refractive index, by which they seem to disappear, is not accurate enough to find the dispersion. Fortunately a linear relation between the refractive index and the dispersion can be assumed for the glass used in the eighteenth and early nineteenth century.

The formula generally used is given by Hovestadt as:[6]

$$\Delta N_{(F-C)} = 0.07812 N_D - 0.10962. \tag{6}$$

Hovestadt's formula is based upon a selection from a list of 44 Jena glasses, published in 1886 by Czapski in the Zeitschrift für Instrumentenkunde.[7] See chapter 8

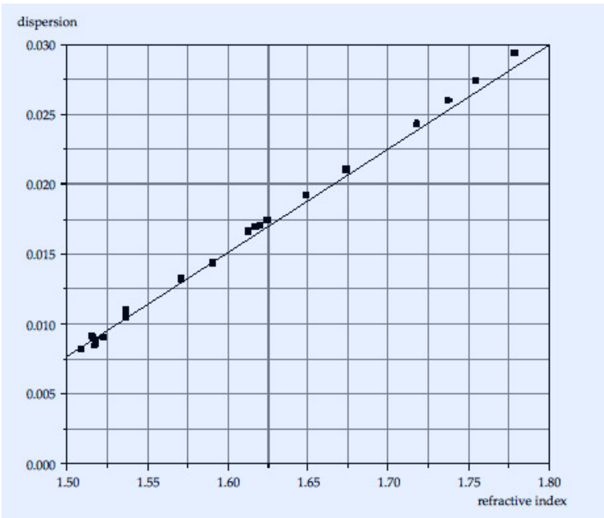


Figure 4: dispersion and refractive index of old glass

In his article Czapski distinguishes two kinds of glass, the older kind for which there is a remarkable linear relation between the refractive index and the dispersion, and the newer kind for which this relation does not hold. This 'new glass' was made by Schott at the request of Abbe, who needed it for his apochromatic microscope objectives.

Though Czapski emphasizes this linear relation for 'old glass', and even plots the refractive indices and the dispersions of the 'old glasses' from his list, he does

6 Hovestadt [64], 36.
7 Czapski [32], 293–299 and 335–348, (338–339)

not derive a formula. A careful analysis of Czapski's list and his graph reveals which were the 'old glasses' used by Hovestadt to derive the formula mentioned above. These 21 glasses are listed in chapter 8. Figure 4 shows along the horizontal axis the refractive index N_D and along the vertical axis the dispersion $\Delta N_{(F-C)}$ for these 21 glasses. The continuous line is drawn using formula 6. The formula for $\Delta N_{(F-C)}$ is calculated by a least-square approximation, the errors are between -5.4% and +4.4%, the average error is 1.5%. This gives a reasonable indication of what we may expect when we use Hovestadt's formula for eighteenth- and early nineteenth-century glass.

To be able to use the formula in OPDESIGN, the following adjustments had to be made:

- Czapski gives the refractive index N_D, for the D-line of 589.3nm, while currently N_d, for the d-line of 587.6nm, is used.
- A second formula relating N_F and N_d had to be derived.

N_d can be calculated by assuming $N_d = N_D + \delta$, for the glass used to derive our formula $\delta \ll 0.009\Delta N_{(F-C)}$. This results in:

$$\Delta N_{(F-C)} = 0.07807 N_d - 0.10954 \tag{7}$$

Since Czapski also lists in his article the refractive index N_F, we can now derive a formula relating $\Delta N_{(F-C)}$ and N_F, again using a least-square approximation. This formula is:

$$\Delta N_{(F-C)} = 0.07393 N_F - 0.1037. \tag{8}$$

Eliminating $\Delta N_{(F-C)}$ from both formulæ gives us the required formula:

$$N_F = 1.056 N_d - 0.079. \tag{9}$$

I discuss in section 4.3.4 the way in which eighteenth-century scientists designed achromatic objectives. The thin-lens approximations which were used at that time resulted in a simple formula relating the focal lengths of the lenses and the dispersive ratios of the glass. As long as the lenses were thin, these doublets were indeed achromatic. But when the thickness of the lenses could not be neglected, as in doublets for microscopes, their chromatic correction becomes insufficient.

2.3 OPTICAL CALCULATIONS

2.3.1 *Opdesign*

In this thesis all optical calculations were performed with the optical design program OPDESIGN, developed by Prof. Dr. L.H.J.F. Beckmann, Delft.[8] It is written in C and originally implemented on an ATARI-ST micro-computer. Versions (5.2 and later) are available for IBM and compatible (MS-DOS) computers and SUN workstations. For the purpose of this thesis I adapted OPDESIGN v5.2

8 Beckmann [6]

(23-08-1990) for Apple Macintosh computers. I have added routines to calculate the magnification and the distortion of eyepieces (section 2.3.2), to calculate the numerical aperture of objectives, and to calculate the focal length for long and short wavelengths. The C version used is Symantecs Lightspeed-C. Available are a version for the Macintosh Plus and one for the Macintosh II-family with a mathematical coprocessor. The method Beckmann uses for raytracing is described by Feder.[9]

2.3.2 *Angular magnfication and distortion of eyepieces*

The angular magnification MA of an eyepiece is defined as:

$$MA = \frac{\tan\beta}{\tan\alpha} \tag{10}$$

in which β is the field angle on the object side, the angle between the optical axis and a line between the outermost point of the object and the point of intersection of the first optical surface and the optical axis; α is the corresponding angle on the side of the eye.

The distortion D of an eyepiece is defined as:

$$D = \frac{MA - MA_0}{MA_0} \times 100\% \tag{11}$$

with MA the angular magnification for a specific angle of view and MA_0 the angular magnification for a very small field angle, usually $\tan\beta_0 = 0.001$. The distortion is given for three values of the angle of view: the maximum angle of view, for the middle of the field, and for a standard value of 34°. For visual observation a value of 1% is still acceptable.

2.3.3 *Conventions and abbreviations*

The x-axis coincides with the optical axis of a system, the positive direction is the direction of the rays, from the left to the right.

Optical surfaces are numbered in the direction of the rays, i.e. in drawings from the left to the right.

The radius of a surface is counted positive if the centre is to the right and negative if its centre is to the left.

bp	distance of the object from the entrance pupil
bkf	back focus, the distance of the reference plane from the last optical surface
CVV′	chromatic difference of magnification
D	distortion
dst	distance between two optical surfaces
ΔN	dispersion, N_F–N_C, unless indicated otherwise
ef	equivalent paraxial focal length for an object at infinity, at mid-wavelength

9 Feder [42]

efl	idem, for a long wavelength
efs	idem, for a short wavelength
epl	entrance pupil
f	focal length
MA	angular magnification
M	linear magnification
mSA	lateral spherical aberration of the marginal axial ray
N	refractive index for mid-wavelength, in general for the d-line
Petz	Petzval sum, always given for a scaled focal length of 10 mm
OPD	Optical path difference
OT	Optical Tolerance for lateral spherical aberration of the marginal axial ray, Zernike's formula
OTz	Optical Tolerance for lateral spherical aberration of the zonal (≈0.71 height) axial ray, Zernike's formula
rds	radius
srf	surface, surfaces are numbered in the direction of the rays, and are drawn from left to right
xpl	exit pupil
zoC	chromatic aberration of a zonal axial ray (by Conrady's method).[10]

2.3.4 *Data of optical systems*

The optical systems which are analysed in chapters three to six fall into two groups:

- designs of lens systems which have not been actualized, or systems of which no actual data is available.
- computations of lens systems which have been investigated and measured.

The data of lens systems from the first group are often not complete enough to perform a recalculation, as a consequence approximations have to be made.

CURVATURES: A minimum condition which has to be fulfilled is that all the curvatures of the optical surfaces are known. When this data is not available or incomplete, a recalculation does not make much sense.

DISTANCES: Many of the designs in the eighteenth and early nineteenth century are derived using thin-lens approximations in which the distances between the optical surfaces of lenses are unimportant. As a consequence these distances are generally not given. Especially the designs which are analysed in chapter three are incomplete in this respect. To do as much justice to their designers I always tried in my simulations with OPDESIGN to make the lenses as thin as possible for a given aperture.

REFRACTIVE INDICES: Most designs are calculated for a specific refractive index, which is also the one used in the computer simulation. In chapter five,

10 Conradi [30]

where the designs of Lister are analysed, the refractive index is not always given. In that case I used the values he gave in earlier comparable designs.

DISPERSIONS: For the rather 'theoretical' designs in chapter three the dispersion of the crown glass lens is always calculated using formula 7, which was derived in section 2.2.4 from the data of a number of optical glasses. The dispersion of the flint lens then is calculated with thin-lens approximations using the method treated in section 4.3.4. For these lens systems I also assumed the refractive index N_d is halfway between the values of N_{short} and N_{long}, the refractive indices for short and long wavelengths respectively. This was the usual practice on which the designs of the eighteenth and early nineteenth century were based. The data of the lens systems in group (b) are measured and calculatedas follows:

CURVATURES: The curvatures of external surfaces of lenses are either measured with a spherometer or with a reflex-method. The spherometer was used for lenses with a diameter larger than 12mm, for smaller lenses the reflex-method was used. Both are described in section 2.5.1.

The curvatures of cemented internal surface of doublet lenses were calculated using data obtained by a through-the-lens measurement of these curvatures. The method is also worked out in section 2.5.1.

DISTANCES: The thickness of lenses was measured with a micrometer. The distances between lenses with vernier callipers.

FOCAL LENGTH: The focal length was measured with a micro foco-collimator. Additional details can be found in section 2.5.2.

REFRACTIVE INDEX AND DISPERSION: The refractive index can now be calculated using formula 4 for the focal length of a lens. The dispersion is calculated using formula 7.

2.3.5 *Spot diagram*

An interesting tool to study the performance of optical systems is the spot diagram. A spot diagram is a plot of points representing the intersections of rays from a given object point with the focal plane of the lens. A spot diagram represents the distribution of the light intensity in the image of a luminous point object and can as such be considered as the geometrical analogy of the star image, treated later in this chapter.[11] The spot diagram of a particular object point is calculated by tracing a number of rays through the optical system.

These rays are spread over the plane of the entrance pupil in a regular way, in general a square matrix, figure 5.1. If the optical system was perfect the image would again be a point. As this is never the case, the point in the image plane will be spread over a certain surface in a particular way which is determined by the aberrations of the system.

11 Stavroudis and Feder [99], 163–170; Herzberger [62], 584–594; Stavroudis and Sutton [100]

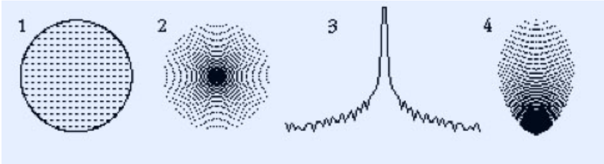


Figure 5: spot diagrams of a 10mm lens, NA=0.083.

The spot diagram of a simple lens in figure 5.2 shows a bright spot in the centre, as we would expect, and a 'halo' of gradually decreasing intensity around it.

The graph of figure 5.3 shows the distribution of the intensity of the light across a line through the middle of the spot diagram, which shows the bright spot as a peak in the middle.

The spot diagram of figure 5.4 was made for an object point at the full field angle of 8°, coma is present in the form of a V-like asymmetrical distribution of the spots.

The number of rays determines how much detail will be shown in the spot diagram; in these examples 1264 rays were calculated.

A more detailed treatment of spot diagrams can be found in the publications already mentioned. Though they appeal to me very much it would fall outside the scope of this thesis to give a detailed analysis of the spot diagrams of the optical systems I investigated.

2.4 OPTICAL TOLERANCES

Already in the seventeenth century it became apparent that spherical lenses and systems of spherical lenses never could give a perfect image, completely free from spherical aberration. One solution was to design aspherical lenses. Though this was a theoretically sound solution, it was not a very practical one. The technology of making lenses was in the seventeenth century not developed enough to tackle this problem. Only in the second part of the twentieth century it did become possible to design and to make these aspherical lenses.

The other solution was to live with spherical aberration and to make it as small as possible so that the quality of the image was not degraded too much by it. This meant in general that the aperture of the objective had to be limited.

Criteria for judging the quality of optical systems evolved together with the increasingly sophisticated mathematical design procedures. It was a known fact that optical systems could not be perfect, but how inperfect were they allowed to be, to be able to do the job they were designed for.

2.4.1 *Rayleigh tolerance*

The British physicist Lord Rayleigh published in 1878 a theorem which was worded by Conrady as:[12]

12 Conradi [29], 136.

> an optical instrument will not fall seriously short of the performance possible with an absolutely perfect system if the difference between the longest and the shortest optical paths leading to a selected focus does not exceed one quarter of a wavelength

This theorem proved to be very useful, the geometrical aberrations of an optical system can be converted by using some simple formulæ into corresponding optical path differences (OPD). Then it is not difficult to determine whether the Rayleigh limit is exceeded by a particular aberration or not. The aberrations which will be considered here are:

- spherical aberration
- chromatic aberration
- the offence against the sine condition (OSC′), a measure for the amount of coma.

2.4.2 *Spherical aberration*

When the optical tolerance for spherical aberration (OT) is calculated two cases have to be considered:

A : The lens system is not completely corrected for spherical aberration. If the aberration is primary, i.e. proportional to the square of the aperture, the maximum permissible value for the longitudinal spherical aberration is:

$$OT = \frac{2\lambda}{N'\,(1 - \cos u')} \tag{12}$$

$N^{'}$ is the refractive index of the medium in which the image is formed (generally air).

$u^{'}$ is the angle which the emerging marginal ray makes with the optical axis. This spherical under-correction is shown in figure 6.1.

B : In lens systems which are trigonometrically corrected for the spherical aberration of the marginal ray, the zonal rays will be undercorrected. The maximum value of this under-correction occurs for a relative incident height of $1/\sqrt{2} \quad (\approx 0.71)$.

The maximum permissible spherical aberration for the zonal ray is:

$$OT_z = \frac{1.46\lambda}{N'\,(1 - \cos u'_z)} \tag{13}$$

u'_z is the angle between the zonal (0.71 aperture) ray and the axis. In this case the OPD between the marginal and the axial ray should not exceed a value of 2λ. The spherical aberration of a doublet in this case is shown in figure 6.2. In figure 6.3 the doublet is over-corrected.

These formulæ differ slightly from those given by Conrady.[13] They were given to the *Nederlandsche Optische Fabriek N.V. Dr. C.E. Bleeker*, by the late pro-

13 Conradi [29], 137, 138.

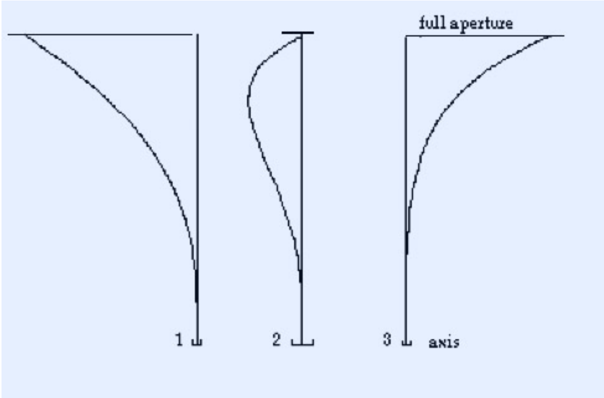


Figure 6: spherical aberration of a doublet

fessor F. Zernike in a private communication to Dr. J. van Zuylen, the optical design engineer from *Bleeker*.

Here these formulæ have to be adopted for lateral spherical aberration as the optical design program OPDESIGN, which is used for analysing the optical systems, calculates the lateral instead of the longitudinal values of the spherical aberration. Assuming λ= 0.54, this results in the following formulæ.

For the primary spherical aberration:

$$OT = \frac{1.08 \tan u'}{N' \left(1 - \cos u'\right)} \tag{14}$$

And for the zonal spherical aberration:

$$OT_z = \frac{0.79 \tan u'_z}{N' \left(1 - \cos u'_z\right)} \tag{15}$$

With a maximal OPD of 1.08μm between the marginal and the axial ray.

2.4.3 *Chromatic aberration*

OPDESIGN calculates the chromatic aberration of the zonal axial ray by Conrady's method; the value of this aberration should not exceed 2λ. Using again λ= 0.54, this comes to 1.08μm.[14] This criterion proved to be a bit too severe for old lenses. For this reason the value found is given, but I mostly used the computed values of the focal length for the short wavelength of the F-line (efs) and for the long wavelength of the C-line (efl) to judge the chromatic correction of a system. When light passes through a simple convex lens in the usual direction, from left to right, the focus for a long wavelength is found to the right of the focus for a short wavelength, this is called chromatic under-correction.

The difference Δef = efs-efl is negative for an under-corrected system and positive for an over-corrected system. Figure 7.1 shows the focal length of an under-corrected doublet as a function of the wavelength (see section 4.4.5), there is no pair of two wavelengths for which the focal lengths are equal. Figure 7.2

14 Conradi [30], 651.

shows the focal length of the triplet by Clairaut (section 4.3.1) as a function of the wavelength. Though the correction is still imperfect there are now wavelength pairs for which the focal lengths are equal.

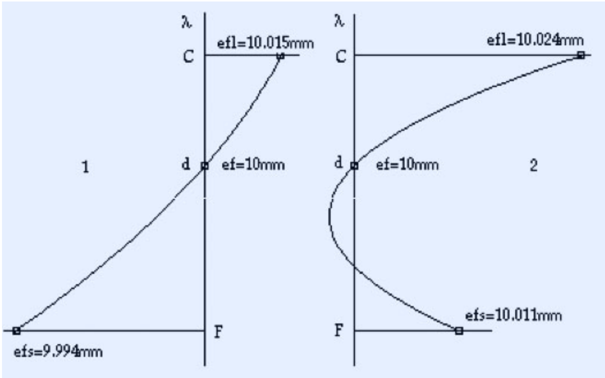


Figure 7: chromatic correction of an achromatic doublet and a triplet

The chromatic correction of eyepieces is expressed by their chromatic difference of magnification, CVV', which is defined as:

$$CVV' = \frac{MA_C - MA_F}{MA_d} \times 100\% \quad (16)$$

In which MA_C is the angular magnification for a long wavelength (the C-line) and MA_F the angular magnification for a short wavelength (the F-line). MA_d is the angular magnification for the mean wavelength (the d-line). Negative values of CVV' mean chromatic under-correction and positive values mean over-correction.

When the absolute value of CVV' is larger than 0.6%, coloured fringes around the objects become rather visible, below that value they are not very inconvenient.

2.4.4 *Offence against the sine condition, OSC'*

Based upon his practical experience a value of 0.0025 is acceptable in Conrady's point of view.[15] In that case the correction for coma is still acceptable.

2.5 OPTICAL MEASUREMENTS

2.5.1 *Curvatures*

The curvature of the surfaces of lenses was measured with a spherometer when their diameter was larger than the diameter of the smallest usable ring, which was 12mm. The spherometer was developed by Van Zuylen, it is a modification of the Watts precision spherometer, described by Twyman in his book *Prism and Lens Making*.[16] The rings are of the usual construction, the surface of the lens to

15 Conradi [29], 395.
16 Twyman [110], 74.

be measured rests on three steel balls which are fitted on equal distances into a recess in an accurately turned steel ring. A plunger of a dial gauge in the centre of the ring is used to determine the sag of the surface.

The radius rds is given by the formula:

$$rds = \frac{C}{0.5s} + 0.5s \pm a. \tag{17}$$

C : a constant the size of $0.5R^2$ with R the radius of the circle passing through the three steel balls. The accurately measured values of C for the six different rings are given in table 1.

S : the difference in reading of the dial gauge between an optical flat and the surface under test. The calibration for an optical flat was always performed for the same reading of the dial gauge, its error being zero at this point (1.700mm). The absolute error of the dial gauge is in this case less than 2μm with a repeatability of the reading of 2μm.

A : the radius of the steel balls, a positive value has to be applied for concave surfaces, a negative value for convex surfaces.

Table 1: spherometer rings

ring	diameter	C	a
1	6.51	2.649	0.5
2	11.83	8.744	1.14
3	16.84	17.733	1.14
4	23.76	35.287	1.14
5	34.2	73.121	1.185
6	48.28	145.72	1.185

Table 2: spherometer errors

ring	number of measurements	average (mm)	error (%)
1	17	0.268	1.2
2	93	0.621	0.6
3	90	0.915	0.43
4	143	1.138	0.36
5	12	1.8	0.27

The accuracy of the measurements is calculated as follows. The accuracy of C is 0.1%, the absolute accuracy of the dial gauge is ca. 1μm and the repeatability is 2μm, giving a total error of 3μm. The errors for the average readings of the five rings I used are collected in table 2.

The reflex method which is used for lenses smaller than 12mm has been described by Van Zuylen.[17] With a microscope with a micrometer-screw eyepiece

17 van Zuylen [115], 309–328, (312 and 323–324).

the distance between the reflections of two small lamps on the surface under test is measured. The two lamps are mounted some distance above and to the left and to the right of the objective of the measuring microscope. The set-up is calibrated against a set of steel balls of an accurately known diameter. For this method Van Zuylen estimates an error of 0.5%.

In a number of cases the curvature of cemented surfaces inside doublet lenses can be measured using this reflex method. As this method is very time-consuming I limited its application to the plano-convex doublet lenses from the Lister Legacy in the collection of the Royal Microscopical Society. Used in a qualitative way–only observing whether a particular reflex is caused by the left or the right lamp, without measuring their distances–it is also a very useful method to determine whether a cemented surface is convex or concave.

Applied to doublet lenses consisting of a plano-concave flint lens and a biconvex crown lens the procedure is as follows.

The focal length f_t and the thickness d_t of the doublet are measured in the usual way. The distance between the reflections of the convex outer surface is measured with the measuring microscope, the radius r of the convex surface can now be calculated. The radius of the cemented surface–measured through the lens–is calculated in the same way, from both the convex side u and the plane side w of the doublet.

The unknown true value of this radius is r_s. The unknown refractive indices are $\mathrm{N}_{\mathrm{crown}}$ for the biconvex crown lens and $\mathrm{N}_{\mathrm{flint}}$ for the plano-concave flint lens. The thickness of the biconvex lens is d. The focal length of the flint lens is $\mathrm{f}_{\mathrm{flint}}$ and of the crown lens $\mathrm{f}_{\mathrm{crown}}$.

Now the following relations between the variables can be formulated:

$$r_s = wN_{flint} \tag{18}$$

and:

$$f_{flint} = \frac{-r_s}{N_{flint} - 1} \tag{19}$$

To simplify the calculations define:

$$p = \frac{(N_{crown} - 1)}{r \times N_{crown}}. \tag{20}$$

From this follows the focal length of the biconvex lens:

$$f_{crown} = \frac{r_s}{(N_{crown} - 1)\left(1 - p + \frac{r_s}{r}\right)}. \tag{21}$$

Applying some simple geometrical optics, the following two equations result:

$$u = \frac{r_s - d}{\frac{r_s}{f_{crown}} + 1 - p} + \frac{d}{N_{crown}(1 - p)} \tag{22}$$

and

$$f_t = \frac{f_{crown} f_{flint}}{f_{crown}(1 - p) + f_{flint}}. \tag{23}$$

As both u and f_t are known, these equations can be solved. There are however three unknown factors, N_{crown}, N_{flint} and d, which means there is not one solution but an infinite number from which one or two reasonable solutions have to be chosen.

Using MATHEMATICA, a very useful *System for Doing Mathematics by Computer* this can be done fairly easy.[18] Mathematica can calculate a number of values for the thickness d and the internal radius of the biconvex lens and the refractive indices N_{crown} and N_{flint}, then one or two plausible values can be chosen as the number of possible values for the refractive indices is very limited ($1.5 < N_{crown} < 1.53$ and $1.56 < N_{flint} < 1.65$).

2.5.2 *Focal length*

The focal length of all lenses, eyepieces and objectives has been measured with a micro foco-collimator. The same instrument was used and described by Van Zuylen in his investigation of all the microscopes of Antoni van Leeuwenhoek.[19] The method is explained by Van Heel.[20]

Table 3: calibration of the micro foco-collimator

Used with micrometer eyepiece Bleeker H10M		
objective	micrometer	Collimator constant
Leitz 1*	1mm=1.81 interval	16.57
Bleeker 4	1mm=4.44 interval	6.924
Bleeker 10	1mm=7.30 interval	4.196

Used with micrometer-screw eyepiece B & L		
objective	micrometer	Collimator constant
Leitz 1*	1mm=0.304 interval	101.53
Bleeker 4	1mm=0.702 interval	43.75
Bleeker 10	1mm=1.14 interval	27.02

2.5.3 *Magnification and angle of view of eyepieces*

The angular magnification MA of eyepieces is given for a distance of distinct vision of 250mm (10 inch), the usual practice nowadays. From this follows, with f the focal length of the eyepiece:

$$MA = \frac{250}{f}. \tag{24}$$

18 Wolfram [124]
19 van Zuylen [115], 309–328, (311–312, 322).
20 Heel [60], 222–223.

The angle of view of eyepieces was not measured directly. Two methods were used for an indirect measurement. The first one employed the field diaphragm of the eyepiece, its diameter d could often be measured. When the focal length of the eye lens is f_e, the angle of view α is:

$$\alpha = 2 \arctan \frac{0.5d}{f_e}. \tag{25}$$

A second method was used when there was no diaphragm or when its diameter could not be measured. In this case the magnification MA and the object field of of the original microscope were measured. The angle of view is in this case:

$$\alpha = 2 \arctan \frac{of \times MA}{2 \times 250}. \tag{26}$$

2.5.4 *Magnification of objectives*

The magnification of objectives is measured using an object-micrometer and a little telescope with a micrometer eyepiece. The objective to be measured is screwed on a microscope which is provided with a standard ×5 or ×10 Huygenian eyepiece. The object micrometer is brought into focus and the telescope is put on the cap of the eyepiece.

The magnification M follows from the formula:

$$M = 0.984 \times \frac{telescope\ scale\ units}{object\ micrometer\ reading}. \tag{27}$$

The constant 0.984 was determined by Van Zuylen in the same way as was done for the collimator with an accuracy of 0.1%. The magnification of the objective alone can easily be found by dividing by the known angular magnification of the eyepiece.

2.5.5 *Numerical aperture*

The numerical aperture of objectives is calculated from the diameter of the exit pupil of the combination objective-eyepiece and the magnification using the formula:

$$NA = \frac{magnification\ \times\ exit\ pupil}{500}. \tag{28}$$

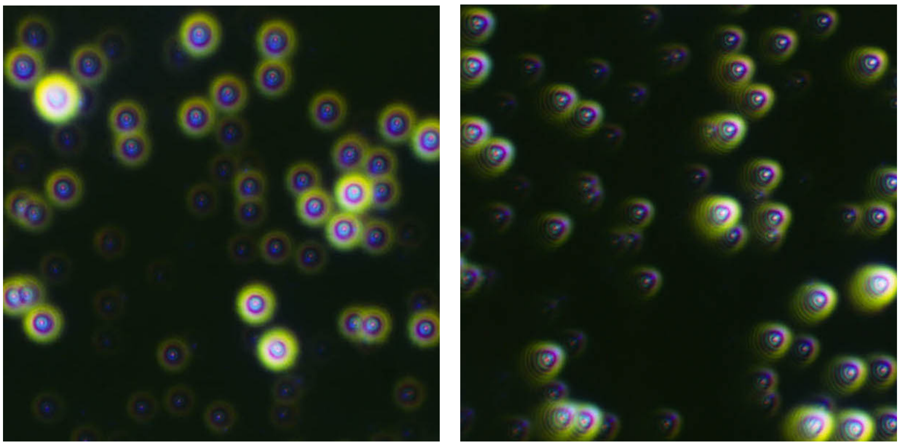
The exit pupil is measured with a little hand microscope with a micrometer eyepiece which is put on the cap of the eyepiece. The diameter of the pupil equals the number of scale units divided by a constant. This constant is measured by means of an object micrometer, the value for the microscope I used is 40.7.

It must be realised that the formula is only an approximation in which the distortion of the eyepiece is neglected. The eyepieces used for determining the magnification of objectives were a ×5 or a ×10 Huygenian eyepiece made by Bleeker in Zeist. For these eyepieces the distortion is sufficiently low (below 1%).

The magnification is sometimes measured using the original eyepiece, which often has a much higher distortion. Especially eighteenth-century eyepieces with a large angle of view and a high distortion will give inaccurate results. Measurements with these eyepieces were, however, only used to find an approximate value for their angle of view.

2.5.6 *Star test*

A star test is used to get an impression of the general quality of objectives. The artificial stars are microscopical holes in a layer of aluminium deposited on an object slide; their diameter varies from less than 0.5μm to a few microns. See figure 8, figure 8a shows the star-image of the Zeiss 40×0.65 objective in its normal state, figure 8b shows a star-image of the same objective with part of it decentered on purpose. The circular pattern has changed to something like a comet with its tail. The method was already known to Lister who made use of the reflection of a light source on small globules of mercury as artificial stars. A good description is found in a little pamphlet which was issued in 1891 by the firm of Cooke & Sons.[21] Also Slater discusses this subject.[22] Recently Fletcher argued that the diameter of the stars should not be too small, 1.5–3μm for a high power lens. The out-of-focus interference rings of a very small star tend to hide the effects due to zonal aberration of the objective.[23]



(a) Objective Zeiss 40×0.65, without coma (b) Objective Zeiss 40×0.65, with coma

Figure 8: Example of a star-test

2.5.7 *Resolving power*

The resolving power is generally determined with a specially made test plate. For some objectives these data were compared with those obtained by the twelve-band Grayson Ruling in the collection of the Utrecht University Museum.[24] The same Grayson Ruling was used by Van Cittert in 1934 to determine the resolving

21 Sons [97]
22 Slater [95]
23 Fletcher [46], 154–159.
24 van Cittert [111], 105–106; Stone [101], 1–6. The inventory number of the Utrecht Grayson Ruling is UM556.

power of the microscopes in his catalogue. For the same reason the ten-band Nobert test plate which Harting described was used for a few tests.[25] In Oxford a few measurements were made with the Grayson Ruling in the possession of the Royal Microscopical Society.[26]

Table 4: line distances of the two test plates

33-band test ruling				28-band test ruling		
group 1 µm	group 2 µm	group 3 µm	group 4 µm	group 1 µm	group 2 µm	group 3 µm
1	3	5	7	9	13	21
1.25	3.25	5.25	7.25	9.5	13.5	22
1.5	3.5	5.5	7.5	10	14	23
1.75	3.75	5.75	7.75	10.5	14.5	24
2	4	6	8	11	15	25
2.25	4.25	6.25	8.25	11.5	16	30
2.5	4.5	6.5	8.5	12	17	35
2.85	4.75	6.75	8.75	12.5	18	40
			9		19	50
					20	100

The test plates which were used for the great majority of all tests were made by ruling lines with a diamond in a thin layer of aluminium deposited on an object slide, which was covered afterwards with a 0.16mm cover glass. I ruled them on 21 and 24 February 1989, with Van Zuylen's ruling engine, according to the specifications in table 4. Every band consists of a number of four to seven lines.

The advantage of this test over the older Grayson Ruling and Nobert's test plate is that the smallest resolvable distance found is nearly independent of the illumination and of the quality of the contrast of the objective under test. The value of the smallest resolvable detail d, found with this test, bears a direct relation to the numerical aperture by the formula:

$$d = k\frac{\lambda}{NA} \; . \tag{29}$$

The value of k depends on whether the light source is coherent (k=0.82) or incoherent (k=0.61).[27] The value actually found will be between these two values. For single lenses Van Zuylen assumes a value of k=0.67, and for achromatic objectives k=0.59 forms a good compromise. Assuming λ=0.54μm this results in:

$$d = \frac{0.37}{NA} \tag{30}$$

25 Harting [59], 369–373; Turner [105], 141–158. The ten-band Nobert test plate in Utrecht has inventory number L1109.

26 Turner [107], 345–346, (catalogue number 435). The Oxford Grayson Ruling is slightly inferior to the Utrecht one as the realgar, in which it is mounted, is a bit cracked. The Utrecht one is in mint condition.

27 Born and Wolf [15], 418–424.

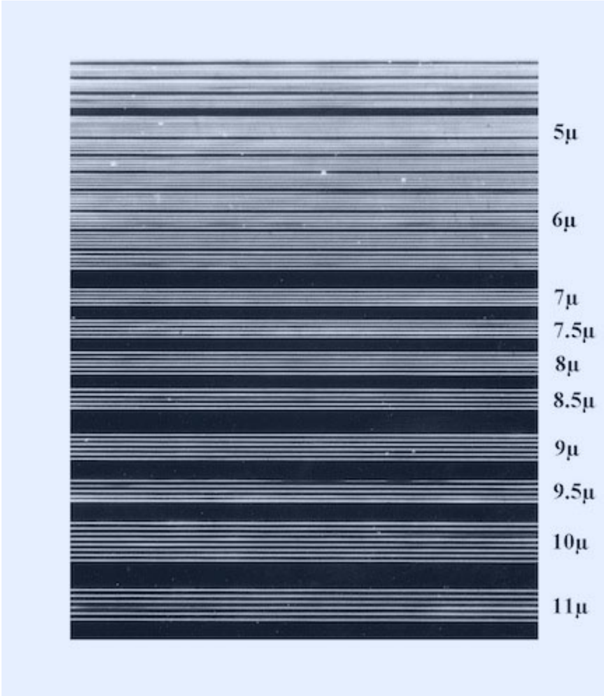


Figure 9: Test plate

for single lens objectives, and

$$d = \frac{0.32}{NA} \tag{31}$$

for achromatic objectives. It is good to realise that these two values of d have no theoretical meaning, they are based upon experience and serve only as a criterion to judge the quality of the objectives.

An important reason for using a test which is rather independent of the contrast of the objective is that the contrast of the objectives has suffered from time, the surfaces of the lenses got scratched, the cement is often not as good as when the objective was just made. A test in which the contrast plays only a minor part does for this reason more justice to the maker.

2.5.8 *Diatom test*

A number of objectives was tested with a diatom test. In Utrecht a Möller diatom slide from Van Zuylen's private collection was used. In England Professor Turner provided me with two test plates, for which the results are assembled in Table table 5. The diatoms marked (*) were the ones we used in Utrecht too.

Table 5: diatom test, collection G. L'E. Turner

diatom	NA for diatom resolved in lines	NA for diatom resolved in dots	d μm
Arachnoidiscus Ehrenbergii	0.054	0.13	2.5
Navicula lyra (*)	0.17	0.20	1.6
Cymbella gasteroides	0.29	0.34	0.94
Stauroneis phoenicenteron (*)		0.44	0.73
Neidum iridis		0.45	0.71
Pleurosigma balticum	0.52	0.58	0.55
Navicula rhomboides		0.60	0.53
Pleurosigma angulatum (*)		0.73	0.44
Surirella gemma (*)	1	>1.4	0.23

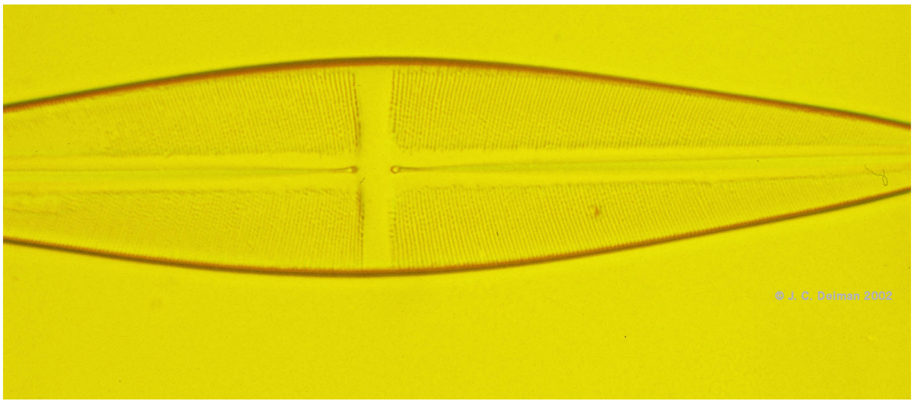


Figure 10: Stauroneis phoenicenteron
(UM37, Arthur Chevalier, 1869, f=3.58, NA= 0.65).

3

THE CHROMATIC MICROSCOPE IN THE EIGHTEENTH CENTURY

3.1 INTRODUCTION

Some authors can be very crude in their judgment of eighteenth-century microscopes. An example is C.R. Goring, who we will meet again in chapter 5 of this thesis. He wrote in 1826, when the 'modern' achromatic microscope was only marginally better than the 'outmoded' chromatic instrument from the eighteenth and early nineteenth century:[1]

> I cannot here refrain from protesting against those preposterous accumulations of eye-glasses which we find in the best common compound microscopes (as they are called). It would appear that the worthy glaziers who preside over the destinies of these unfortunate instruments, have not yet discovered the right end of a microscope from the wrong one–at least they have vented their rage for improvement entirely on the eye-piece: having first doubled the anterior eye-glass, then tripled it, and finally interposed a body-glass of long focus between the field-glass and object-glass (making the eye-piece to consist in fact of 5 lenses), they sit down contented, and imagine they have arrived at the very extreme verge of perfection. The object-glass is allowed to remain a pitiful double convex lens, being I suppose either above or below their art!

And further on:[2]

> Still, however, I can only consider the common compound microscopes of commerce as mere toys, without a grain of science in their composition, fit for little else but to shew ladies a wood-cutting, and unworthy of the confidence of an observer. If a radical reform is not made in their construction by achromatic object-glasses, I shall expect that the Amician microscope will supplant them, for it can be produced at an expense not greater than that of the best of this class of instruments.

The large amount of distortion, caused by the complicated eyepieces is mentioned as a reason for their bad quality.[3] Other authors stress the blur caused by spherical aberration and the coloured fringes which are caused by chromatic aberration.

During the investigation of the optical parameters of microscopes in the collections of the Utrecht University Museum, the Science Museum and the Wellcome

1 Goring [54], 34–49, (38).
2 Goring [54], 34–49, (49).
3 Bradbury [18], 151–173; Nuttall [85], 71–88, (71).

Collection it was found that though eighteenth-century microscopes are indeed not as good as modern instruments, they are definitely not as bad as is often claimed. In particular the claim that these chromatic microscopes suffer from spherical and chromatic aberration needs to be qualified.

The chromatic microscope has its limitations, as I will show in the following paragraphs. The numerical aperture–and hence the resolving power and the magnification–cannot be increased beyond certain limits. But within these limitations the instrument can be as useful as a modern microscope. It is in this context good to realise that the human eye is also a very imperfect imaging system, which is corrected to a great extent by our brains. Problems arise when historians of science start taking photographs using antique microscopes, to prove how bad these instruments were. This is in my opinion not a very realistic approach since the photographic plate is without mercy and does not correct any defect in the image: on the contrary, it shows defects we even don't notice. These old microscopes were never made for such a purpose and it is methodologically wrong to judge them from the results of such a severe test.

3.2 OBJECTIVES

It is rather simple to calculate the maximum value of the numerical aperture of single lens objectives. The limiting factor for the NA is the spherical aberration of the lens. As long as the marginal spherical aberration is smaller than twice the optical tolerance for spherical aberration, the quality of the image does not degrade much.[4]

The influence of the eyepiece on the spherical aberration of the compound microscope is determined by the diameter of the exit pupil of the microscope, which is in general smaller than 1mm for old chromatic microscopes. For such a small value the influence of the spherical aberration of the eyepiece on the spherical aberration of the microscope can be neglected.

Achromatic microscopes from the 1840s onwards have an exit pupil which can be larger (1.5–2.5mm), but even then the influence of the spherical aberration of the eyepiece on the spherical aberration of the total microscope can be neglected.

The calculated example in section 3.4 shows that the influence of the spherical aberration of the eyepiece on the spherical aberration of the complete microscope is indeed negligible

Table 6 lists for a range of focal lengths the numerical aperture and the smallest resolvable detail d for two values of the marginal spherical aberration mSA. In the first series mSA=OT and in the second one mSA equals twice the optical tolerance OT. The lens is biconvex and has a refractive index of 1.53 and a body tube of 160mm. The smallest resolvable detail d is calculated using formula 30 from section 2.5.7.

The magnification of this microscope is supposed to be 1000× the NA. For higher values of the magnification, sharpness and contrast of the image decrease. This is generally called empty magnification. The last column of table 6 gives the magnification of the objective for a body of 160mm.

4 van Zuylen [115], 309–328, (325).

Table 6: focal length, spherical aberration and NA of lenses

	mSA = OT		mSA = 2×OT		
f	NA	d	NA	d	MA
1	0.205	1.79	0.244	1.5	160
2	0.168	2.19	0.199	1.84	80
3	0.150	2.45	0.178	2.06	52
4	0.138	2.65	0.164	2.23	39
5	0.130	2.82	0.154	2.37	31
6	0.123	2.97	0.147	2.50	26
7	0.118	3.11	0.140	2.61	22
8	0.113	3.23	0.135	2.72	19
9	0.109	3.35	0.130	2.82	17
10	0.106	3.46	0.126	2.91	15
15	0.093	3.95	0.110	3.32	10
20	0.084	4.35	0.100	3.65	7
25	0.077	4.73	0.092	3.98	5.4
30	0.072	5.10	0.085	4.29	4.3
40	0.063	5.86	0.075	4.92	3
50	0.055	6.67	0.065	5.61	2.2

Presuming that the average magnification of eighteenth-century eyepieces is ×5, which is a realistic value, it follows from table 6 that the minimum useful focal length of the objective of a chromatic compound microscope will be ca. 5mm, and when the body is shorter even 4mm. Single objective lenses with a focal length smaller than 4–5mm result only in empty magnification, when used on a compound microscope.

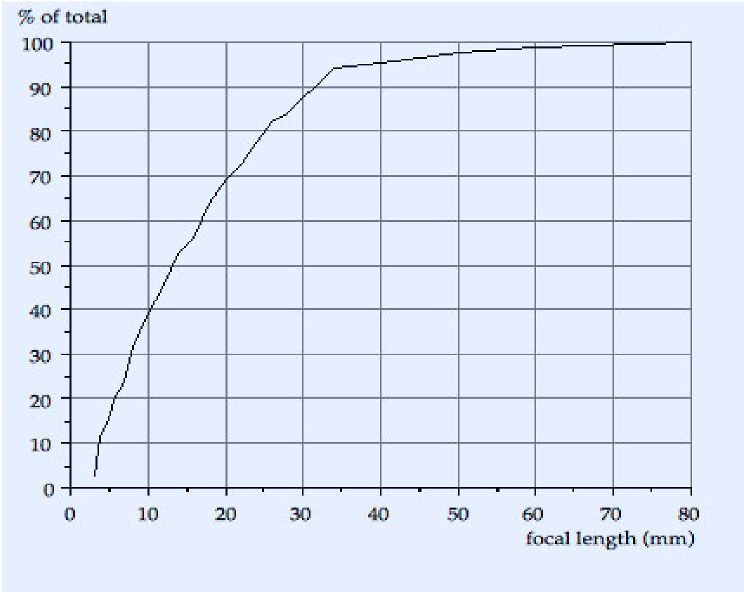
For lenses with a focal length larger than 25mm the magnification with a ×5 eyepiece will be smaller than 27 diameters. Assuming a resolving power of the naked eye of 100μm, this results in a too low magnification to drain the well dry.

A very large number of measurements was made of the focal length, the numerical aperture and the resolving power of single lens objectives of non-achromatic compound microscopes. The data on 243 of these lenses are listed in chapter 9.

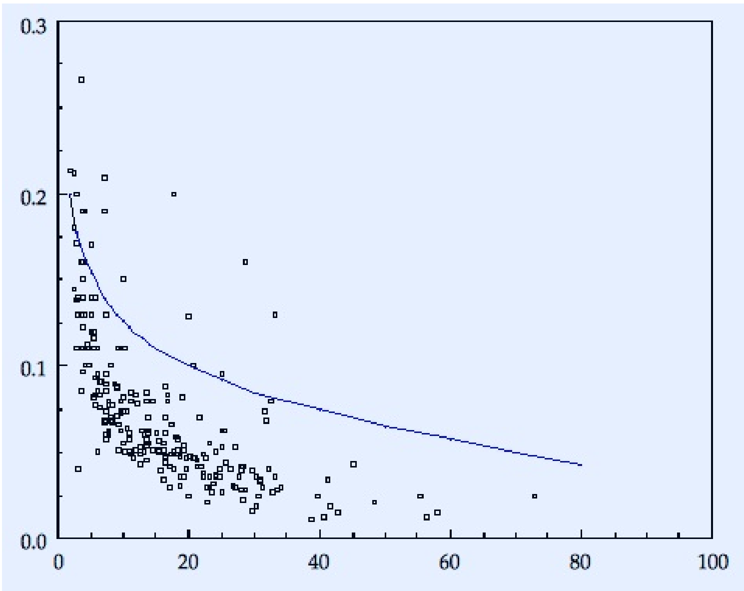
The focal length of 155 (i.e. 64%) of these lenses falls between the limits of 5mm and 25mm. For 19% the focal length is larger than 25mm and for 17% the focal length is smaller than 5mm. It is good to realise that in many cases the objective lenses of a compound microscope were used as simple microscopes. This means we cannot automatically conclude from the percentages given above that 17% + 19% = 36% of all objective lenses have a focal length which makes them impractical for use in a compound microscope, they might well never have been intended for that purpose.

In figure 11a the distribution of the focal length over the range 2–80mm is shown. The number of objectives with a focal length longer than 34 mm is very small, only 15 in the range 34–80mm, in the graph this is shown as a sharp break.

In figure 11b the measured values of the NA are plotted with their corresponding focal lengths, as they were measured for the 243 single objective lenses listed in chapter 9. As figure 11b shows, only a few objectives exhibit too much spherical aberration, the majority of these lenses could bear a higher aperture.



(a) focal length of single lens objectives



(b) NA and focal length of single lens objectives

Figure 11: Single lens objectives

Legends:

horizontal axis:	focal length in mm
vertical axis:	Numerical Aperture
square dots:	NA and focal length of the lenses in chapter 9
line:	Numerical Aperture for which the spherical aberration equals twice the Optical Tolerance, using the values from table 6.

To test this, lens number '1' of microscope A645008 (Wellcome Collection) was put in the mount of lens '2', which had a wider aperture. The focal length of lens '1' was 3.15mm, the magnification with a ×5 Huygenian eyepiece and 188mm body was 279 diameters. The results of the experiment were as follows:

lens	NA	d (μm)	MRP
own mount	0.1	3.5	3.25
mount of '2'	0.137	2.7	2.75

The increase of the NA indeed resulted in an improved resolving power, though it was observed the contrast diminished slightly by the increase of the spherical aberration. It can also be seen from these data that there is a lot of empty magnification; 100 diameters would be an acceptable value (NA=0.1), but a value of 279 diameters was measured on the test microscope. On its own microscope it would have been even more. Objective '4' (focal length 20.71mm) had a magnification of 52.5 diameters with its own eyepiece, lens '1' would have a magnification of ca. $(20.71/3.15) \times 52.5 = 345$ diameters, which is really too much.

The measurements showed an important cause for the bad reputation of eighteenth-century microscopes, which is not revealed by these theoretical considerations, namely the inadequate quality of the polishing of the lenses. This could not be measured quantitatively, but the frayed diffraction rings of the star test indicate that the polishing of the lenses is of an insufficient quality. Also the mechanical construction tends to be primitive, the lenses are not centred or fixed in their mounts, and this will result in axial coma. Together with the empty magnification of the strong objectives these three factors form a much better explanation for the disappointing quality of eighteenth-century microscopes than simply stating that they suffer from spherical and chromatic aberration.

3.3 EYEPIECES

Many eighteenth-century eyepieces are modifications of the two-lens eyepiece Huygens invented in 1662. Huygens's description is not very precise, according to Lorenz and Korteweg in the introduction to volume 13 of the Œuvres Complètes, this lack of precision was caused by the experimental nature of Huygens's discovery.[5] In Huygens's descriptions the focal length of the field lens is three to five times as big as that of the eye lens, while the distance of the lenses should be about twice the focal length of the eye lens. Huygens did not specify the use of plano-convex lenses, though in his manuscript a plano-convex eye lens is drawn next to the drawing of the complete telescope.[6] The distinctive characteristic of Huygenian eyepieces is the real image of the object which is formed between the field lens and the eye lens. The eye lens is used as a simple magnifier to observe this image. Later, in the nineteenth century, it became usual practice to use two plano-convex lenses, both with their convex sides towards the object.

I will analyse in section 3.5 a number of these eighteenth and early nineteenth-century eyepieces and compare them with a relatively modern one which was

5 Lorenz and Korteweg [77], Lorenz and Korteweg (1916), 50 and 89.
6 Huygens [68], 462.

designed by Van Zuylen for Bleeker in Zeist, of this eyepiece all the relevant data were available.

The eighteenth-century eyepiece was in general constructed using biconvex lenses; plano-convex lenses are rarely used.

The usual construction of an eighteenth-century microscope with a two-lens eyepiece and a biconvex objective lens is given by Dellebarre:[7]

> Tous ces microscopes, du moins tous ceux qui sont parvenus à ma connoissance, portent deux oculaires, dont le foyer du second ou intermédiaire est le double du foyer du premier: ces deux verres, presque toujours placés de maniere que la distance du premier oculaire au second est la même que celle du foyer du second, & que celle de ce dernier verre à la lentille objective fait le double de cette distance, sont invariablement fixés à la même place.

This design is used for a computer simulation for a complete eighteenth-century chromatic microscope in section 3.4. Goring's tirade which I cited in section 3.1 'against those preposterous accumulations of eye-glasses' in the eighteenth-century microscope suggests that those instruments were mere toys, invented and made by ignorant people who did not know how to construct a proper microscope. However, one must realise that Goring's 'worthy glaziers' were the same instrument makers who were able to provide astronomers, surveyors and navigating officers with the instruments they needed for their work. Instruments which we, after two centuries, still value as desirable collectors items, the microscopes not excluded. It was not the fault of the instrument makers that optical knowledge was still limited, let alone its application in designing optical systems. The development of the eyepiece of the microscope in the eighteenth century shows us that the instrument makers improved the instrument considerably. When we compare the distortion and the angle of view of the eyepieces in section 3.5–section 3.8 the decrease of the distortion together with an increasing angle of view are noticeable. In section 3.9 the resulting figures of a comparison of the analysed 36 eyepieces are summarised and plotted in two graphs.

7 Dellebarre [36], 6.

3.4 two-lens eyepiece, computer model

The construction which Dellebarre describes as the usual one for microscopes with two-lens eyepieces has an eye lens with a focal length of f, a field lens with a focal length of 2f. The distance between the two lenses also is 2f. The distance of the field lens to the objective should be 4f. The glass used in this simulation is Zink-Kron 1 from Schott.[8] This glass was chosen because it corresponds reasonably well with the eighteenth-century crown glass used by Dollond in the achromatic prism in the collection of the Utrecht University Museum (inventory number Li92).

This achromatic combination of three prisms was bought by the University of Utrecht in 1776 at an auction of the effects of Burgomaster Hasselaar of Amsterdam.[9]

Table 7: Data for a two lens eyepiece, case I (surface 1 towards the objective)

srf	radius	distance	N
1	84.2	6	1.53315
2	-84.2	80	1
3	42.1	3	1.53315
4	-42.1		1

	N	ef
N_C	1.53036	85.89
N_d	1.53315	86.48
N_F	1.53954	87.948
$\Delta ef_{F\text{-}C}$		2.054

This prescription of Dellebarre proved to be inconsistent with the facts. A distance of $0.5(f_{\text{eye lens}} + f_{\text{field lens}})$, which is also given by Conrady as appropriate, was much closer to the measured data of these eyepieces.[10]

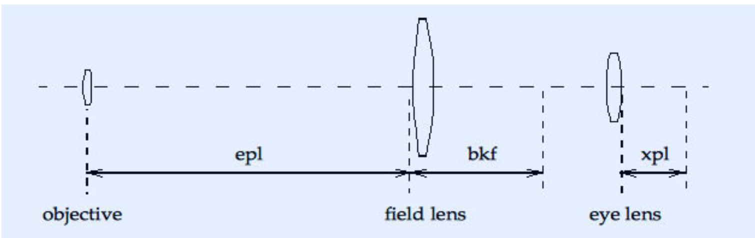


Figure 12: focal length of single lens objectives

For this reason a second case was calculated with again $f_{\text{eye lens}} = 40$mm and $f_{\text{field lens}} = 80$mm, and a distance between the lenses of 60mm. The influence of the distance of the two lenses on the chromatic difference of magnification CVV′ is considerable, as the values in table 10 show, even a sign reversal is possible. The assembly of the optical elements of a three-lens compound microscope and the relative position of its pupils is shown in figure 12.

In both cases the following lens is used as the objective lens:

In case I a converging pencil is traced which emerges from the imaginary exit pupil of the objective at a distance of 160mm in front of the field lens. This pencil

8 Jenaer Glaswerk Schott & Gen. Jena [70], 6.
9 Boegehold [11], 86–89.
10 Conradi [29], 483.

Table 8: Data for a two lens eyepiece, case II (surface 1 towards the objective)

srf	radius	distance	N		N	ef
1	84.2	6	1.53315	N_C	1.53036	56.09
2	-84.2	60	1	N_d	1.53315	56.12
3	42.1	3	1.53315	N_F	1.53954	56.19
4	-42.1		1	$\Delta ef_{F\text{-}C}$		0.103

Table 9: objective lens

srf	radius	distance	N		N	ef
1	10.4	1.5	1.53315	N_C	1.53036	10.06
2	-10.4		1	N_d	1.53315	10.04
				N_F	1.53954	9.87
				$\Delta ef_{F\text{-}C}$		-0.188

converges to an imaginary point, indicated by bkf (back focus), which for this eyepiece lies at a distance of ca. 95mm to the right of the front of the field lens. The total length of the eyepiece, measured between the two outer optical surfaces is only 89mm, which means that the back focus lies some 6mm above the eye lens. The real image however is formed between the two lenses, which makes this a Huygenian eyepiece. The exit pupil of the eyepiece, the Ramsden disk, is at 25mm above the eye lens. The pupil of the eye of the observer should be placed close to this point for comfortable use of the microscope. In most eighteenth-century microscopes an eye cap was provided to facilitate this. In case II the real image and the back focus are both situated between the two lenses, this is also a Huygenian eyepiece according to our definition.

The combination of eyepiece and objective is calculated in two directions. Once from the eye to the object, to find the distance between object and the front of the objective. The angle of view, angular magnification, distortion and chromatic difference of magnification are all calculated for a pencil emerging from this object point.

Making use of the position of the exit pupil, which results also from the former computation, a second computation is performed, from the eye to the object. The diameter of the exit pupil is chosen in such a way that the NA of the combination of objective and eyepiece has the same value as when the objective is used as a simple microscope. From this computation result the marginal spherical aberration mSA, and the Offence against the Sine Condition OSC′.

The magnification M is calculated using the formula:

$$M = \frac{500 \times NA}{pupil\ \ diameter}\,. \tag{32}$$

When we compare the distortion and the chromatic difference of magnification caused by the eyepiece alone and of the complete microscope we see the influence of the objective on them can be neglected. On the other hand, the spherical aberration of the eyepiece has a negligible influence on the spherical

Table 10: computer simulation of a three-lens chromatic microscope

	case I eyepiece	case I+ objective	objective only	case II eyepiece	case II+ objective	objective only
field	34‘°	34°		34°	34°	
MA	-3.03	-2.89		-3.68	-3.51	
D rim	2.9	2.8		6.36	6.27	
D mid	0.86	0.83		1.5	1.48	
CVV′ rim	0.74	0.82		-0.49	-0.4	
CVV′ mid	0.3	0.37		-0.65	-0.57	
Petz.	0.214			0.139		
epl	-160			-160		
xpl	24.96	-24.96		27.14	-27.14	
bkf	94.98		-254.98	34.26		-194.26
$\Delta ef_{(F\text{-}C)}$	2.054	0.065	-0.188	0.103	0.082	0.188
pupil dia.		0.88	1.28		0.754	1.3
NA		0.127	0.127		0.126	0.126
mSA		-0.033	-0.033		-0.034	-0.034
OT		0.017	0.017		0.017	0.017
OSC′		0.011	0.008		0.008	0.008
M		72			83	

aberration of the total microscope. Only the OSC′ can be increased by the eyepiece, as the example of case I shows. For both microscopes the magnification is well below the limit set by the NA. The smallest resolvable detail for these microscopes would be ca. 3μm.

In the following sections I will compare this simulated microscope with a number of microscopes of which the eyepieces were investigated.

3.5 TWO-LENS EYEPIECES

Table 11: two-lens eyepieces, overview

	UM1846	UM578	A62993	UM16	UM18	UM13	1925 -136
ef	20.13	50.67	45.45	44.08	44.14	61.74	53.54
efl	20.24	50.58	45.43	44.07	44.13	61.62	53.47
efs	19.89	50.88	45.50	44.11	44.16	62.03	53.73
efs-efl	-0.35	+0.30	+0.06	+0.05	+0.03	+0.40	+0.25
bkf	-17.91	40.29	26.9	36.32	27.97	31.22	23.49
epl	-90	-115	-110	-140	-110	-142	-105
xpl	23.5	23.7	24.7	20.7	24.23	25.36	25.6
Petz.	0.034	0.154	0.134	0.139	0.135	0.154	0.140
field	34.4	35.6	35.4	32	19.6	26	26
MA	-3.91	-3.31	-3.27	-4.24	-3.21	-2.87	-2.45
D rim	9.32	8	8.44	6.08	2.7	2.46	2.12
D mid	2.1	1.85	1.92	1.42	0.65	0.63	0.91
D 34°	9.13	7.30	7.78	6.79	8.24	4.01	3.45
CVV′rim	-2.47	-0.26	-0.67	-0.76	-0.8	-0.28	-0.75
CVV′mid	-2.28	-0.49	-0.85	-0.87	-0.84	-0.43	-0.9

	A159980	A212741 (a)	A212741 (b)	1928 -850	A54219	1921 -189	H5×
ef	63.92	29.06	29.20	20.01	36.78	12.324	50.30
efl	63.79	29.07	29.15	20.04	36.75	12.324	50.10
efs	64.25	29.03	29.34	20.00	36.86	12.327	50.79
efs-efl	+0.47	-0.04	+0.19	-0.04	+0.11	0.003	0.69
bkf	40.94	1.64	33.57	19.00	14.14	7.31	30.70
epl	-137	-155	-150	-160	-220	-45	-117
xpl	26.3	7.4	9.1	8.66	7.47	4.12	12.81
Petz.	0.162	0.127	0.160	0.126	0.142	0.138	0.182
field	38.6	16	38.2	34	34	43.4	23.5
MA	-2.92	5.47	-6.53	-9.4	-6.64	-4.55	-2.95
D rim	4.92	1.49	3.92	5.25	4.3	7.16	0.62
D mid.	1.39	0.36	1.07	1.27	1	1.85	0.19
D 34°	4.00	7.14	4.85	5.25	4.30	4.8	0.87
CVV′rim	-0.03	-0.43	0.25	-0.43	0.09	-0.3	0.3
CVV′mid	-0.37	-0.45	0.03	-0.55	-0.07	-0.49	0.15

The average value of the distortion of this group of two-lens eyepieces for an angle of view of 34° is 5.9%. In the following subparagraphs these eyepieces are discussed shortly.

3.5.1 *Screw-barrel microscope, Culpeper type (UM1846)*

Signed 'Culpeper Fecit' and 'Culpeper Londini', ca. 1720. Brass screw-barrel microscope on a pillar and a flat folding tripod, with an ivory compound tube.

Table 12: data Um1846

srf	radius	distance	N	ΔN		lens	f
1	40.32	2.7	1.524	0.0095		field lens	38.94
2	-40.32	0.77	1	0		eye lens	38.94
3	40.32	2.7	1.524	0.0095			
4	-40.32		1			total	19.88

It is not clear whether the lenses from this eyepiece are original, unlike most other lenses from the period the curvatures, thickness and refractive index are equal. Also their rim has a beautiful bevel, which is not so usual for lenses from that period.

The distance between the two lenses is so small that the second lens is much more a second eye lens than a field lens. The back focus of this eyepiece is in front of the field lens, as in a Ramsden eyepiece. The angle of view was not measured but 34° was used as a reasonable value. The distortion has the highest value of all two-lens eyepieces and also the chromatic difference of magnification CVV′ is higher than for the other eyepieces.

3.5.2 *Cuff-type microscope (UM578)*

Signed 'J. Cuff Londini Invt. & Fecit', 1743–1760.

Table 13: data UM578

srf	radius	distance	N	ΔN		lens	f
1	71.95	3.88	1.529	0.0099		field lens	68.64
2	-71.88	55	1	0		eye lens	32.31
3	32.88	3.87	1.519	0.0092			
4	-32.88		1			total	50.63

The angle of view of 35.6° was calculated from the magnification, being 38.37 diameters using objective '5'; the object field was 4.2mm. In the computations a distance of 54.6mm between the lenses was used as this value gave a better correspondence between the measured and the calculated focal length. This distance is slightly larger than half the sum of the focal lengths of the lenses. The focal lengths of the lenses are to each other nearly as 2 to 1. The distance between the objective and the field lens is slightly less than four times the focal length of the eye lens. The diminished real image and the back focus are situated between the two lenses. According to our definition this is a Huygenian eyepiece. With anangle of view of well over 35° the distortion of the outer zone is much higher than the average of this group and much too high. The calculated chromatic difference of magnification is below the 0.6% limit.

(a) UM578 (b) UM16

Figure 13: microscopes with two lens eyepieces.

3.5.3 *Cuff-type microscope (A62993)*

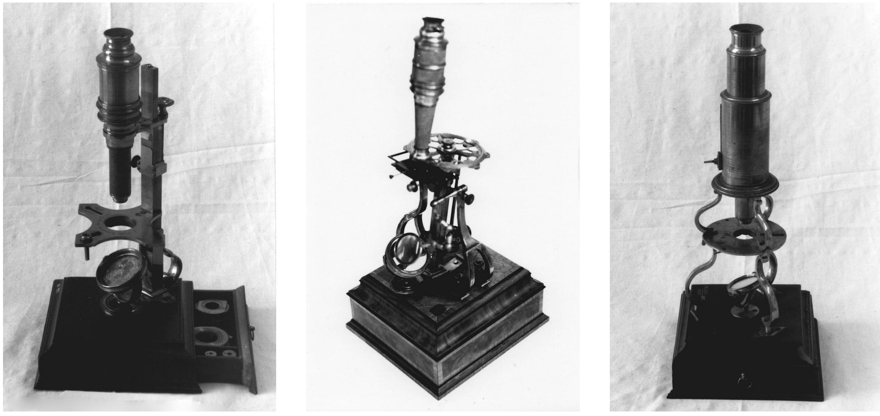
Signed 'J. Cuff Londini Inv =&= Fecit', 1743–1760.
For a description, see: Bracegirdle, 2005.

Table 14: data A62993

srf	radius	distance	N	ΔN
1	75.86	4.97	1.565	0.013
2	-75.86	48.6	1	0
3	35.32	4.03	1.564	0.011
4	-35.32			

lens	f
field lens	67.9
eye lens	33.14
total	45.19

The angle of view of this microscope was not measured, the same value was used as for the previous one, i.e. 35.6°. As in the previous microscope by Cuff, the distance between the two lenses is also nearly half the sum of their focal lengths. The focal lengths are also nearly to each other as 2 to 1. The distance between the objective and the field lens is ca. 3.3× the focal length of the eye lens. The real image is again situated between the lenses, which makes this to a Huygenian eyepiece. The distortion of the outer zone is too high; for the reduced angle of 34° the distortion of both Cuff eyepieces is larger than the average value in this group. The chromatic difference of magnification CVV′ is too large.



(a) A62993 (b) SCM1925-136 (c) A159980

Figure 14: microscopes with two lens eyepieces.

3.5.4 *Cuff-type microscope (UM16)*

Signed 'Geo Sterrop Maker', 1744–1756.

Table 15: data UM16

srf	radius	distance	N	ΔN	lens	f
1	74.81	4.15	1.536	0.0105	field lens	70.42
2	-74.81	49.3	1	0	eye lens	29.46
3	32.63	4.14	1.567	0.0129		
4	-32.63		1	0	total	44.03

The angle of view of 32° was calculated from the magnification, being 57.07 diameters using objective '4'; the object field was 2.55mm. There was also a field diaphragm, with a diameter of 16.4mm, which results in an angle of view of 31°; the computation was performed for 32°. Anyhow, it is surprising how well both values correspond. A distance of 50.1mm between the lenses was used, giving a better correspondence between the measured and the calculated focal lengths. The distance between the lenses equals half the sum of their focal lengths, while the distance to the objective is comparatively large, 4.7× the focal length of the eye lens. The diminished real image is situated between the two lenses, so this is a Huygenian eyepiece. The focal length of the field lens is to that of the eye lens as 2.3 to 1, slightly more than usual. The distortion could be lower and the chromatic difference of magnification is a bit too large.

3.5.5 *Cuff-type microscope (UM18)*

Signed 'Lincoln London', 3/4 18th C.

The field diaphragm of this eyepiece has a diameter of 11mm, which results in an angle of view of 19.7°. The distance between the lenses is 48.5mm but a value of 48.1mm was used as this gave a better correspondence between the measured and the calculated focal length. This distance is again slightly less than half the

Table 16: data UM18

srf	radius	distance	N	ΔN
1	65.66	4.71	1.531	0.0101
2	-78.69	48.5	1	0
3	32.88	3.21	1.527	0.0097
4	-32.88		1	

lens	f
field lens	68.12
eye lens	31.76
total	44.19

sum of the focal length of the two lenses. The distance to the objective lens is smaller, only 3.5x the focal length of the eye lens. The distortion is lower than usual; this is caused by the small angle of view, for 34° the distortion increases to 6.79%, which is above the average of the group. The chromatic difference of magnification is too large.

(a) UM18 (b) UM13

Figure 15: microscopes with two lens eyepieces.

3.5.6 *Culpeper-type tripod microscope (UM13*

Signed 'J. Scarlet London', 2/2 18th C.

The field diaphragm of this eyepiece has a diameter of 20mm, which results in an angle of view of 26°. The eye cap of this microscope has its aperture 21mm above the eye lens. The exit pupil is ca. 25mm above the eye lens. The difference is somewhat small but it works well enough. The distance between the two lenses is smaller than the usual half sum of their focal lengths, and the distance to the objective is small as well, only 3.2× the focal length of the eye lens. The distortion is low and when the angle of view is increased to the usual 34° it increases to

Table 17: data UM13

srf	radius	distance	N	ΔN
1	72.78	4.94	1.539	0.0107
2	-72.78	61.3	1	0
3	45.93	2.47	1.538	0.0106
4	-45.93			

lens	f
field lens	68.35
eye lens	43.08
total	61.54

4%; apart from the 'Prince of Wales Microscope' in section 3.5.7 the lowest value of all eighteenth-century eyepieces in this group. For this angle the chromatic difference of magnification is also small, only -0.1%.

3.5.7 *Prince of Wales microscope (1925-136)*

Signed 'Invented and made by Geo Adams in Fleet Street. Instrument Maker to His Royal Highness the Prince of Wales', ca. 1755. (King George III Collection in the Science Museum).
For a description, see: Bracegirdle, 2005.

Table 18: data 1925-136

srf	radius	distance	N	ΔN
1	72.18	5.14	1.581	0.014
2	-72.18	54.3	1	0
3	22.97	4.22	1.574	0.013
4	-3500			

lens	f
field lens	62.96
eye lens	39.77
total	53.02

The angle of view of 26° was calculated from the magnification, being 41.3 diameters using objective '6'; the object field was 2.8mm. The distance between the lenses is nearly half the sum of their focal lengths, the distance to the objective only 2.5× the focal length of the eye lens. The diminished real image is also situated between the two lenses, this is a Huygenian eyepiece. The distortion is very small, even when the angle of view is increased to 34° the distortion increases to 3.45%, the lowest value in this group. The chromatic difference of magnification, being 1%, is too large.

3.5.8 *Culpeper-type microscope (A159980)*

Signed 'Adams London' (George Adams junior), 1772–1795, according to Bracegirdle Dudley Adams, ca. 1790–1820.

A brass microscope with scrolled legs, on a wooden box foot. The focusing is by a rack and pinion working on the barrel.
For a description, see: Bracegirdle, 2005.

The angle of view of this microscope was not measured. However, as the aperture of the field lens was 33mm and the distance to the objective 137mm, the tangent of the pencil entering the eyepiece cannot be much larger than

Table 19: data A159980

srf	radius	distance	N	ΔN	lens	f
1	86.76	5.05	1.518	0.0088	field lens	71.80
2	-63.85	64.3	1	0	eye lens	41.42
3	43.00	3.51	1.526	0.0095		
4	-43.00				total	63.91

$0.5 \times 33/137 \approx 0.12$. Using this an angle of view of 38.6° was calculated. The distance between the lenses was 64.3mm but a value of 64.1mm was used as this gave a better correspondence between the measured and the calculated focal lengths. The distance between the lenses is again slightly less than half the sum of their focal lengths, the distance to the objective is only 3.3× the focal length of the eye lens. The diminished real image is again situated between the two lenses, which makes this also to a Huygenian eyepiece. For an eyepiece with such a large angle of view the distortion and the chromatic difference of magnification are small. When the angle of view is increased to 34° the distortion of this eyepiece is still smaller than the average value of 5.92%.

3.5.9 *Jones's 'Most Improved Compound Microscope' (A212741)*

Signed 'W & S Jones 30 Holborn London', 1/4 19th C. With this microscope go two eyepieces, (a) and (b).
For a description, see: Bracegirdle, 2005.

Table 20: data A212741 (a)

srf	radius	distance	N	ΔN	lens	f
1	22.58	3.04	1.510	0.0084	field lens	44.31
2	∞	33.7	1	0	eye lens	16.62
3	8.53	1.85	1.514	0.0087		
4	∞				total	29.77

The field diaphragm of eyepiece (a) has a diameter of 7.8mm, which results in an angle of view of 16°. There are two plano-convex lenses, their focal lengths do not differ very much. As a result the back focus lies in the field lens, the real image is formed close to the field lens. It is an example of an early Huygenian eyepiece with plano-convex lenses. The distance between the two lenses is slightly more than half the sum of their focal lengths. When the angle of view is increased to 34° the distortion increases to 7.14%, which is higher than might be expected from one of the younger nineteenth-century eyepieces in this group. The chromatic difference of magnification is not notably small, though constant over the field.

The field diaphragm of eyepiece (b) has a diameter of 11.5mm, which results in an angle of view of 38°. Both lenses are plano-convex like in the previous eyepiece, the position of the diminished real image is now situated between the two lenses. This is an early example of a Huygenian eyepiece of the construction as it is still

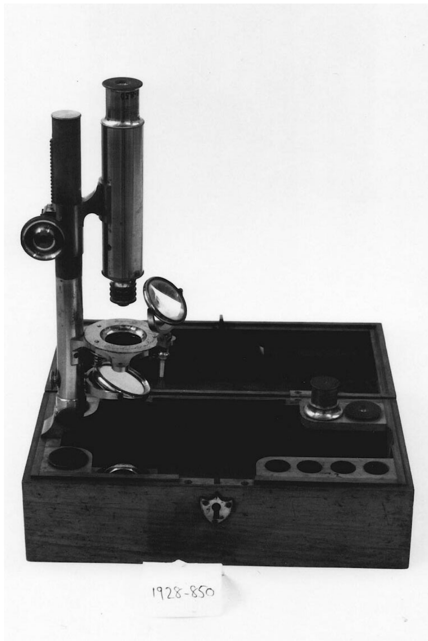
Table 21: data A212741 (b)

srf	radius	distance	N	ΔN
1	22.58	3.04	1.510	0.0084
2	∞	33.7	1	0
3	8.53	1.85	1.514	0.0087
4	∞			

lens	f
field lens	44.31
eye lens	16.62
total	29.77

made. The distortion and the chromatic difference of magnification are small, for an angle of view of 34° the distortion, being 3.19%, is the lowest value in this group. The chromatic difference of magnification is much smaller than its limit of 0.6%.

(a) A212741



(b) SCM1928-850

Figure 16: microscopes with two lens eyepieces.

3.5.10 *Chest Microscope (1928-850)*

Signed 'Utzschneider und Fraunhofer in München', ca. 1820.
For a description, see: Bracegirdle, 2005.

The angle of view of this eyepiece was not measured, it was calculated for a value of 34°. This is also a Huygenian eyepiece of the modern construction with two plano-convex lenses. The distance between the lenses is smaller than half the sum of their focal lengths, the focal length of the field lens is 2.5× as large as the one of the eye lens. The distortion is for this angle of view rather large. The chromatic difference of magnification is large, nearly 0.6%.

Table 22: data 1928-850

srf	radius	distance	N	ΔN	lens	f
1	21.96	2.36	1.516	0.0089	field lens	42.53
2	∞	25.42	1	0	eye lens	13.85
3	7.27	1.38	1.525	0.0096		
4	∞		1	0	total	20.31

3.5.11 *Pillar microscope (A54219)*

Signed 'Selon Euler Perfectionné Par Vinct. Chevalier ainé et fils. Ing.rs Opt.ns. Brevetes quai de l'Horloge n. 69 à Paris', 1824–1826. This microscope was owned by J.J. Lister, who used it for his experiments with achromatic doublets (see section 5.5.2).
For a description, see: Bracegirdle, 2005.

Table 23: data A54219

srf	radius	distance	N	ΔN	lens	f
1	22.98	4.58	1.533	0.0103	field lens	43.08
2	∞	35.35	1	0	eye lens	25.49
3	14.71	3.61	1.531	0.0101		
4	∞		1		total	36.45

The angle of view of this eyepiece was not measured, a value of 34° was used in the computations. The distance between both plano-convex lenses is nearly half the sum of their focal lengths, and the focal length of the field lens is less than twice the one of the eye lens. The distortion of 4.3% for an angle of view of 34° is smaller than the average value of the eyepieces in this group. The chromatic difference of magnification is very small. Lister's remarks which suggest that Chevalier's optical knowledge was very limited, are absolutely not justified by this eyepiece.[11]

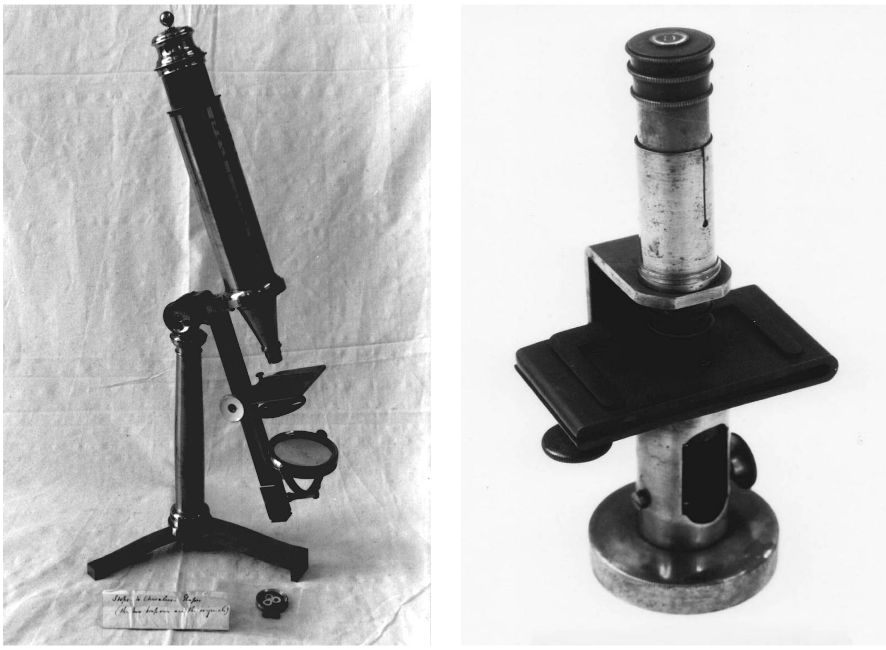
3.5.12 *Miniature drum microscope (1921-189)*

Unsigned, the optical parts are made by Amici, 2/4 19th C.

Amici's mounting of the eye lenses and the notch are very characteristic. Coarse focusing is by means of a draw tube, fine focusing is by means of a tilting table. For a description, see: Bracegirdle, 2005.

The field diaphragm of this eyepiece has a diameter of 7mm, which results in an angle of view of 43.4°. The distance between the two lenses is smaller than half the sum of their focal lengths, the focal length of the field lens is slightly more than twice the one of the eye lens. The distortion is normal for eyepieces of this period, the chromatic difference of magnification could be smaller.

11 Lister Archive, folio L20 (chapter 11).



(a) A54219 (b) SCM1921-189

Figure 17: microscopes with two lens eyepieces.

Table 24: data 1921-189

srf	radius	distance	N	ΔN
1	9.44	3.87	1.515	0.0088
2	∞	11.48	1	0
3	4.52	2.53	1.513	0.0084
4	∞			

lens	f
field lens	18.35
eye lens	8.81
total	12.46

3.5.13 *Huygenian eyepiece '×5' (Utrecht)*

Designed in 1948 by Dr. J. van Zuylen, drawing No. OS11206, made by Bleeker, Zeist, The Netherlands.

Table 25: data Bleeker H ×5 eyepiece

srf	radius	distance	N	ΔN		lens	f
1	23.92	4.00	1.523	0.0094		field lens	45.73
2	∞	45.84	1	0		eye lens	30.10
3	15.74	2.00	1.523	0.0094			
4	∞		1	0		total	50.4

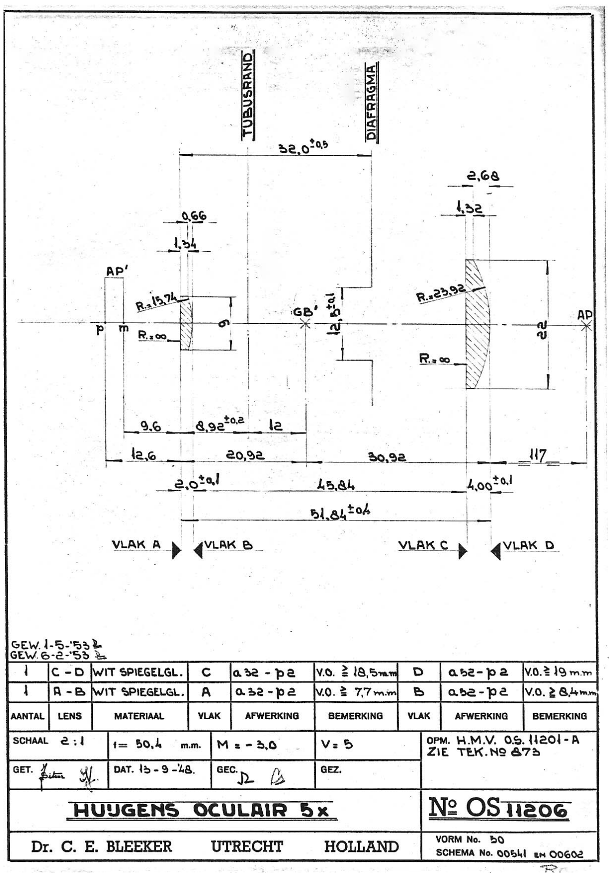


Figure 18: default

The field diaphragm of this eyepiece has a diameter of 12.5mm, which results in an angle of view of 23.5°. The distance between the two lenses is considerably larger than half the sum of their focal lengths, the focal length of the field lens is only 1.5x the one of the eye lens. The distortion being 1%, is much smaller than for the older eyepieces. The chromatic difference of magnification is of the same order.

3.6 THREE-LENS EYEPIECES

Some of the three-lens eyepieces analysed below can be considered as Huygenian eyepieces with a double eye lens. The argument was that by doubling the lens the radii of the surfaces could be made larger, which kept the spherical aberration small. The spherical aberration of the eyepiece is of no influence on the spherical aberration of the microscope, but it influences the distortion of the eyepiece. The result is that with two eye lenses the angle of view can be increased without increasing the distortion.

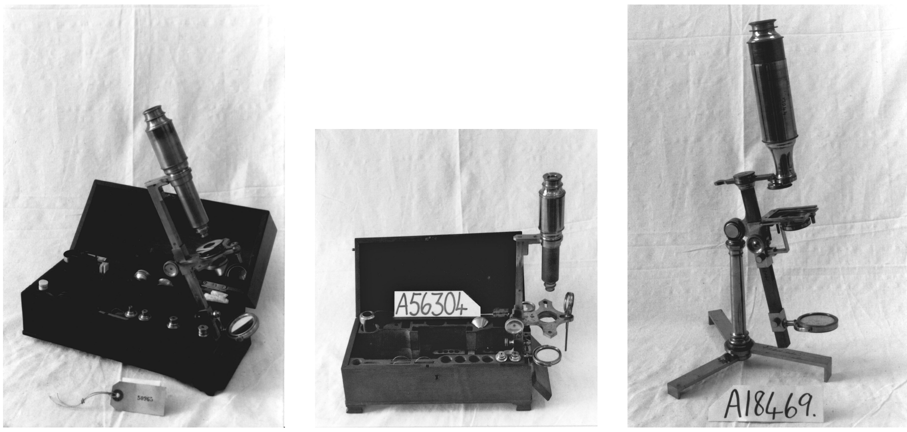
Table 26: three-lens eyepieces, overview

	A159502	A600168	1918-84	A645025	A159192	A56301
ef	39.71	47.27	59.87	39.75	55.23	36.85
efl	39.65	47.12	59.43	39.60	54.99	36.77
efs	39.86	47.64	60.97	40.11	55.81	37.06
efs-efl	+0.21	+0.52	+1.54	+0.51	+0.82	+0.29
bkf	40.35	63.10	48.92	45.21	148.48	35.99
epl	-113	-120	-23.5	-81	-120	-70
xpl	10.24	17	22.13	11.36	16.15	11.94
Petz.	0.166	0.176	0.258	0.192	0.225	0.172
field	59	43.8	21.4	41.8	61	50
M ang	-4.35	-4.22	1.22	-3.43	-5.9	-3.12
D rim	12.95	8.89	1.1	8.09	21	8.56
D mid.	3.1	2	0.29	1.89	4.1	2.05
D 34°	4.27	5.24	2.60	5.39	5.99	3.91
CVV′rim	0.11	-0.02	-0.97	+0.09	-0.12	-0.31
CVV′mid	-0.29	-0.22	1.03	-0.13	-0.37	-0.49

	A56305	A56801	A50965	A56304	A18469
ef	44.51	45.53	46.56	47.65	55.39
efl	44.40	45.33	46.28	47.43	55.06
efs	44.79	46.02	47.26	48.20	56.20
efs-efl	+0.39	+0.69	+0.98	+0.77	+1.13
bkf	51.97	63.84	84.84	89.46	92.88
epl	-130	-115	-110	-105	-110
xpl	8.65	12.9	5.68	10.33	9.3
Petz.	0.188	0.194	0.25	0.228	0.248
field	63.4	36.5	54	54	45.8
M ang	-4.48	-4.12	-4.46	-4.5	-3.87
D rim	9.6	4.56	6.68	10.24	5.72
D mid.	2.98	1.11	2.02	2.52	1.48
D 34°	3.24	3.99	3.00	4.09	3.24
CVV′rim	+0.87	+0.13	+1.11	+0.46	+0.53
CVV′mid	+0.04	-0.03	+0.50	-0.09	+0.21

In general the angle of view of these eyepieces is larger than for the two-lens ones, the distortion lies usually between 7% and 10%. When the angle of view is reduced to the standard value of 34° the distortion lies between 2.6% and 6%, the average value is 4.1%. This is smaller than the average of the two-lens eyepieces, so there was some improvement after all.

The chromatic difference of magnification lies between 0.2% and 1%, which does not differ much from the other eyepieces. The main drawbacks of the addition of an extra lens are the increased cost and the unfavourable influence on the contrast of the image. However, this does not show in the computations of the systems.



(a) A50695 (b) A56304 (c) A18469

Figure 19: microscopes with three lens eyepieces.

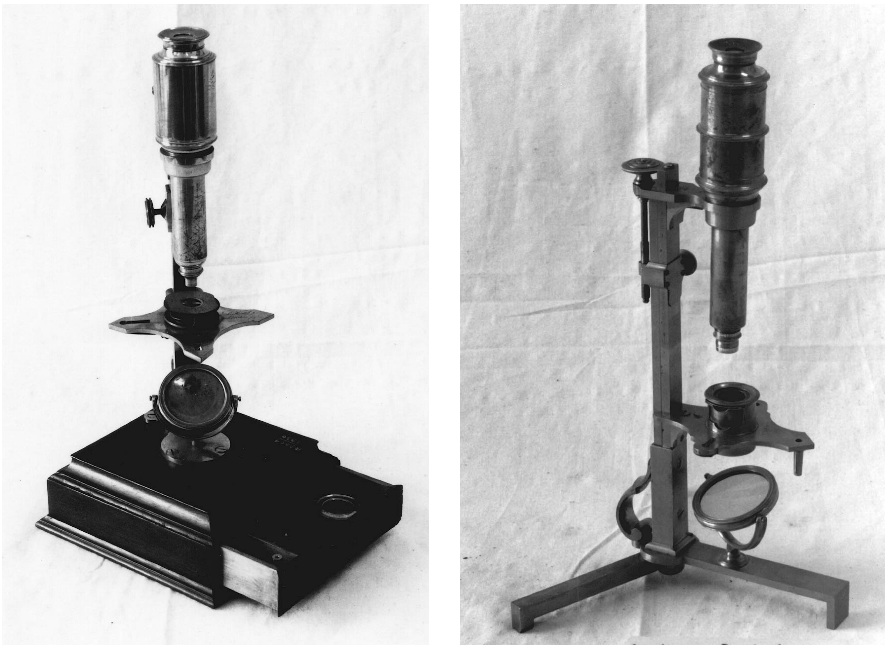
3.6.1 *Culpeper-type microscope on box-foot with drawer (A159502)*

Signed 'Dollond London', 3/4 18th C.
For a description, see: Bracegirdle, 2005.

Table 27: A159502

srf	radius	distance	N	ΔN	lens	f
1	72.48	4.44	1.534	0.0103	field lens	68.64
2	-72.48	39.51	1	0	eye lens 2	40.78
3	43.11	2.48	1.534	0.0103	eye lens 1	41.42
4	-43.11	13.67	1	0	eye lens 1+2	25.41
5	43.00	3.24	1.526	0.0097		
6	-43.00				total	39.51

The aperture of the field diaphragm of this microscope was too large to be effective. The angle of view is supposed to be limited by the free aperture of the field lens, resulting in an angle of 59°. The distance between the lenses is 39.51mm but a value of 38.37mm was used as this gave a better correspondence between the measured and the calculated focal lengths. The focal length of the combination of the two eye lenses is to the focal length of the field lens as 1 to 2.7, the distance between them is slightly more than half the sum of their focal lengths. The real image of the eyepiece lies between the field lens and the eye lens. According to our definition this eyepiece can be considered as a modified Huygenian eyepiece. The distortion is considerable, but when the angle of view is reduced to the standard value of 34° a much better figure results, though it is still a little bit more than the average. The chromatic difference of magnification is small.



(a) A159502 (b) A600168

Figure 20: microscopes with three lens eyepieces.

3.6.2 *Cuff-type microscope on flat folding tripod (A600168)*

Signed 'Geo Adams No.60 Fleet Street London', 1765–1795.
For a description, see: Bracegirdle, 2005.

The field diaphragm of this eyepiece has a diameter of 20.5mm, the resulting angle of view is 43.8°. The distance between the eye lenses and the field lens could be changed from 52.5mm to 67.5mm by means of a draw-tube. The eyepiece was measured using the smallest value of 52.5mm, the computation was performed using 51.8mm for a good correspondence between the measured and calculated focal lengths. For this value the back focus is situated in the eye lens.

Table 28: A600168

srf	radius	distance	N	ΔN	lens	f
1	73.47	4.23	1.533	0.0102	field lens	69.59
2	-73.47	52.5-67.5	1	0	eye lens 2	63.51
3	5900	1.97	1.537	0.0102	eye lens 1	38.11
4	-34.31	3.75	1	0	eye lens 1+2	25.49
5	38.71	3.72	1.516	0.0089		
6	-38.71				total	47.22

The diminished real image is formed between the field lens and the eye lens, which makes this a modified Huygenian eyepiece. There is some doubt as to which extent the eye lenses are original or mounted in their original position: the image of the field diaphragm is not sharp and the distance between the two eye lenses has been changed by means of a small ring. The distortion is large for the full angle of view of 43.8°. When this is reduced to 34° it is still larger than 5%. The chromatic difference of magnification is very small.

3.6.3 *Adams's 'Compound Compendious Pocket Microscope' (1918-84)*

Unsigned, 4/4 18th C.
For a description, see: Bracegirdle, 2005.

Table 29: 1918-84

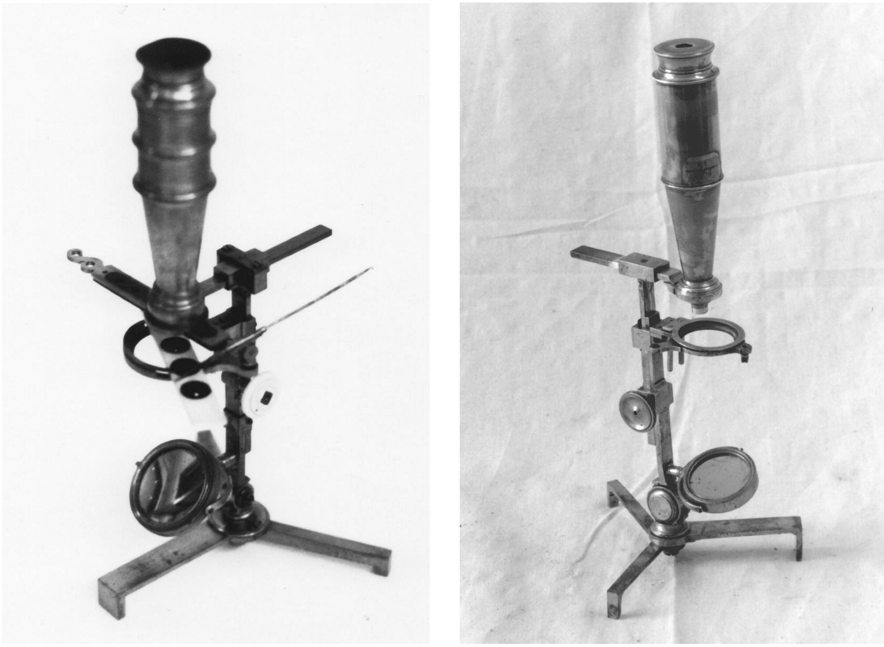
srf	radius	distance	N	ΔN	lens	f
1	65.49	1.43	1.540	0.0105	between l.	60.75
2	-65.23	35.50	1	0	field lens	39.77
3	44.83	4.97	1.534	0.0100	eye lens	41.42
4	-38.80	30.20	1	0		
5	22.64	1.96	1.547	0.0110		
6	∞				total	59.65

The angle of view of 21.4° was calculated from the magnification, being 15.74 diameters using objective '5'; the object field was 6mm. The distances between the lenses of this eyepiece are such that it can be considered as a two-lens eyepiece with a between lens. The distance between the eye lens and the field lens can be changed. The eyepiece was measured and calculated for a minimum value of this distance, for larger values the position of the focus became such that the distance between the objective of the measuring microscope and the eye lens became too small. The distortion of this eyepiece is small, of all three-lens eyepieces this one had the smallest value. Sadly the chromatic difference of magnification is large.

3.6.4 *Adams's 'Compound Compendious Pocket Microscope' (A645025)*

Signed 'Adams London', probably Adams junior, 1772–1795. The brass instrument is silvered.
For a description, see: Bracegirdle, 2005.

The field diaphragm of this eyepiece has a diameter of 16mm, which results in an angle of view of 41.8°. The computation was performed with a distance of 36.45mm between the field lens and the second eye lens, this value gave a better correspondence between the measured and the calculated focal lengths. The distortion at the full angle of view is lower than 10%, for 34° the value is 5.4%, which means it is one of the largest in this group of eyepieces. The chromatic difference of magnification on the other hand is very small.



(a) SCM1918-84 (b) A645025

Figure 21: microscopes with three lens eyepieces.

Table 30: A645025

srf	radius	distance	N	ΔN	lens	f
1	44.83	4.23	1.530	0.0100	field lens	50.20
2	-63.39	38.87	1	0	eye lens 2	39.35
3	∞	2.75	1.525	0.0096	eye lens 1	36.35
4	-20.67	6.95	1	0	eye lens 1+2	20.99
5	37.11	3.55	1.519	0.0091		
6	-37.11				total	39.77

3.6.5 *Pillar microscope (A159192)*

Signed 'Adams London', probably Adams junior, 1772–1795.
For a description, see: Bracegirdle, 2005, (cat.no.19/45).

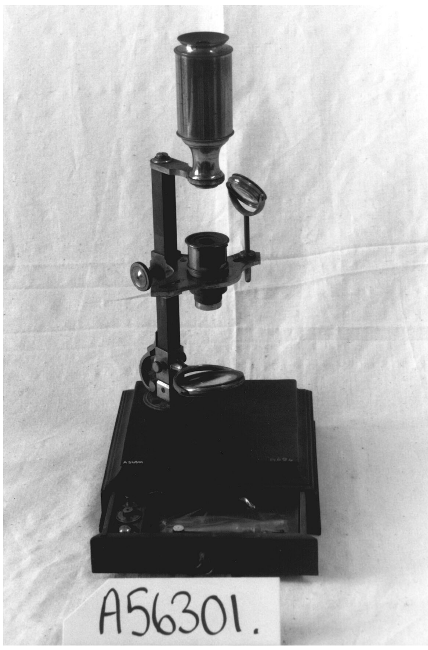
Pillar on flat folding tripod, focusing by means of rack and pinion, acting on the limb carrying the body.

Table 31: A159192

srf	radius	distance	N	ΔN	lens	f
1	62.71	4.2	1.497	0.0074	field lens	103.56
2	-281.3	66.77	1	0	eye lens 2	76.22
3	76.03	4.66	1.504	0.0080	eye lens 1	26.51
4	-76.03	11.12	1	0	eye lens 1+2	22.37
5	22.74	4.25	1.517	0.0090		
6	-32.24				total	55.23

The eyepiece has no field diaphragm, the angle of view is limited by the aperture of the field lens of 33mm. This results in an angle of view of 61° for a distance of 120mm to the objective lens. For this value the distortion is 21%. When the angle is reduced to 34° the distortion is 6%, which is the largest value in this group of eyepieces. The chromatic difference of magnification is small.

(a) A159192



(b) A56301

Figure 22: microscopes with three lens eyepieces.

3.6.6 *Improved Double and Single Microscope (A56301)*

Signed 'D. Adams London', 1800–1810.
For a description, see: Bracegirdle, 2005.

Table 32: A56301

srf	radius	distance	N	ΔN	lens	f
1	54.94	3.92	1.530	0.0100	field lens	52.47
2	-54.94	35.83	1	0	eye lens 2	38.66
3	22.89	3	1.526	0.0097	eye lens 1	38.66
4	-173.8	7.97	1	0	eye lens 1+2	not meas.
5	22.86	3.03	1.525	0.0096		
6	-173.8				total	36.45

The angle of view was calculated from the magnification, being 51.17 diameters using objective '3' (f=11.08mm). The objective field of 11mm was measured using objective '6' (f=26.92mm). When reduced to the focal length of objective '3', the resulting angle of view was 50°. The distance between the eyepiece and the objective could be varied from 60–90mm, a value of 70mm was used in the computations. The focal length of the two eye lenses together was calculated as ca. 22mm. The distance between the eye lenses and the field lens is slightly smaller than half the sum of their focal lengths. The diminished real image is situated between the field lens and the eye lens. Therefore this is also a modified Huygenian eyepiece. For the full angle of view the distortion is still smaller than 10%, when it is reduced to 34° the distortion is 3.9%. This is just under the average value in this group. The chromatic difference of magnification is acceptable

3.6.7 *Chest microscope (A56305)*

Signed *D. Adams London*, 1795–1820.
For a description, see: Bracegirdle, 2005.

Table 33: A56305

srf	radius	distance	N	ΔN	lens	f
1	72.10	6.55	1.520	0.0092	field lens	66.28
2	-63.86	41.88	1	0	eye lens 2	41.42
3	42.94	4.17	1.527	0.0098	eye lens 1	41.42
4	-42.94	12.93	1	0	eye lens 1+2	25.49
5	43.22	3.37	1.529	0.0099		
6	-43.22				total	44.18

The angle of view was not measured. Presuming the aperture of the field lens of 36mm being the limiting factor for the angle of view, a value of 63.4° was obtained. Even for this large angle the distortion was smaller than 10%. When reduced to 34° the distortion was 3.2%, smaller than the average value in this group. The chromatic difference of magnification in the outer zone of the image is too large, but it decreases to the centre of the field.

(a) A56305

(b) A56801

Figure 23: microscopes with three lens eyepieces.

3.6.8 *Tripod microscope (A56801)*

Signed 'W & S Jones Opticians No.30 Opposite Furnivals Inn Holborn London', after 1799.

Tripod microscope with scrolled legs, on a circular brass plate.
For a description, see: Bracegirdle, 2005, cat.no.13/115.

Table 34: A56801

srf	radius	distance	N	ΔN	lens	f
1	64.15	4.04	1.535	0.0104	field lens	60.75
2	-64.15	48.19	1	0	eye lens 2	41.42
3	43.78	2.76	1.534	0.0103	eye lens 1	41.42
4	-43.78	4.65	1	0	eye lens 1+2	22.78
5	44.01	2.51	1.537	0.0105		
6	-44.01				total	45.56

The field diaphragm of this eyepiece has a diameter of 15mm, the resulting angle of view is 36.5°. In the computation a distance of 47.55mm between the field lens and the eye lens was used as this value gave a better correspondence between the measured and the calculated focal lengths. The distortion for a reduced angle of view of 34°, being 4%, is smaller than the average of this group. The chromatic difference of magnification is very small.

3.6.9 *Chest microscope (A50965)*

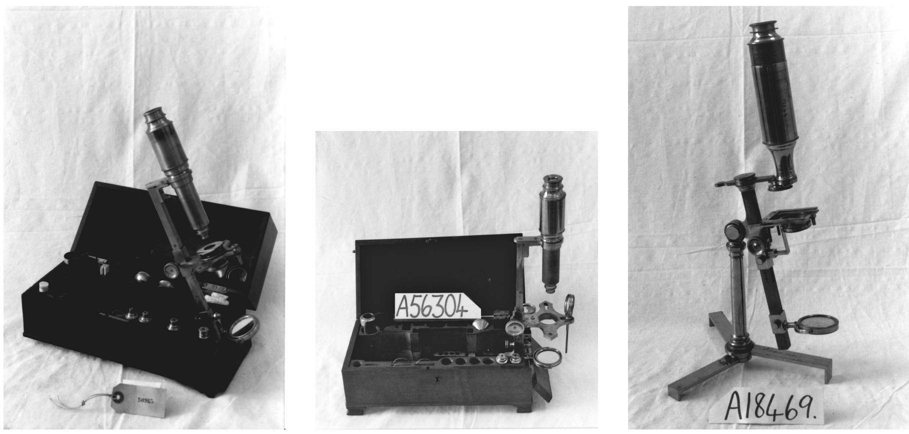
Signed 'Dollond London', 4/4 18th C.
For a description, see: Bracegirdle, 2005.

Table 35: A50965

srf	radius	distance	N	ΔN
1	72.25	3.71	1.528	0.0098
2	-72.25	43.6	1	0
3	32.12	3.72	1.53	0.0100
4	-35.53	14.78	1	0
5	29.35	3.4	1.532	0.0101
6	-29.35		1	0

lens	f
field lens	69.04
eye lens 2	32.45
eye lens 1	28.17
eye lens 1+2	20.99
total	46.39

The field diaphragm of this eyepiece has a diameter of 21.6mm, the resulting angle of view is 54°. The virtual image produced by the field lens lies above the eye lens. The distortion is small, even for the full angle of view. When this is reduced to 34° the distortion is 3%, one of the smallest values in the group. The chromatic difference of magnification is 1.1% for the margin of the field, which is too large. It decreases to the centre of the field but even there it is large, namely 0.5%.



(a) A50695 (b) A56304 (c) A18469

Figure 24: microscopes with three lens eyepieces.

3.6.10 *Chest microscope (A56304)*

Signed 'Dollond London', 4/4 18th C.
For a description, see: Bracegirdle, 2005.

The angle of view was not measured, the same value of 54° as of the previous Dollond microscope (A50965) was used. This resulted in a distortion of slightly over 10% at the margin of the field. The distortion for an angle of view of 34° equals the average value in this group of three-lens eyepieces. The chromatic

Table 36: A56304

srf	radius	distance	N	ΔN	lens	f
1	41.49	4.84	1.518	0.0091	field lens	78.70
2	-2350	49	1	0	eye lens 2	41.42
3	41.82	3.79	1.513	0.0086	eye lens 1	29.00
4	-41.82	14.09	1	0	eye lens 1+2	22.37
5	29.25	3.62	1.515	0.0088		
6	-29.25				total	47.64

difference of magnification is rather large at the margin of the field, though under the 0.6% limit. In the centre of the field it is much better corrected.

3.6.11 *Dollond's form of the 'Most Improved' microscope (A18469)*

Signed 'Dollond London', 1/4 19th C.
For a description, see: Bracegirdle, 2005.

Table 37: A18469

srf	radius	distance	N	ΔN	lens	f
1	73.30	7.12	1.519	0.0091	field lens	71.80
2	-73.30	48.78	1	0	eye lens 2	42.34
3	44.48	4.11	1.534	0.0103	eye lens 1	33.63
4	-44.48	15.59	1	0	eye lens 1+2	24.22
5	32.50	3	1.531	0.0101		
6	-38.38				total	55.23

The angle of view of 45.8° was calculated from the magnification, being 175.7 diameters using objective '1'; the object field was 1.2mm. Like the two previous Dollond microscopes (A50965 and A56304) this microscope has a weak field lens, which results in a back focus lying above the eye lens. The distortion of this eyepiece is small, only 3.2% for an angle of view of 34°. The chromatic difference of magnification is acceptable.

3.7 FOUR-LENS EYEPIECES

These eyepieces can be divided in two categories, the Martin-type eyepieces with two eye lenses, a field lens and a between lens; and the Adams/Jones eyepieces with three eye lenses and a field lens. The average distortion for an angle of view of 34° is 4.24%. For this angle of view the eyepieces with a between lens have an average distortion of 2.9%. The Adams/Jones eyepieces have a larger average distortion, being 4.6%.

Table 38: four-lens eyepieces, overview

	UM293	A101926	A159473a	A159473b
ef	113.42	103.5	46.37	39.80
efl	111.35	101.92	46.29	39.66
efs	118.73	107.57	46.57	40.13
efs-efl	7.38	5.65	+0.28	+0.47
bkf	175.53	167.44	97.34	95.57
epl	-43	-51	-120	-127
xpl	18.93	23.94	16.86	10.4
Petz.	0.43	0.348	0.176	0.209
field	30	44	36	47.4
M ang	-1.96	-2.22	-4.96	-6.14
D rim	1.93	5.33	5.76	9.83
D mid.	0.49	1.34	1.35	2.18
D 34°	2.46	3.28	5.11	4.83
CVV′rim	-0.3	-0.41	-0.72	+0.02
CVV′mid	-0.35	-0.56	-0.70	-0.11

	A56523a	A56523b	A56300	A600166a	A600166b
ef	49.69	50.98	30.13	30.78	55.21
efl	49.54	50.80	30.16	30.82	54.94
efs	50.06	51.42	30.06	30.72	55.87
efs-efl	0.52	+0.63	-0.10	-0.10	0.92
bkf	107.73	87.96	27.81	25.00	145.42
epl	-123.5	-130.5	-110	-100	-41.5
xpl	17.07	14.24	12.76	14.37	13.77
Petz.	0.175	0.203	0.130	0.128	0.251
field	36.8	36.8	53.6	60	60
M ang	-4.93	-4.49	-5.05	-4.72	-3.91
D rim	5.97	4.8	10.36	16.33	15.53
D mid.	1.39	1.15	2.31	3.42	3.29
D 34°	5.06	4.09	3.92	4.84	4.58
CVV′rim	-0.46	-0.12	-1.05	-1.02	-0.53
CVV″mid	-0.46	-0.19	-0.93	-0.92	-0.55

3.7.1 *Martin's 'Universal Microscope' with between lens (UM0293)*

Unsigned, possibly Benjamin Martin, ca. 1770.
The microscope is part of a microscopical cabinet.

Table 39: UM293

srf	radius	distance	N	ΔN	lens	f
1	89.57	1.91	1.543	0.011	between l.	82.84
2	-89.57	48	1	0	field lens	69.59
3	73.47	3.53	1.532	0.010	eye lens 2	62.96
4	-73.47	33.39	1	0	eye lens 1	62.96
5	33.97	3.45	1.540	0.011	3 eye lenses	33.37
6	∞	4.88	1	0	total	
7	33.97	3.31	1.540	0.011	without	
8	∞				between l.	36.45

The angle of view of 30° was calculated from the magnification, being 26.5 diameters using objective '4'; the object field was 5.15mm. The distance between the eye lenses and the field lens was reduced in the computation to get a better correspondence between the measured and calculated value of the focal lengths (without between lens). The focal length with the between lens was not measured. See also the next microscope, A101926.

3.7.2 *Tripod and pillar microscope (A101926)*

Signed 'B. Martin Invt. & Fecit No.4', ca. 1770.
The instrument is provided with a racked table and a fine adjustment screw.
For a description, see: Bracegirdle, 2005.

Table 40: A101926

srf	radius	distance	N	ΔN	lens	f
1	54.53	1.65	1.555	0.012	between l.	89.95
2	-581.8	48.9	1	0	field lens	121.51
3	65.66	3.22	1.538	0.011	eye lens 2	70.42
4	-14100	35.89	1	0	eye lens 1	54.44
5	39.20	2.63	1.556	0.012	eye lens 1+2	33.14
6	-35500	6.98	1	0		
7	29.18	3.88	1.536	0.010		
8	-35500				total	103.56

The eyepiece of this microscope, like the previous one, is of Martin's construction. It has two eye lenses, a field lens and a between lens. All lenses are more or less plano-convex. They were found in the position as indicated in the table, but there is no certainty as to whether this is the original one. The distance between the field lens and the between lens was reduced in the computation to 46.1mm

Figure 25: four lens eyepiece A101926

to give a better correspondence between the measured and the calculated focal lengths. The angle of view was not measured but estimated, assuming the aperture of the field lens of 18mm to be the limiting factor. From this a value of 44° resulted. The distortion of A101926 is small, namely 3.28%, like the other Martin-type eyepiece of UM293. The difficulty of controlling the value of a parameter like the chromatic difference of magnification shows in table 44. For UM293 the value of CVV′ is only half the one of A101926. Though eyepieces were assembled in such a way as to give the best possible visual result, this can vary considerably.

3.7.3 *'Universal Compound Microscope', (A159473)*

Signed 'Adams London', ca. 1790.
For a description, see: Bracegirdle, 2005.

Table 41: A159473 (a)

srf	radius	distance	N	ΔN
1	62.61	5.61	1.506	0.0082
2	-278.2	59.4	1	0
3	75.95	4.29	1.514	0.0088
4	-75.95	1.73	1	0
5	76.03	4.98	1.527	0.0098
6	-76.03	3.06	1	0
7	51.54	2.72	1.523	0.0095
8	-51.54			

lens	f
field lens	101.48
eye lens 3	74.56
eye lens 2	72.90
eye lens 1	49.71
eye lens 1-3	23.93
total	46.39

The angle of view of 36° was calculated from the diameter of the field diaphragm of 15.6mm and the focal length of the combination of the three eye lenses. The distortion of this eyepiece is, like the nearly identical one of A56523 (a), higher than the average in this group. The chromatic difference of magnification is, like that of A56523 (a), again very constant over the field. Its value is a bit too large, however this might improve when it is used in combination with an objective.

Table 42: A159473 (b)

srf	radius	distance	N	ΔN	lens	f
1	76.20	6.4	1.507	0.0082	field lens	76.22
2	-76.20	52	1	0	eye lens 3	76.22
3	75.95	4.8	1.504	0.0079	eye lens 2	74.56
4	-75.95	2.48	1	0	eye lens 1	26.51
5	75.95	5.21	1.515	0.0088	eye lens 1-3	17.84
6	-75.95	1.06	1	0		
7	26.17	5.23	1.511	0.0085		
8	-26.17				total	39.77

The angle of view of this eyepiece is limited by the field diaphragm of 15.6mm. The focal length of the eye lenses is smaller than in the combination described above, namely 17.84mm. As a result the angle of view is 47.4°. For this large angle the distortion is nearly 10%. The reduced value of the distortion of 4.83% for an angle of 34° is smaller than in the previous eyepiece. The chromatic difference of magnification is smaller as well. however it is not constant over the field any more.

3.7.4 *'Universal Compound Microscope' (A56523)*

Signed 'Adams London', ca. 1790.
For a description, see: Bracegirdle, 2005.

Table 43: A56523

srf	radius	distance	N	ΔN	lens	f
1	62.61	5.51	1.517	0.0090	field lens a	99.41
2	-278.7	61.1	1	0	eye lens 3	76.22
3	76.03	4.73	1.504	0.0080	eye lens 2	76.22
4	-76.03	2.64	1	0	eye lens 1	48.88
5	76.03	4.58	1.504	0.0080	eye lens 1-3	23.67
6	-76.03	2.03	1	0		
7	51.54	3.05	1.533	0.0102		
8	-51.54		1	0	total	49.71
Data of field lens 'b':						
1	76.03	5.3	1.505	0.0080	field lens b	76.22
2	-76.03	54.3	1	0		

This is a microscope similar to the previous one (A159473), the difference being that this one is only provided with an exchangeable field lens, while A159473 had two separate eyepieces. The diameter of the field diaphragm of this microscope is

16mm, which results in an angle of view of 36.8°. The differences between both eyepieces 'a' are extremely small compared to other eighteenth-century eyepieces. It would be interesting to measure more of these eyepieces to see whether they are all so much alike. It could indicate that the lenses of these two microscopes were made at the same time or shortly after each other. Possibly the same pieces of glass were used.

To get a better correspondence between the measured and the calculated focal length the distance between the field lens and the third eye lens was increased from 61.1mm to 64.2mm, being the value used in the computations.

The combination of these eye lenses with field lens 'b' gives a slightly smaller distortion. The chromatic correction of magnification is even much smaller than the maximum value of 0.6%.

This type of microscope was investigated by Frison, and Bradbury.[12] Frison investigated a specimen in the private collection of Mr. Marcel de Decker in Antwerp, Bradbury the one in the Museum of the History of Science in Oxford.

Frison measured the magnification of all the objective lenses, used as simple microscopes and also on the compound microscope. He found a magnification of 568 diameters for the strongest lens. This '568' is incorrectly cited by Bradbury as '560', and repeated ever since.

Frison did not realise that the two strongest lenses, which he called 'capped lens (a)' and 'capped lens (b)' were never intended for use on a compound microscope. I found similar lenses with the two instruments in London and they are obviously for single use only. The data for A56523 were: (a) f=2mm, NA=0.21, resolved 2.75μm; (b) f=2.8mm, NA=0.17, resolved 4μm. For A159473: (a) f=1.79mm and (b) f=3mm. The NA of the 2mm lens is a bit high but the quality of the image of these simple microscopes was quite acceptable.

Bradbury measured a numerical aperture of 0.19 for lens '1' (f=9.60mm). I do not believe this to be correct. A numerical aperture of 0.19 is much too large for a lens of 9.6mm focal length, the spherical aberration would be excessive. Bradbury did not measure the magnification himself but used Frison's value of 560 [!] diameters for the highest power lens. However, the 560 (568) diameters of Frison were not measured with lens '1', as Bradbury seems to think, but with the 'capped lens (a)'; for lens '1' Frison gives a magnification of 142 diameters, which corresponds much better with the values I found myself.

Bradbury's conclusion that the

> ... empirical addition of more lenses in the body tube and the eyepiece has resulted in so much spherical aberration in the image that the end result is a worse performance than in many earlier microscopes in which no attempt has been made to overcome their optical shortcomings.

is totally unfair to Adams.

Summarizing:

- Firstly, the NA that Bradbury mentions is not realistic for a lens of that focal length, either his measurements are wrong or somebody has messed up the lenses

12 Frison [49], 199–206, (204); Bradbury [18], 151–173, (169).

- Secondly, if the NA is indeed 0.19, not the lenses of the eyepiece but the too high aperture of the objective itself is responsible for the excessive spherical aberration observed by Bradbury
- Thirdly, the magnification of 560 diameters which Bradbury assumes for the Oxford microscope with lens '1' was measured by Frison with a much stronger lens, namely one of the capped lenses. These capped lenses were intended only for use as simple microscopes. As a consequence the magnification of the eyepiece is not 30 diameters, as Bradbury writes, but only 5 diameters. This is a normal value for an eighteenth-century eyepiece.

Mistakes like this would not be very serious in many other branches of science. But in history of science, where not many scientists investigate primary sources, as scientific instruments are, the consequences are disastrous. During one or more generations such mistakes are quoted in the literature and complete theories are being built upon the conclusions inferred from them.

To stress my points it was decided to simulate the whole optical system of this microscope with OPDESIGN, which was possible as by chance the curvatures and other optical data of the objectives were also measured. The method is the same as used in the computer simulation of the two-lens eyepiece earlier in this chapter.

The objective lens '1', which is used in this simulation is biconvex, its radius is 10.62mm, the thickness 1.45mm, the focal length 10.65mm and the refractive index as calculated from these data is 1.51. The free aperture of the lens was 1.712mm, the diameter of the lens itself was 3.3mm. The NA was 0.073 when measured with a ×5 Huygenian eyepiece, the body tube of the measuring microscope was 150mm. The construction of the optical parts of the microscope is shown in figure 26.

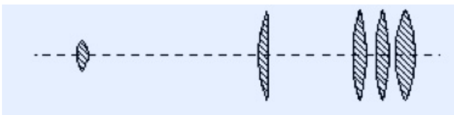


Figure 26: lens system of A56523

The objective alone was now calculated from image to object. The image is situated at a distance of 123.5mm + 107.7 = 231.2mm (the sum of the measured distance between objective lens and field lens and the calculated back focus of the eyepiece). Using this, an object distance of 10.67mm was found. Later this distance is necessary to calculate the entire microscope from object to eye, to find the angle of field, the distortion and the chromatic difference of magnification, in the same way as this is done for the eyepieces alone.

This computation of the objective alone also gives values for the NA, the marginal spherical aberration, the Optical Tolerance and the Offence against the Sine Condition.

It also reveals that an NA of 0.19, which Bradbury measured, would result in a marginal spherical aberration which is a factor 11 larger than its Optical Tolerance! The aperture of the lens for this NA would have to be 4.1mm, while the diameter of the lens I measured was only 3.3mm.

The complete optical system of the microscope could now be computed in two directions. Firstly from object to eye for an object distance of 10.67mm, and secondly from eye to object. The entrance pupil in these computations is what is usually called the Ramsden disk, its diameter was 0.365mm for a NA of 0.077. From this the magnification of the microscope, being 105.1 diameters, could be calculated. This is about one fifth of the 560 diameters of Frison. For an objective with a NA of 0.077 this is a bit too much, it will result in empty magnification.

Table 44: Simulation of microscope A56523

	eyepiece	total	objective
field	36.8	36.8	
MA	-4.93	-4.72	
D rim	5.97	5.97	
D mid	1.39	1.39	
D 34°	5.06	5.03	
CVV′ rim	-0.46	-0.39	
CVV′ mid	-0.46	-0.40	
epl	-123.5	0	
xpl	17.07	17.07	
bkf	107.7	-10.67	10.67
$\Delta ef_{(F-C)}$		0.053	-0.173
pupil dia.		0.365	1.712
NA		0.077	0.077
mSA		-0.0084	-0.0084
OT		0.028	0.028
OSC′		0.003	0.003
M	5.4	105.1	20.76

Table 44 shows clearly that the spherical aberration of this microscope – and all other microscopes I did not analyse in such detail – is completely determined by the spherical aberration of the objective, as I already stated in section 3.4. The combination of an objective and an eyepiece has less chromatic difference of magnification than the eyepiece alone, as they compensate each other to a certain extent.

3.7.5 *'Improved Compound Microscope' (A56300)*

Signed 'W & S Jones 30 Holborn London', ca. 1800–1810.
For a description, see: Bracegirdle, 2005.

The eyepiece of this microscope was not complete, as the between lens was missing. I analysed it because its construction was very similar to the eyepiece of the following instrument (A600166). The latter is analysed without (A600166a) and with (A600166b) its between lens. Regrettably the angle of view could not be measured. The attachment of the revolving disk with its six objective lenses was not in working order any more, so that it was not possible to measure the magnification of the total microscope. When the free aperture of the field lens would limit the field an angle of view of nearly 90° would result. For this angle

(a) A56523 (b) A56300 (c) A600166

Figure 27: microscopes with four lens eyepieces.

Table 45: A56300

srf	radius	distance	N	ΔN
1	72.33	6.38	1.528	0.0098
2	-72.29	33.05	1	0
3	72.48	5.62	1.528	0.0098
4	-72.48	0.36	1	0
5	72.48	5.46	1.528	0.0098
6	-72.48	3.43	1	0
7	27.25	2.9	1.527	0.0098
8	-176.3		1	0

lens	f
field lens	69.59
eye lens 3	69.59
eye lens 2	69.59
eye lens 1	44.97
eye lens 1-3	22.10
total	30.12

the distortion, being 44%, is too large. A more modest angle seemed appropriate, 53.6° resulted in a distortion of 10.36% for the margin of the field. As in the four-lens Adams eyepieces of A159473 and A56523 the chromatic difference of magnification is very constant over the field, ca. 1%, which is too large. This also indicates that the eyepiece was never intended to be used without its between lens.

3.7.6 *'Most Improved Compound Microscope' (A600166)*

Signed 'W & S Jones 30 Holborn London', 1800–1830.
For a description, see: Bracegirdle, 2005.

Table 46: A600166

srf	radius	distance	N	ΔN	lens	f
1	73.30	5.75	1.528	0.0098	field lens	70.42
2	-73.30	37.69	1	0	eye lens 3	72.90
3	73.47	5.24	1.510	0.0084	eye lens 2	72.90
4	-73.47	0.26	1	0	eye lens 1	47.64
5	73.47	5.24	1.510	0.0084	eye lens 1-3	23.20
6	-73.47	3.94	1	0		
7	44.72	3.28	1.526	0.0097	total 1-4	30.77
8	-55.47		1	0	total 1-5	55.23
Between lens:						
9	184.6	2.37	1.508	0.0083	between l.	182.26
10	-184.6	56.5	1	0		

This microscope has a four-lens eyepiece and a between lens. The eyepiece is analysed without (A600166a) and with (A600166b) its between lens. The diameter of the field diaphragm was 27.5mm, it did not limit the angle of view. The focal length of the three eye lenses was 23.2mm, this resulted in an angle of view of 60°. To get a better correspondence between the measured and calculated focal lengths the distance between the first and the second eye lens used in the computations was 3.5mm instead of 3.94mm and the distance between the field lens and the third eye lens was reduced to 31mm. For these values the results for this eyepiece differed not much from the previous one, the chromatic difference of magnification also being too large.

When combined with its between lens the eyepiece performed well. The angle of view was still too large, the distortion at the margin of the field being 15.53%. Reduced to 34° the distortion, being 4.58%, was slightly above the average in this group. The chromatic difference of magnification, being 0.53%, was constant over the field of view. This indicates that the eyepiece of A56300 would also perform better in this respect if the between lens were still present.

3.8 DELLEBARRE-TYPE EYEPIECES

The Dellebarre microscope with its distinctive mechanical form and its deviant eyepiece was successfully marketed by the Frenchman L.F. Dellebarre (1726–1805) from 1770 onwards. In his Mémoire ..., published in The Hague in 1777, Dellebarre states that his microscope has five eye lenses, made of different kinds of glass, and having different focal lengths.[13]

Table 47: Dellebarre type eyepieces, overview

	RMS 18	A135495	UM23	UM576
ef	18.67	19.70	39.63	-15.97
efl	18.75	19.77	39.46	-16.22
efs	18.49	19.56	40.08	-15.41
efs-efl	-0.26	-0.21	0.61	0.81
bkf	-7.325	0.269	43.55	-91.26
epl	-100	-160	-80	-31.8
xpl	11.74	4.42	10.21	23.96
Petz.	0.085	0.104	0.186	0.060
field	61.2	47.8	37.2	41.2
M ang	-5.9	-8.85	-3.27	-4.08
D rim	19.1	8.82	4.93	9.65
D mid.	3.88	2	1.19	2.14
D 34°	5.43	4.33	4.11	6.43
CVV′rim	-2.2	-1.32	0.16	0.001
CVV′mid	-1.77	-1.21	0.02	-0.14

I could investigate a number of these microscopes but many of them were incomplete. The construction with its exchangeable lenses is to blame for this. Dellebarre's claim that he used different kinds of glass could only be confirmed for one specimen in Utrecht (UM23). The other ones which I investigated, both the complete ones I included in this thesis and the incomplete ones I found in the Science Museum and the Wellcome Collection, did not contain any flint lenses. Harting's statement that Dellebarre's eyepieces consisted of crown glass–flint glass pairs, could not be confirmed.[14] The number of investigated instruments was smaller than I hoped.

Besides they fall apart in two distinct groups, the classical Dellebarre microscopes: RMS 18, A135495 and UM23, and the modern form of UM576.

The average value of the distortion for an angle of view of 34° is 5.1% and only of a limited interest. It can serve to show that the fame of Dellebarre's microscopes was certainly not based upon the quality of his eyepieces.

3.8.1 *Dellebarre microscope (RMS 18*

Unsigned, made in Holland according to Turner, ca. 1795.[15]

13 Dellebarre [36], 11.
14 Harting [59], 123–124.
15 Turner [107], 202–204.

Table 48: RMS 18

srf	radius	distance	N	ΔN	lens	f
1	64.15	5.1	1.529	0.0099	lens IIII	61.51
2	-64.15	1.04	1	0	lens III	65.15
3	64.03	5.1	1.529	0.0099	lens II	57.53
4	-72.63	2.68	1	0	lens I	51.44
5	63.98	5.75	1.523	0.0095		
6	-55.11	0.88	1	0		
7	51.36	5.75	1.509	0.0083		
8	-51.36		1	0	total	16.84

The field of this microscope was not measured, but I assumed that the angle of view was limited by the diameter of the lens closest to the objective. This resulted in an angle of view of 61.2°. For this value the distortion is excessive and the chromatic difference of magnification is too large as well. Dellebarre's claim that he used different kinds of glass in his eyepieces is not substantiated by the values of the refractive indices I found, though it is always possible that a lens no. 'IIIII' with a different refractive index once belonged to this microscope.

(a) RMS18 (b) A135495

Figure 28: Dellebarre type microscopes.

3.8.2 *Dellebarre microscope (A135495)*

Unsigned, probably French, 3/4 18th. C.
For a description, see: Bracegirdle, 2005.

This is a rather exceptional specimen. Unlike the other microscopes it was contained in a beautifully worked case covered with red leather with a gold tooled coat of arms. Traces of silver and perhaps gold were still visible on the instrument. Though it has the five eye lenses mentioned in Dellebarre's article none of these is a flint lens. The angle of view was not measured, I assumed it to be limited by the diameter of the lens closest to the objective, like in the previous microscope.

Table 49: A135495

srf	radius	distance	N	ΔN	lens	f
1	81.45	4.93	1.517	0.0090	lens IIIII	79.53
2	-81.45	3.55	1	0	lens IIII	69.04
3	72.48	5.62	1.532	0.0101	lens III	63.51
4	-72.48	1.54	1	0	lens II	66.28
5	58.28	6.18	1.517	0.0090	lens I	48.52
6	-72.48	1.84	1	0		
7	66.60	5.89	1.510	0.0085		
8	-66.66	2.66	1	0		
9	48.16	6.92	1.508	0.0083		

An angle of view of more than 100° and a distortion of 50% resulted from this. Limiting the field to half this value resulted in an angle of view of 47.8° and a distortion which was still larger than 8%. CVV′ is for this eyepiece also too large.

3.8.3 *Dellebarre microscope (UM23)*

Unsigned, under the table is scratched 'L.F. Dellebarre', 3/4 18th C.

The microscope once belonged to the Zoological Laboratory of the University of Utrecht.

Table 50: UM23

srf	radius	distance	N	ΔN	lens	f
1	55.06	5.79	1.600	0.015	lens I	51.56
2	-67.37	37	1	0	lens IIII	60.25
3	64.21	5.66	1.5412	0.011	lens III	49.71
4	-64.21	2.17	1	0	lens II	65.28
5	51.32	6.43	1.527	0.010		
6	-51.28	0.96	1	0	II, III, IIII	22
7	72.63	5.01	1.529	0.010		
8	-64.27				total	39.6

This is the only Dellebarre-type microscope I found with a flint lens in it. The order of the lenses I used to get a usable combination is as indicated. Number I being the field lens and the combination II-III-IIII acted as an eye lens. The angle of view was calculated from the magnification with the weakest of the two objectives, which was 56 diameters. The object field was 3mm. From this an angle of view of 37.2° resulted. The distortion was still large, the chromatic difference of magnification was very small.

3.8.4 *Dellebarre microscope (UM576)*

Signed 'Dellebarre / 1797 / Onderdewijngaart Canzius / Confecit / Delft / 1797'.

Table 51: UM576

srf	radius	distance	N	ΔN
1	63.74	3.37	1.539	0.011
2	-63.74	185	1	0
3	63.98	6.11	1.545	0.011
4	-63.98	10.23	1	0
5	45.54	5.44	1.535	0.010
6	-45.54			

lens	f
between l.	59.65
field lens	59.65
eye lens	43.49

Though the mechanical construction is as usual, the eyepiece is of a totally different design. There are two eye lenses and a between lens close to the objective. The result is a combination with a negative focal length and a back focus which is to the left of the objective lens. The angle of view was measured with objective '4'. The magnification was 47.23 diameters and the object field 4mm. This resulted in an angle of view of 41.2°. The chromatic difference of magnification is much smaller than for the other Dellebarre eyepieces but the distortion is still too large.

3.9 CONCLUDING REMARKS

In section 3.5 to section 3.8 the analysis of 36 eyepieces is reported; 13 with two lenses; 11 with three lenses; 8 with four lenses; and 4 Dellebarre-type eyepieces. The data resulting from a computer analysis using OPDESIGN is assembled in the tables 8, 9, 10, and 12. The values of the distortion for an angle of view of 34° are collected in figure 29.

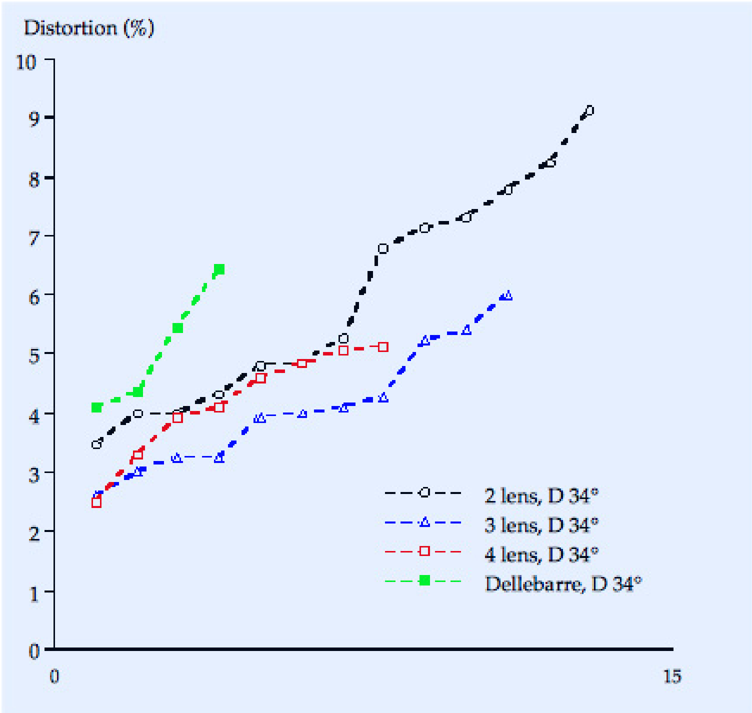


Figure 29: distortion of analysed eyepieces

For the purpose of clarity the points representing the distortion of a particular type of eyepiece have been connected by a dotted line. In figure 30 the measured or calculated values of the angle of view have been collected in the same way. In both cases the data are sorted in an ascending order. The horizontal axis only represents the various microscopes.

The group of two-lens eyepieces is rather heterogeneous. Not only eighteenth-century ones, but also a number of nineteenth-century ones with plano-convex lenses are included. When only the ten older ones which use biconvex lenses are considered, the average distortion for an angle of view of 34° is even 6.3%. The average angle of view for these eyepieces is 30.2°.

These values are rather unfavourable compared to the three- and four-lens eyepieces of the later eighteenth century. Their average distortions for an angle of view of 34° are 4.1% and 4.2% respectively. The average angles of view of these three- and four-lens eyepieces are 48.2° and 43.1° respectively. This clearly shows that the instrument makers of the period aimed for an increasing angle of view; at the same time they succeeded in decreasing the distortion.

When we compare this with the four Dellebarre eyepieces, with their average angle of view of nearly 47° and an average distortion for an angle of view of 34°

of 5.1% this shows that Dellebarre's claims of being able to produce an improved eyepiece are rather hollow.

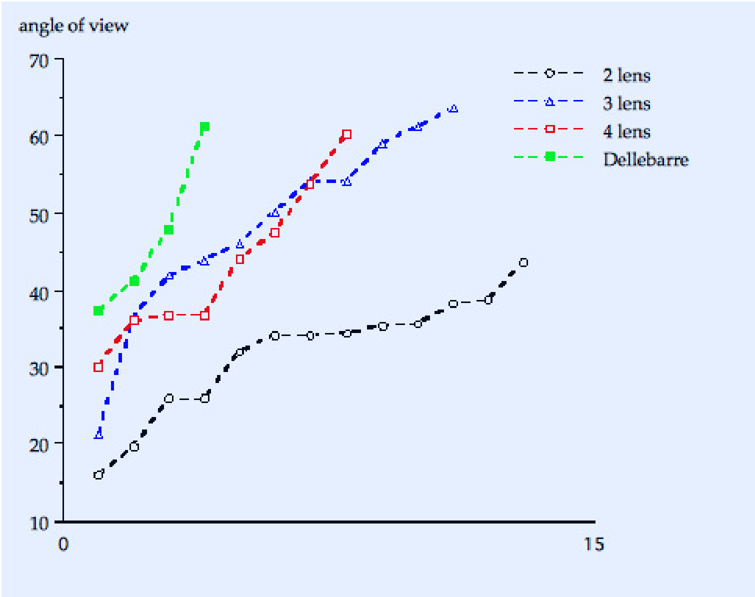


Figure 30: angle of view of analysed eyepieces

Figure 29 and figure 30 show that the differences between the three-lens and the four-lens eyepieces are only marginal. The extra cost and the higher number of optical surfaces, causing loss of light, makes the four-lens eyepiece unattractive from both an economical and optical point of view. That these four-lens eyepieces were made and used, though, was a whim of fashion more than a necessity.

The large angle of view of these eyepieces–combined with the moderate amount of magnification these microscopes can bear–also indicates what kind of use they were intended for: a general view of the objects under investigation. A weak objective with a low NA is advantageous in this case as its depth of field is much larger than for a strong objective with a high NA. For a magnification of 50 diameters and NA=0.1 James gives a depth of field of ca. 150μm for objects with a cover glass and 100μm for objects without a cover glass.[16] A typical eigthteenth-century microscope with an objective lens of 15mm focus, a NA of 0.11 and a $\times 5$ eyepiece–see table 6 for the source of these values–is well suited for this purpose. Its magnification is ca. 50 diameters, which is about 500$\times$ the NA, so there is no empty magnification. The resolving power can be as good as 3.5μm and the depth of field will be ca. 150μm. With an angle of view of the eyepiece of 40° this results in an object field of 3.6mm.

16 James [69], 67–69, 68.

3.10 REFRACTIVE INDEX

Two important subjects I have not dealt with in this thesis are optical glass and the technology of lens making. The reason for this omission is the consideration that these two subjects are too extensive to be treated only partially.

A good bibliography on the subject is found in Duncan's *Bibliography of Glass*.[17] Some isolated samples have been analysed by Boegehold, Von Rohr and recently by Mills and Jones.[18] McConnells (probably unpublished) paper on the development of glass making in the period 1500–1800 is of great interest.[19]. Turner analyses the factors limiting the development of the glass industry in England in the period 1650–1850.[20]

Lens making is treated by Varley, Crommelin, and Bedini.[21]. See also Willach about the invention and subsequent development of the polishing technique in the seventeenth century.[22]

In this thesis I can only contribute the following short analysis of the refractive indices I calculated. I used the measurements of 254 lenses of eyepieces (see Appendix 6). The range of refractive indices from N=1.495 to N=1.57 was divided in fourteen bands, see table 52. The number of samples found in each band was counted subsequently.

Table 52: distribution of refractive indices

bar.no.	N	bar.no.	N
1	1.495-1.500	8	1.530-1.535
2	1.500-1.505	9	1.535-1.540
3	1.505-1.510	10	1.545-1.550
4	1.510-1.515	11	1.550-1.555
5	1.515-1.520	12	1.555-1.560
6	1.520-1.525	13	1.560-1.565
7	1.525-1.530	14	1.565-1.570

The result of this has been plotted in figure 31. It is very tempting to infer from this plot that there were two distinct groups of crown glass in the eighteenth and early nineteenth century. One group has its refractive index centred around the group $1.51<N<1.515$ and those of the second group are centred around $1.53<N<1.535$.

17 Duncan [40]
18 Boegehold [11], 86–89; Rohr [92], 18–20; Mills and Jones [84], 173–182.
19 McConnell [82]
20 Turner [109]
21 Varley [118], 3–52; Crommelin [31]; Bedini [7], 3–52; Bedini [8].
22 Willach [123]

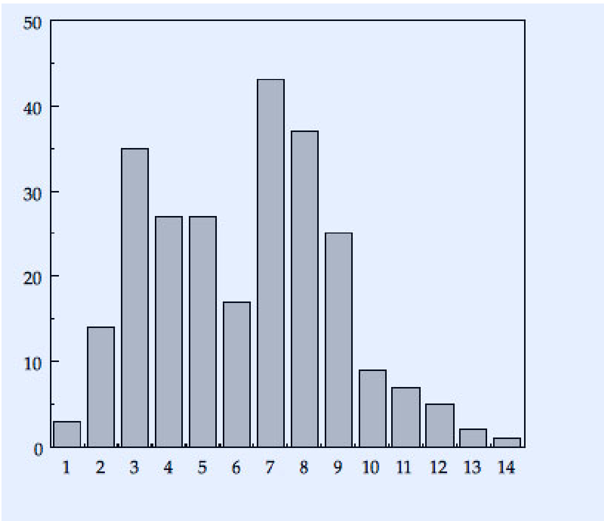


Figure 31: distribution of refractive indices

4 THE ACHROMATIC OBJECT-GLASS

4.1 INTRODUCTION

It was shown in chapter three that the single lens objective used in telescopes and microscopes suffered from two drawbacks, spherical and chromatic aberration. To keep an acceptable image quality the aperture of the objective lens had to be limited as a consequence. This resulted in telescopes and microscopes which were heavily stopped down. For this reason the resolving power of microscopes was limited to ca. 2μm.

It was discovered in the eighteenth century that a positive lens of crown glass and a negative lens of flint glass could be combined in such a way as to compensate chromatic aberration. These achromatic doublets were made for telescopes from 1758 onwards by John Dollond (1706–1761) and his son Peter (1730–1820). Their invention gave rise to great scientific interest. Mathematical physicists like L. Euler (1707–1783), A.C. Clairaut (1713–1765) and J. le Rond D'Alembert (1717–1783) published learned treatises explaining the theory of this achromatic lens, thus giving it a mathematical basis. They also investigated spherical aberration and the way in which both spherical and chromatic aberration could be compensated more or less independently in an achromatic doublet. In this chapter the coming into being of the achromatic telescope is treated as it forms the basis for later work on the achromatic lens for the microscope.

Some low power achromatic lenses for microscopes were designed and perhaps made around 1770 by Benjamin Martin and by Van Deijl from Amsterdam but not much is known about them.[1] Van Deijl indicates in his article, written in 1807, that the people who bought microscopes did not seem to be very interested in expensive achromatic microscopes. He also mentions that it cost him as much effort and time to make an objective for a telescope as for a microscope, so it did not make much sense to spend too much effort constructing the latter.

4.2 THE DEVELOPMENT OF THE ACHROMATIC OBJECTIVE

The history of the achromatic telescope objective is treated in detail by Danjon & Couder, Boegehold, King, Herzberger and Fellmann.[2]

The relation between Chester Moor Hall, who had an achromatic objective made in 1733, and Dollond is treated by Robischon.[3]. Later investigations by Willach of a number of surviving early achromats show in detail the development of the achromatic objective and the problems that had to be overcome before it could be manufactured on a commercial scale.[4]

1 Martin [79], Martin [80], Deijl [34], 133–151.
2 Danjon and Couder [33], 217–244; Boegehold [11], 7–40; Boegehold [12], 97–111; Boegehold [14], 81–114; King [72], 81–114; Herzberger [63], 7–13; Fellmann [44], 296–322.
3 Robischon [90], 283–329.
4 Willach [122]

The idea to cancel spherical aberration by a combination of a positive and a negative lens was formulated by Huygens in 1665 and 1669, though it was not published completely until 1916.[5] Korteweg and Lorenz, the editors of Huygens's optical writings, give the following three reasons why Huygens discontinued this line of research:

- Huygens's aim was to increase the aperture of the objective. He doubted whether his simplified formulæ would be valid for these higher apertures. When he compared an exact calculation with the result of his formulæ the improvement was only small.[6]
- Huygens knew all too well how difficult it was to make lenses which were perfectly spherical and which radii corresponded to the calculated values.
- After 1672, when Newton published his theory of colours in the *Philosophical Transactions*, Huygens became convinced that in 'telescopes un peu longs' chromatic aberration was more harmful than spherical aberration.

Korteweg and Lorenz are of the opinion that the third reason was considered by Huygens as the most important one to discontinue his line of research.[7]

Before I continue it might be useful to indicate shortly Newton's theory of dispersion. From the experiments with two prisms, one of glass and the second one of water, which Newton performed in 1672, he concluded that, $\Delta N / (N - 1)$ the dispersive power, was independent of the material used. Fellmann presumes that this wrong result was caused by the fact that the dispersive power of Newton's crown glass had about the same value as the dispersion of water.[8] As a result, this combination of a water and a crown glass prism could not be made achromatic.

In the opinion of Whiteside the 'unfortunate, ambiguous phrase' in Newton's Opticks that:[9]

> 'the improvement of Telescopes of given length by Refractions is desperate', his eighteenth-century successors–no less than the majority of modern scholars–came to believe that Newton in the late 1660's turned to the construction of reflecting telescopes because he was convinced of the theoretical impossibility as well as the practical difficulty of constructing a colour-free refracting lens combination.

Newton had probably the same problems as Huygens, i.e. he thought that the compensation of spherical and chromatic aberration by using a combination of two lenses was possible from a theoretical point of view, but from a technical point of view too difficult to be made. In his monumental *The Correspondence of Isaac Newton* Turnbull also emphasizes this point in a footnote to a letter Newton wrote in 1671 to Oldenburg.[10]

5 Lorenz and Korteweg [77], 62–66.
6 Lorenz and Korteweg [77], 65.
7 Lorenz and Korteweg [77], 409, Huygens [67], p.460, lettre no. 1744, Christiaan Huygens à H. Oldenburg, 26 juin 1669.
8 Fellmann [43], 296–322, (301–302); Boegehold [13]), 7–40.
9 Whiteside [121], 442.
10 Turnbull [102], 92–107, (104).

The achromatic doublet lens is in a way modelled after the human eye, in which the image forming system also consists of two different substances. Fellmann mentions this in his introduction to *Leonardo Euleri, Opera Omnia, Commentationes Opticae*. Two lines of thought were possible. According to the first line of thought the eye was imperfect, as it shows chromatic aberration. A different view was hold by other authors, for instance the Oxford mathematician David Gregory (1659–1708). Gregory was convinced of the perfection of the Creation and he believed that as a consequence the eye should be perfect too.[11] According to Fellmann the very religious Euler was even obsessed by this idea.[12]

Chester Moor Hall, the inventor of the achromatic doublet, may have been working along this line. The experiments by Desaguliers, which were published in the *Philosophical Transactions* of 1727 could also have influenced Moor Hall. In his experiments Desaguliers repeated Newton's experiments with a combination of glass and a water prism to prove that Newton was right and an opponent, the Italian Count Rizzetti, wrong.[13] Chester Moor Hall is supposed to have worked out his ideas between 1729 and 1733, when his doublet was made. It did not raise much interest. A reason for this might be that though its chromatic aberration was perhaps well corrected it is very doubtful that the spherical aberration was corrected very well. An argument for this is the story that Chester Moor Hall had his two lenses made by different instrument makers. This makes it improbable that the lenses were corrected afterwards to improve the quality of the image.[14] After 1758, even Dollond had to correct his first lenses by zoning to bring the spherical aberration down to an acceptable level.[15].

(a) Leonhard Euler

(b) John Dollond

Figure 32: Euler and Dollond

In 1749 Euler published a treatise in which he showed that an achromatic objective could be realised.[16] Dollond did read this and by making use of Newton's

11 Browne [21]
12 Fellmann [44], 296–322, (303–304).
13 Boegehold [14], 81–114.
14 Boegehold [14], 81–114.
15 Kilz [71], 41–46.
16 Euler [41] (published in 1749), 274–296; Cherbuliez [24], 1–21.

relation ($\Delta N/(N-1)$= constant) he showed that Euler was wrong.[17] The letters Dollond published in the *Philosophical Transactions* were read by S. Klingenstierna (1698–1765), a Swedish mathematician and physicist, who had published a treatise on achromatic lenses in 1754. This was based upon Euler's treatise of 1749. Klingenstierna had his treatise translated into Latin and sent it to Dollond. This led Dollond in 1757 to repeat Newton's experiments, first with a glass and water prism, then with combinations of different kinds of glass. It appeared from these experiments with crown glass and with flint glass that the dispersion could be compensated when the angles of the prisms were to each other as 3:2. In 1758 Dollond made a combination of two lenses. A positive one of crown glass and a negative one of flint glass, their focal lengths being as 3:2, thus compensating the chromatic aberration. After completing the doublet lens the spherical aberration was diminished by polishing specific areas of the lens, a technique called zoning. This technique, applied to mirrors for reflecting telescopes, was described by the astronomers Molyneux (1689–1728) and Hadley (1682–1744) and published in 1738 by Robert Smith (168–1768) in his influential *A Complete System of Optics*.[18]

I discussed this point with Van Zuylen, who had some 40 years of practical experience in optics. He is of the opinion that zoning is a very difficult technique. It could be applied to special telescopes where the price did not matter very much. But he thinks it is doubtful whether Dollond could apply it to all the small telescopes he made in great quantities. Van Zuylen investigated a number of dated telescopes made by Van Deijl from Amsterdam, and he discovered that Van Deijl gradually changed his curvatures to better ones for which the correction of the spherical aberration was much improved.[19] It is very probable that Dollond also improved his lenses in this gradual way, but more research has to be done in this field before a definite opinion can be formed. The development of a special zoning tool by Dollond as described by Willach throwns now light on this process. [20]

4.3 THE THEORETICAL BACKGROUND

Dollond was very secretive about the invention and construction of doublets. Neither in his article in the Philosophical Transactions nor in his patent application he mentions curvatures or the theory of these lenses.[21]

However, this did not prevent Jan (ca. 1715–1801) and Harmanus (1738–1809) van Deijl to copy Dollond's objectives. In 1807 Harmanus wrote that he and his father saw such a telescope in the beginning of 1762. It arouse their interest and on 8 November 1762, after having studied the theory of these lenses, they sold their first achromatic telescope.[22]

According to Van Zuylen it is not very difficult to copy such an objective. The curvatures could be measured with a spherometer, the s.g. of the glass could be determined and the focal lengths of both the crown lens and the total objective

17 Dollond [37]
18 Smith [96], 309–312.
19 van Zuylen [116], 208–228, (220–222).
20 Willach [122]
21 Dollond [38], 733–743; Dollond [39]
22 Deijl [34], 133–151, (133–134).

could be measured.[23] With these data an experienced optical instrument maker could copy the original objective.

4.3.1 *Clairaut and D'Alembert*

The French mathematician A.C. Clairaut (1713–1765), who learned about all these developments, thought it useful to provide a thorough theoretical basis for the construction of these achromatic objectives. This would enable other 'artists', who did not have the same glass at their disposal as Dollond, to make them too.[24]

Jean le Rond D'Alembert (1717–1783) wrote his contributions a few years later. He worked on the lines set by Euler and Clairaut, but his designs are more complex.[25] Some examples of these designs are analysed in section 4.4.2 and section 4.4.3.

(a) Clairaut (b) Alembert

Figure 33: Clairaut and D'Alembert

4.3.2 *Herschel*

In his article about the achromatic lens, written in 1821, the astronomer J.F.W. Herschel (1792–1871) started criticizing his learned predecessors Euler, Clairaut, and D'Alembert. From their work nothing has resulted but a mass of complicated formulæ,

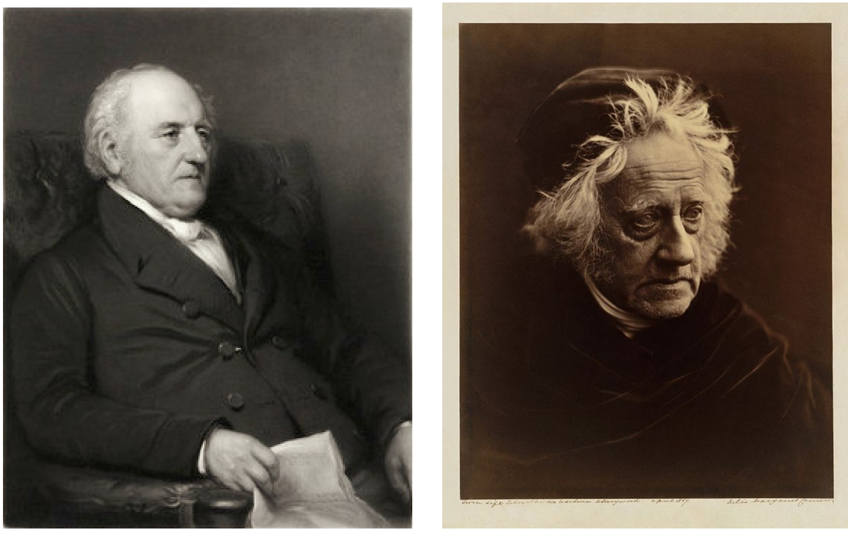
> which, though confessedly exact in theory, have never yet been made the basis of construction for a single good instrument, and remain therefore totally inapplicable, or at least not applied, in practice.[26]

23 Van Zuylen, in a private communication dated 11 September 1991.
24 Clairaut [25], 380–437, (387); Clairaut [26], 524–550; Clairaut [27], 578–631.
25 Alembert [1], 75–145; Alembert [2], 53–105; Alembert [3], 43–108.
26 Herschel [61], 222–267, (222).

Herschel is too severe in his criticism, though it is true that the articles of Euler, Clairaut, and D'Alembert are no easy reading because of the long formulæ–sometimes with a length of one page in quarto.

Euler's designs were adapted by Fuss.[27] D'Alembert relates that Mr. l'Estang made triplets after his own designs, which were intended for small telescopes.

Herschel analysed a number of specific combinations of two thin lenses. For these he gives the curvatures for different values of the ratio of the dispersions of crown and flint glass. Spherical and chromatic aberration are treated separately, which is of great practical value. The correction of chromatic aberration is relatively simple as it depends only of the focal lengths of the crown and the flint components. This ratio can be chosen such as to accommodate the available glass. The second step of the design is to choose the curvatures of the lenses in such a way as to obtain a minimum of spherical aberration.



(a) Barlow (b) Herschel

Figure 34: Barlow and Herschel

4.3.3 *Barlow*

In the opinion of Peter Barlow (1776–1862), a professor of mathematics at the Royal Military Academy in Woolwich, even Herschel's article was in Barlow's opinion 'highly scientific'. Barlow means that it was too difficult for practical opticians. The purpose of his own treatise, published in 1827, was:

- to describe a simple method of how to measure the refractive indices of glass and the ratio of the dispersions of two glasses. From these data the focal lengths of the two lenses could be determined
- to calculate the curvatures of the four surfaces of these two lenses, using simple formulæ and a table, in such a way that the spherical aberration was minimal. Using this table and some simple rules made it possible for 'practical opticians' to calculate their doublets.[28]

27 Fuss [52]

4.3.4 *Chromatic Aberration*

The lens systems analysed below were all calculated by their designers using thin-lens and third-order approximations. When applied to telescope objectives this is not problematic. The aperture of eighteenth-century telescopes was rather limited because it was difficult to obtain pieces of optical glass larger than three or four inch in diameter.[29] These designs can be applied to microscope objectives as well, by inverting them and scaling them to a suitable focal length. However, when applied to microscope objectives, which have a much higher aperture, all the residual aberrations become manifest.

The approach to chromatic aberration is relatively simple and can be easily worked out in detail.

The focal length of a thin lens is calculated as (see section 2.2.2):

$$f = \frac{N r_1 r_2}{(N-1)\left((r_2 - r_1) N - d(1-N)\right)} \tag{33}$$

This formula shows that the focal length will change when the refractive index changes. The refractive index for red light is slightly smaller than that for blue light. As a result the focal length of a positive lens is smaller for blue light than for red light. This is called chromatic under-correction. For a negative lens this is inverted.

A combination of a positive lens made of crown glass, which has a low refractive index and a low dispersion, and a negative lens of flint glass, which has a higher refractive index and a dispersion which can be twice as much as the dispersion of crown glass, can now result in an objective which shows much less chromatic aberration than an equivalent single lens would do. This was what Dollond did after he discovered that the dispersion of crown glass and flint glass differed considerably.

The condition of achromatism was calculated as follows. Using the thin-lens formula the focal lengths of the crown and the flint lenses were calculated as fc and ff. The dispersion could be measured as the difference between the refractive indices for violet and red light, $\Delta N = N_V - N_R$. This small quantity (≈0.008 to ≈0.02) could not be measured accurately, simply because violet and red are not precisely defined concepts. Only when Fraunhofer discovered fixed lines in the spectrum and how to use these as standard wavelengths for measuring the optical properties of glass a direct and accurate measurement could be performed. Usually the dispersive ratio was defined as $\Delta N/(N-1)$. Herschel called this quantity $\bar{\omega}$, while Barlow used a d. Much later in the nineteenth century Abbe inverted this quantity, this is called the *Abbe Number* V:

$$V = \frac{N_d - 1}{N_F - N_C}\,. \tag{34}$$

A simple calculation shows that a doublet is achromatic when:

$$\frac{f_{crownlens}}{f_{flintlens}} = -\frac{\bar{\omega}_{crownglass}}{\bar{\omega}_{flintglass}}\,. \tag{35}$$

28 Barlow [5], 231–267.
29 Kitchiner [73], 17, 26.

or expressed in Abbe numbers:

$$\frac{f_{crownlens}}{f_{flintlens}} = -\frac{V_{flintglass}}{V_{crownglass}} \,. \tag{36}$$

This is an equation we also find in Conrady's Applied Optics.[30]

For triplets, the focal length of the two crown lenses was calculated using the formula:

$$1/f_{crownlens} = 1/f_1 + 1/f_2 \,. \tag{37}$$

Then f was applied in formula 36 as $f_{crownlens}$.

Barlow describes in great detail how to determine this dispersive ratio in an experimental way. Once this was done for two specific batches of glass it could be used for all the objectives which were to be made out of this. It was done by making a test achromat, and changing its curvatures until the chromatic correction was acceptable. The focal lengths of the crown and the flint lens were then measured. After this the ratio $\bar{\omega}_{crownglass}$ / $\bar{\omega}_{flintglass}$ was automatically known.

The designs treated in the next pages were calculated using these simplifications. It was also presumed that the dispersion was equally divided over the interval red–blue. The refractive index for the'mean ray', somewhere in the yellow–orange region of the spectrum, was midway between that of the red and violet rays. Unfortunately this is not true. It can be true for one kind of glass if the wavelength of the 'mean ray' is properly defined, but then it will not be true for another kind of glass. As a result, when analysed with OPDESIGN, most of these combinations will show under- or over-correction. This is caused by the thickness of the lenses, their distances, and some higher order aberrations.

4.3.5 *Spherical aberration*

After having determined the focal lengths of the crown and the flint lenses in such a way that the pair would be achromatic the spherical aberration could be calculated. Very complicated formulæ, of about the length of one printed page in quarto, were derived. They could only be used for specific combinations of lenses.

When applied properly they gave the curvatures of the lenses which resulted in a minimum of spherical aberration. I will not treat this subject in more detail as it is extremely complicated and technical.

Moreover, there is no evidence to show that the practitioners of the late eighteenth and early nineteenth century ever used these formulæ to design their lenses.

30 Conradi [29], 149.

4.4 ANALYSIS OF SOME DESIGNS

The question of why instrument makers did not immediately start constructing achromatic objectives after the designs of Euler, Clairaut or D'Alembert becomes obvious when these designs are studied more closely:

- Though the curvatures are given, none of them gives the dimensions of the lenses or their distances. As a result an infinite number of objectives is still possible.
- The optical parameters of the glass were not reproducible to a sufficient accuracy. From batch to batch there were differences in refractive index and dispersion. A precise value of the refractive index or the dispersion could not be determined as it was impossible to determine the wavelength accurately. Generally the designs of achromatic lenses were calculated for a specific value for the refractive indices of crown and flint glass. It is not always easy to adapt them to glass with a different refractive index. The resulting amount of chromatic aberration is very sensitive to slight changes in refractive index and dispersion.
- The third problem is formed by the curvatures of the surfaces. So not much had changed since Huygens's time, in which it was not possible to grind and polish lenses exactly to a specified curvature.

To be able to compare some designs of triplet lenses with each other their focal lengths have been scaled to 10mm. The triplets are calculated for a numerical aperture of 0.133. Their thickness is chosen as low as possible, only Fuss/Euler specify a size, all others have been dimensioned accordingly. The thickness which results from this is in general too small to be practical; when a more realistic thickness is chosen the dispersion of the flint has to be increased to correct the resulting chromatic under-correction.

An important question is whether it was worth all the cost and trouble to make such a triplet. To judge this they are compared with a single plano-convex lens, also of 10mm focal length. For this lens the numerical aperture for which its spherical aberration equals twice its Rayleigh Tolerance is 0.133, using a body tube of 160mm. The refractive index is 1.53, the radius 5.3mm and its thickness is 1.8mm.

4.4.1 *Euler*

The triplet analysed here is described by Fuss in his *Instruction Détaillée* of 1774.[31] The microscope mentioned on page 77 of that book has a triplet objective. The two biconvex crown lenses have a refractive index of 1.53 and the biconcave flint lens is made of a special flint glass with a refractive index of 1.60. The ratio of the dispersive powers of the glasses is as 178:309 (Fuss assumes a refractive index of 1.58 for normal flint glass and a ratio of 2:3 for the dispersive powers). Assuming a dispersion for the crown glass of 0.01, the flint glass would need one of ca. 0.02 to achromatize the objective. However, this is not a very realistic value for eighteenth-century glass. The refractive index for a short wavelength is calculated

31 Fuss [52], (77).

assuming that the dispersion is equally divided over the intervals red–mean and mean–violet, an assumption which was generally used until Fraunhofer proved it to be wrong.

The chromatic aberration of this triplet is not well corrected (see table 57). Checking Fuss's numerical values shows that the ratio of the focal lengths of the combined positive lenses to the negative lens is 0.707, while the ratio of the dispersive powers is given as 0.576.

Starting from Fuss's original objective, a second one was designed using a different dispersion for the flint lens. A value of 0.01615 resulted in an acceptable value of the chromatic aberration, the ratio of the dispersive powers is also closer to that of the focal lengths. The resulting dispersion of the flint lens has also a more realistic value.

The meridional rays show a very symmetrical pattern, which results from the small OSC′, there is not much coma. The correction for sagittal rays over the field is much better than was expected as Euler, whose formulæ were used by Fuss when he designed this triplet, only took axial rays into account. The formulæ for meridional and sagittal rays became so lengthy that Euler thought it impossible and not worth while to derive them.[32] Further research of these designs could be of interest, but it would be outside the scope of this thesis.

Table 53: System data of a triplet by Fuss/Euler (scaled to a focal length of 10mm):

srf	radius	distance	N	ΔN Fuss	ΔN Deiman
1	5.434	0.495	1.53	0.01	0.01
2	-5.434	0.021	1	0	0
3	-4.947	0.142	1.60	0.01965	0.01615
4	4.947	0.018	1	0	0
5	5.182	0.353	1.53	0.01	0.01
6	-11.63				

4.4.2 *Clairaut*

In his three articles in the *Mémoires de Mathématique & de Physique de l'Académie Royale des Sciences* Clairaut gives a number of examples of triplet lenses. The two I analysed here are taken from the third *Mémoire*. They were intended for small refracting telescopes, like opera glasses.

Compared with their focal length their aperture is generally considerable. This made it advantageous to use a triplet, as its curvatures can be made smaller than for a similar doublet.[33] Five surfaces of the first triplet analysed here have the same radius, the sixth and last surface is plane.[34]

32 Herzberger [63], 7–13, (7).
33 Clairaut [27], 624.
34 Clairaut [27], 627–628.

Table 54: Triplet by Clairaut, 1

srf	radius	distance	N	ΔN
1	4.547	0.546	1.55	0.0116
2	-4.547	0.136	1.6	0.0174
3	4.547	0.364	1.55	0.0116
4	∞		1	0

Table 55: Triplet by Clairaut, 2

srf	radius	distance	N	ΔN
1	+7.895	0.45	1.55	0.0116
2	-4.832	0.04	1	0
3	-4.5	0.15	1.6	0.0174
4	+4.5	0.04	1	0
5	+4.832	0.45	1.55	0.0116
6	-7.895		1	0

The second triplet is symmetrical.[35] Both triplets were adopted as microscope objectives by reversing them, after which the front of the telescope objective corresponds to the back of the microscope objective.

In the first triplet the convex crown glass lenses have a refractive index of 1.55. The dispersion is 0.0116, equally divided round the mean value. The ratio between the focal lengths of the positive and the negative components is 0.727. It follows from this that the dispersion of the flint should be 0.0174. The triplet was still rather under-corrected for this value.

In the second triplet the ratio between the focal lengths of the positive and the negative components is 0.727 too. From this follows, as in the previous case, a dispersion of the flint of 0.0174. The triplet was also under-corrected.

In respect to the correction for meridional rays these two doublets are much worse than was expected, and their OSC′ is also too large. The correction of sagittal rays over the field is good.

4.4.3 *D'Alembert*

The triplet by D'Alembert distinguishes itself from other designs from this period by the use of surfaces of equal curvature.[36] The refractive indices of his glass are 1.55 and 1.6, the same values as used before by Clairaut. The dispersion of common crown glass for a refractive index of 1.55 will be ca. 0.0116. The ratio of the focal lengths of the crown and the flint components is also 0.727, the dispersion of the flint which follows is again 0.0174. For these values the triplet was slightly under-corrected. The refractive index for a short wavelength is calculated in the usual way. D'Alembert gives no dimensions of the lenses, only their curvatures. The dimensions are chosen in such a way that the numerical aperture can be

35 Clairaut [27], 631.
36 Alembert [3], 75–145, (101).

given a value of at least 0.133, to be able to compare it with the plano-convex lens. For this triplet the meridional rays show a very unsymmetrical pattern, indicating coma and a too large OSC′.

Table 56: triplet by D'Alembert

srf	radius	distance	N	ΔN
1	5.924	0.693	1.55	0.0116
2	-3.221	0.148	1.6	0.0174
3	7.212	0.396	1.55	0.0116
4	-17.93		1	0

Table 57: eighteenth-century designs of achromatic objectives):

	PlaCx	Euler,1	Euler,2	Clairaut,1	Clairaut,2	Alembert
ef	10	10	10	10	10	10
efl	10.057	9.935	10.004	10.024	10.024	10.021
efs	9.869	10.066	9.996	10.011	10.011	10.014
efs-efl	-0.187	+0.13	-0.009	-0.013	-0.013	-0.008
msA	-0.032	0.017	0.017	-0.01	0.0078	-0.0041
NA	0.133	0.133	0.133	0.133	0.133	0.133
OSC′	-0.0043	-0.0021	-0.0021	-0.0052	0.011	-0.0028
OT	0.016	0.016	0.016	0.016	0.016	0.016
Petz	0.0654	0.0725	0.0725	0.0692	0.0701	0.0706
zoC	-0.204	0.155	-0.0002	-0.012	-0.0063	0.0026
th/ef	0.18	0.1	0.1	0.1	0.11	0.12

4.4.4 *Herschel*

The doublet analysed here is given by Herschel in 1821 in table 4 of his article.[37] I choose the one with a very low dispersive ratio of 0.5, the internal curvatures are very strong for those with a higher ratio. Using crown glass with a dispersion of 0.0095 the flint glass must have a dispersion of 0.02121 to fulfill the condition of formula 35. For these values the doublet appears to be well corrected. The correction of meridional rays is symmetrical, coma and OSC′ are small. The aberrations of the sagittal rays are constant over the field as well.

Table 58: triplet by Herschel

srf	radius	distance	N	ΔN
1	6.6655	0.7902	1.524	0.0095
2	-4.23	0.0395	1	0
3	-4.1064	0.6914	1.585	0.02121
4	-14.193			

37 Herschel [61], 222–267, (261).

4.4.5 *Barlow*

The objective analysed here is computed by Barlow as a telescope objective of 80 inch focal length.[38] The formulæ used by him result in a doublet which can be used with low apertures (<0.05), but when used as a microscope objective with a numerical aperture of 0.133 its defects show clearly. The OSC′ is too large, resulting in a large amount of coma.

The data of the doublet are given after scaling to 10mm. The aberrations are calculated for a tube length of 160mm and a tangent of the field angle of −0.05. The dispersion of the crown glass, which has a refractive index of 1.515, is 0.0088. Barlow gives a ratio of 0.66 for the two dispersive powers. This results in a dispersion for the flint of 0.0155. Using this value the chromatic aberration is too large. A better correction is obtained using a dispersion of 0.0161, the ratio of the dispersive powers is then 0.637.

Table 59: doublet by Barlow

srf	radius	distance	N	ΔN
1	3.734	0.646	1.515	0.0088
2	-3.515	0.0123	1	0
3	-3.513	0.258	1.6	0.0161
4	35.135			

Table 60: doublets by Herschel and Barlow

	Herschel	Barlow
ef	10	10
efl	10.004	10.015
efs	9.996	9.994
efs-efl	-0.009	-0.021
msA	-0.0048	-0.017
OSC′	0.00126	-0.02
OT	0.016	0.016
Petz	0.0690	0.0703
zoC	0.0004	-0.02
th/ef	0.5	0.09

38 Barlow [5], 231–267, (249–251).

4.5 MICROSCOPE OBJECTIVES

All the achromatic objectives analysed in the preceding paragraphs were 'designs'. They show what could have been made in the last quarter of the eighteenth century if an instrument maker had taken the trouble to execute them.

Besides, apart from the triplet by Euler/Fuss, they were designed for telescopes and adapted by me to the microscope by reversing and scaling.

Benjamin Martin might have made triplets for his microscopes. He drew one in 1771 in the description of the 'Polydynamic Microscope'; and the 'Opake Solar Microscope' of 1774 was provided with a triplet lens too.[39] The triplet from the 'Polydynamic Microscope' looks like the usual telescope objective with two biconvex crown lenses and a biconcave flint lens in between. The triplet of the 'Opake Solar Microscope' is drawn large enough to see that it resembles the one described in Clairaut's first example, with a plane front. This triplet is, however, combined with a simple biconvex lens so that the quality of the image is doubtful. I have never seen one of these microscopes and in my opinion it remains questionable whether they were ever made.

4.5.1 *Beeldsnyder*

In the collection of the Utrecht University Museum is a triplet lens (inventory number UM298) which was found in a junk box by Pieter Harting (1812–1885), the professor of Zoology in Utrecht. In this box Harting found a Martin-type solar microscope too, which was signed and dated 'François Beeldsnyder à Amsterdam 1791'. From this Harting inferred that Beeldsnyder made the triplet too.[40] Neither Harting nor Van Cittert have investigated this triplet very carefully. They both state that it has two biconvex crown lenses and a biconcave flint lens in between. A superficial observation already shows that one of the biconvex lenses is blue/greenish, which is normal for crown glass from that period. But the other biconvex lens is as white and shiny as flint glass can be. Measurements confirmed my suspicions: the biconcave lens and one of the biconvex lenses are both made of flint glass.

Used on a microscope the magnification was 29.5 diameters with a body of 190mm and a $\times 5$ Huygens eyepiece. The measured numerical aperture was 0.087, the smallest resolvable detail ca. 4μm and the measured resolving power 5μm. The objective was very astigmatic and its contrast was bad. The polishing of the lenses was not well executed, the surfaces of the lenses showed lots of little pits and scratches.

From this we can conclude that the 'first achromatic objective' of 1791 is a myth.[41] It is obvious from the large difference in focal length efs–efl that this objective certainly does not deserve the title 'achromatic'; it was probably made by an unknown amateur at the beginning of the nineteenth century.

39 Martin [80]; Martin [81]
40 Harting [59], 132; van Cittert [111], 63.
41 Deiman [35], 577–581.

Table 61: Beeldsnyder triplet UM298

srf	radius	distance	N	ΔN	measured	f
1	25.31	1.38	1.513	0.0087	lens 1	24.92
2	-25.41	0.017	1	0	lens 3	22.15
3	-23.85	0.85	1.582	0.014		
4	23.97	0.017	1	0	total	26.309
5	25.56	1.6	1.583	0.014		
6	-25.47		1	0		

Table 62: optical parameters of UM298

ef	27.26
efl	27.39
efs	26.95
efs-efl	-0.44
mSA	-0.040
OT	0.025
NA	0.087
OSC′	0.0036
Petz(10mm)	0.068
th/ef	0.14

4.5.2 *Van Deijl*

The first instrument maker who made achromatic objectives for microscopes on a commercial scale was Harmanus van Deijl (1738–1809) from Amsterdam. In 1807 he published a description of his microscope and its optical system.[42] A small number of these instruments survive, in Utrecht there are two of them (inventory numbers UM25 and UM26). The four doublet objectives in Utrecht were examined by Van Zuylen.[43] One is in Teyler's Museum.[44] There are two in the Museum Boerhaave in Leyden, which were investigated in 1940 by Rooseboom.[45] A third one was acquired by the Boerhaave around 2000. The last one known to Turner is in the Billings Microscope Collection. This one was acquired in 1966 as a part of the collection of the Dutch collector Dr. A.J.W. Kaas. Of its lenses no detailed information is available.[46]

4.5.3 *Marzoli*

Some very early achromats were made by the Italian Bernardino Marzoli. The one in the collection of the Royal Microscopical Society is regrettably lost since 1965. It is described as a cemented doublet, having the plane side of the flint glass lens

42 Deijl [34], 133–151.
43 van Zuylen [116], 208–228, (222–228).
44 Turner [104], 301–302.
45 Rooseboom [93], 301–302.
46 Purtle [88], 191–192.

towards the object.[47] A microscope by Marzoli dated 1811 is in the *Museo di Storia della Scienza in Florence* (inventory number 3430).[48] I have not investigated this microscope; data on the one remaining objective, a cemented doublet, are not available.

4.6 conclusions

When simulated on a computer the designs of triplets by Euler, Clairaut, D'Alembert and the doublet by Herschel can be made to look quite good. The amount of experimental effort required by a 'practical optician' to execute them would however be considerable.

In the eighteenth century and well into the nineteenth century it was very difficult, if not impossible, to grind and polish lenses accurately to a given curvature. In 1827 Goring wrote that it was not even possible to make two curvatures the same, as the tools changed during the process. From this point of view Clairaut's first design in which all four surfaces have the same curvature is a very favourable one. This allows checking all surfaces against each other.

In general it will have meant that such a triplet, made for a microscope, would be very expensive and it certainly would have larger aberrations than the computer simulations predict. Compared with a single lens the chromatic aberration of a triplet could be made smaller, allowing a larger aperture.

A serious problem is caused by the great number of glass to air surfaces–in uncemented triplets there are six–causing internal reflections and loss of contrast.

Generally, users of the microscope would not have considered the much higher price worth the small increase in resolving power. The importance of the doublet and the triplet is that they shifted the attention of the instrument makers from the eyepiece to the objective.

Instrument makers could increase their skill in executing these complicated designs, preparing them for the real difficulties they would encounter when they had to make compound objectives of doublets and triplets from 1837/1839 onwards.

47 Turner [107], 309.
48 Turner [108], 50.

5

JOSEPH JACKSON LISTER

5.1 INTRODUCTION

As I discussed in §4.5 there had been attempts in the beginning of the nineteenth century to improve the objective of the microscope. This resulted in the doublet lenses of Van Deijl and Marzoli. However, though Van Deijl published his discoveries and apparently sold a number of his achromatic microscopes, these attempts were too isolated to have much influence. Besides, the social and political climate on the Continent was unfavourable, the Napoleonic wars were rather disturbing and people had other concerns.

In the 1820s a more peaceful period started and in London an amateur, both as an optical designer and as a microscopist, picked up the thread again. The importance of this Joseph Jackson Lister (1786–1869) was that he was able to combine theoretical knowledge with practical experience. After a period of ten years of experiments this resulted in the first series of commercially available achromatic compound objectives which were more than only a combination of doublet lenses.

Lister was born in 1786 in London as the third child and only son of John Lister and Mary Jackson, both Quakers. At the age of six Joseph Jackson went to a Quaker school at Hitchin, which he left at the age of eleven. After that he went to Rochester School for a year and then spent two years at Thomas Thompson's school at Compton, which he left at the age of fourteen to join his father, who was a wine-merchant. In 1818 Joseph Jackson married Isabella Harris, a school teacher. They lived above the wine business at 5 Tokenhouse Yard until 1822, when they moved to Stoke Newington. Shortly afterwards they moved to Upton House in West Ham, a considerable property in a still rural area of London.

About 1822 his nephew Richard Beck became a partner in the wine business. This allowed Lister enough spare time to devote himself to microscopical research and to improve the microscope, which in that time was still a rather crude instrument.

Lister started improving the triplet lenses made by W. Tulley (1789–1835) on the instigation of C.R. Goring. In 1826 he acquired a 'microscope selon Euler', made by Vincent Chevalier (1770–1841) from Paris. The achromatic lenses of Chevalier's microscope were assembled of one or two cemented doublet lenses, unlike those by Tulley who used uncemented triplets. Studying this instrument Lister became aware of the importance of the aperture of the lenses, which he found in Chevalier's microscope to be smaller than the lenses could bear. It also showed him that an achromatic object glass could be assembled from a series of doublet lenses, which were after all much easier to make than Tulley's triplets. In 1829 Lister could borrow from the botanist Robert Brown (1773–1858) another doublet microscope, made by Fraunhofer (1786–1826) from Munich.

Fraunhofer's doublets were uncemented, so Lister could analyse them in great detail.

These studies led him to the principle of the aplanatic foci of the doublet lens, which he published in the Philosophical Transactions for 1830. Lister ends his article with the following remarks:1

> ... it would give me pleasure to see that principle demonstrated, if it deserve it, by some abler hand than mine, and treated in a more rigorous manner than my own limited acquaintance with mathematical science qualifies me to undertake.

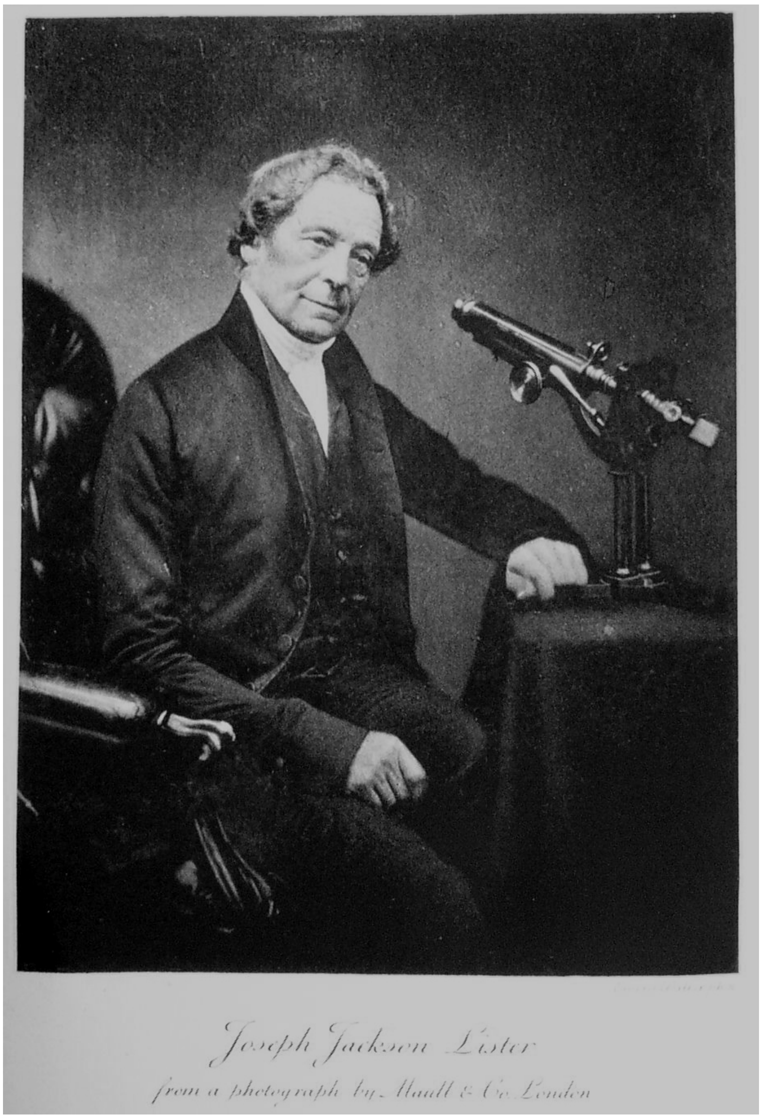


Figure 35: J.J. Lister

At the end of 1830 Lister started a new series of experiments. His first notes are dated November 1830 and the last ones are dated February 1831. These experiments led him to the construction of an objective consisting of a front doublet, a middle triplet and a back doublet. The article Lister wrote about these experiments was never published, however. He left the subject in the hope that others would start constructing object glasses along the guide-lines he had given.

This did not happen, and in 1837 Lister gave Andrew Ross the construction details for a series of lenses. Ross started making and improving them. In 1839 James Smith received the data enabling him to construct a 1/4 in. objective.

In the following decade Lister's activity gradually decreased, his last drawing of an objective for a microscope is dated 1851. One reason for this is given by Fischer as being the death of his oldest son John in 1846, which he took very hard.1

5.2 improvement of goring's and tulley's triplets, 1825–1829

Lister became involved with the improvement of the microscope after seeing the triplet lenses made by Tulley at Dr. Goring's request in 1825. Lister writes about these early designs:[1]

> The 4/10 and 2/10 achromatic Object Glasses made by W. Tulley at Dr. Goring's suggestion delighted me by their beautiful performance but they appeared to me to have a great disadvantage in consequence of the thickness in proportion to their focal length which W. Tulley thought could not be avoided. I therefore induced him to make for me one of 9/10 much thinner in proportion & had the satisfaction to find its performance very nearly equal to his best 2/10.

Goring, the designer, writes about the thickness of these lenses:[2]

> ... is thicker than is desirable, (which causes it to exhibit round bodies somewhat oval towards the edges of its field, at least when charged with a low power).

The vast thickness of the material is considered by Goring to be a very serious evil, but he considers it absolutely necessary in order to 'obtain a spherical figure in the curves with any sort of precision'. This indicates that the lenses were not well supported during the process of grinding or/and polishing. As a result they bent, from which an incorrect figure could easily result.

The earliest triplet design by Lister, the 9/10in. for Tulley, shows a striking resemblance with the triplet in Fuss/Euler. Both have an equally biconvex back lens, an equally concave flint lens and a biconvex front lens of which the curvature of the back is to that of the front as about 1:2.

The values in table 63 have been calculated for a body tube of 160mm and a tangent of the field angle of -0.05.

Comparing the different values of the ratio thickness/focal length (th/ef) in table 63 shows that Lister indeed made the triplets much thinner and smaller. Tulley's original 4/10in. objectives have a ratio of thickness/focal length of about 0.7 and Lister's designs have one of 0.4. The earlier designs by Fuss/Euler, Clairaut and D'Alembert were calculated by me with a ratio of about 0.1. In the following sub-paragraphs a number of designs and surviving examples will be examined more closely.

1 Lister Archive, folio L60 (see chapter 11).
2 Goring [55], 265–284, (274).

Table 63: triplet lenses

	4/10in. Tulley	9/10in. Lister	0.933in. Goring	0.3in. Lister
ef	10	10	10	10
efl	10.027	10.010	10.012	10.010
efs	9.973	9.990	9.987	9.990
efs-efl	-0.053	-0.020	-0.025	-0.020
msA	-0.016	-0.017	-0.007	-0.026
OSC′	-0.0032	-0.00006	-0.00027	0.00082
Petz	0.0776	0.0748	0.075	0.0749
OT	0.016	0.016	0.016	0.016
th/ef	0.72	0.39	0.411	0.412
zoC	-0.062	-0.017	-0.025	-0.01671

5.2.1 *Tulley's original 4/10in. object glass*

The data of this triplet were found in a drawing by Lister where it is called 'JJL's object glass'.[3] Though it suggests that this is one of Lister's designs, it is not the case. When we compare the ratio of its thickness to its focal length, which is about twice as large as for the other triplets, it is obvious that this must be a drawing of the triplet made by Tulley on the suggestion of Dr. Goring.

Table 64: Tulley's original 4/10in. triplet (measures in mm)

srf	radius	dst	N	ΔN
1	5.74	2.78	1.53	0.01
2	-6.78	0.52	1	0
3	-4.7	0.43	1.6	0.0164
4	4.7	0.07	1	0
5	4.83	2.97	1.53	0.01
6	-5.84		1	0

The ratio of the focal lengths of the crown and the flint components is calculated by Lister as 60:100. This appeared to be a serious mistake as Lister used a refractive index of 1.5 for the crown and flint lenses.

This mistake he repeated in all his designs of this period. I calculated the triplet using a refractive index of 1.53 for crown glass and 1.6 for flint glass, values which are given by Lister in a later design.[4] When the values of 1.53 and 1.6 are applied to this triplet, the ratio between the focal lengths is 0.688. The dispersion of flint glass is calculated using this value. The focal length will be 0.34in., when calculated for thin lenses. When the thickness of the lenses is taken into account a value of 9.35mm (0.37in.) is found. Lister gives a value of 0.36in., which must have been the focal length of the triplet which he measured. Applying the values of the refractive indices and the dispersion given above the triplet shows chromatic

3 Lister Archive, folio L60b, drawing 1, (see chapter 11)
4 Lister Archive, folio L62, drawing 1, (see chapter 11)

under-correction. In his drawing Lister allows a pencil of rays with an angle of 31° to enter the triplet. At the back there is a stop with a diameter of 0.2in. resulting in a numerical aperture of 0.26. When calculated, the spherical under-correction amounts to eight times its optical tolerance. Stopped down to a NA of 0.17, the spherical aberration equals twice its optical tolerance. This is acceptable. Even then the OSC′ is about twice as high as Conrady considers acceptable. It is good to realise that the sine theorem was unknown in Lister's time. This made it extremely difficult to design objectives free from coma .

5.2.2 *Lister's 9/10in. triplet*

J.J. Lister, a friend of Goring, later asked Tulley to construct a triplet of longer focus. According to Goring this resulted in a triplet with a focal length of 0.933 [sic!] inch. Lister thought that such a triplet might be easier and more accurate to make so that it would be just as good as those of shorter focus. Lister's drawing of this triplet is dated 2 March 1826, its focal length is 9/10in.[5]

Table 65: Lister's 9/10in. triplet (measures in mm)

srf	radius	dst	N	ΔN
1	14.48	3.8	1.53	0.01
2	-14.48	0.13	1	0
3	-13.21	1.28	1.6	0.017
4	13.21	0.16	1	0
5	13.97	3.8	1.53	0.01
6	-21.34		1	0

For this triplet Lister gives a ratio of 'concave to convexes as 100 to 59'. As in the previous objective a refractive index of 1.5 is used to calculate the focal lengths. When the refractive indices which are given as 1.53 and 1.6 are used, the ratio is 0.668.

Assuming a value of 0.01 for the dispersion of the crown glass, the dispersion of the flint glass has to be 0.01694. Using this value the triplet was chromatically under-corrected. The focal length is 23.3mm (0.92in.). The pencil of rays which enters the front lens in the drawing has an angle of 25°, from which results a NA of 0.216. When used with this NA the spherical under-correction equals 10 times its optical tolerance, which is excessive. Stopped down to a NA of 0.12 the spherical aberration equals about twice its optical tolerance, which is a reasonable value.

5.2.3 *Lister's 9/10in. triplet, Goring's version*

In the article about these triplets which Goring published in 1827 the data of Lister's 9/10in. triplet differ slightly from the ones given by Lister himself. Goring calls it a 0.933 inch triplet.[6]

5 Lister Archive, folio L62, drawing 1, (see chapter 11)
6 Goring [55], 265–284, (276–277).

Table 66: Lister's 9/10in. triplet, after Goring (measures in mm)

srf	radius	dst	N	ΔN
1	14.60	4.44	1.53	0.01
2	-14.60	0.22	1	0
3	-12.70	1.41	1.6	0.016
4	12.70	0.10	1	0
5	13.33	3.81	1.53	0.01
6	-20.95		1	0

Though Goring specfies the glass of the lenses by its specific gravity, this did not result in consistent values for the refractive indices. For this reason the same refractive indices were used as in the previous triplet, 1.53 and 1.6.

The ratio between the focal lengths of the crown and the flint components for these values is 0.687, which results in a dispersion of the flint glass of 0.01649. A focal length of 24.3mm (0.972in.) was calculated using these data. Goring gives a clear aperture of 0.5in., which equals a NA of 0.23. The over-correction for this NA is excessive. When stopped down to a NA of 0.182 the marginal and the axial rays come to the same focus. The remaining zonal spherical aberration is 1.5 times its optical tolerance according to Zernike. The OPD between the marginal and the axial rays is 1.6μm, while 1.08μm is allowed according to Zernike .

5.2.4 *Lister's 0.3in. triplet*

This triplet of Lister's design had a focal length of 0.3in. In his own words:[7]

> Taking therefore the same curves for the concave the construction Fig.2 has been suggested, by which a focal distance of 0.3 In. will be obtained instead of 0.36 and though the diameter is much smaller an equal pencil will be admitted, while it is presumed that as the total of both aberrations produced and corrected will be considerably less, the incorrigible portion of each will be reduced in proportion, so as to allow magnifying power to be carried much farther. Tried many experiments to ascertain the best means of correcting small errors in aberration.

Table 67: Lister's 3/10in. triplet (measures in mm)

srf	radius	dst	N	ΔN
1	5.33	1.36	1.53	0.01
2	-5.08	0.075	1	0
3	-4.70	0.4	1.6	0.017
4	4.70	0.045	1	0
5	4.83	1.4	1.53	0.01
6	-7.11		1	0

7 Lister Archive, folio L60, (see chapter 11)

For this triplet the same refractive indices of 1.53 and 1.6 were used. The ratio of the focal lengths of the crown to the flint components being 0.658, the flint was given a dispersion of 0.0172. This resulted in chromatic under-correction. In the drawing of this triplet Lister gives the entering pencil of rays an aperture angle of 31°. This corresponds with a NA of 0.267. For this NA the spherical aberration equals twelve times its optical tolerance. After stopping down the objective to a NA of 0.164 the spherical aberration equals two times the optical tolerance. This is acceptable.

5.3 MEASUREMENTS OF SURVIVING EXAMPLES

Of the 9/10in. triplet three examples were found. One of these was on a microscope made by Tulley and signed 'Tulley & Sons / Islington London', Science Museum inventory number 1938-686. This triplet forms the back part of a compound objective. A second one was found on the microscope made by James Smith for Lister in 1826, Wellcome Collection inventory number A54204, which was described by Bracegirdle.[8] The third one formed the back part of a compound objective in the collection of the Royal Microscopical Society in Oxford, Turner cat. no. 382.44 (Lister Legacy).[9] A detailed investigation of these lenses can be found below.

In table 68 the triplets are calculated for a NA=0.133 and the tangent of the field angle of −0.05.

Table 68: overview of measured triplet lenses

	1938-686	A54204	382/44/bk
ef	10	10	10
efl	10.024	10.022	10.012
efs	9.953	9.956	9.984
efs-efl	-0.071	-0.067	-0.028
msA	0.015	0.011	-0.0026
OSC′	0.0024	-0.00038	0.0021
Petz	0.073	0.0734	0.0750
OT	0.0136	0.013	0.016
th/ef	0.315	0.435	0.34
zoC	-0.074	-0.07	-0.026

5.3.1 *Tulley (Science Museum, 1938-686)*

The focal length of this triplet was 23.66mm. Measured with a body tube of 250mm the magnification was 9.7×. The NA was 0.152 and the resolving power was 2.75μm. There was axial coma, caused by bad centering of the lenses which were fitted loosely in their mount. The spherical correction seemed to be good, though this is difficult to judge when coma is present. The front triplet of the

8 Bracegirdle [16], 273–297, (274–277).
9 Bracegirdle [16], 273–297, (297), no. 44.

compound objective could not be taken apart and analysed, its focal length was 15.11mm.

Table 69: Tulley, triplet (Science Museum, 1938-686)

srf	radius	dst	N	ΔN
1	14.57	3.595	1.525	0.0096
2	-14.43	0.13	1	0
3	-12.36	0.42	1.58	0.0139
4	12.25	0.11	1	0
5	13.44	3.251	1.525	0.0096
6	-20.23		1	0

The compound objective of two triplets had a focal length of 10.07mm, the magnification was 24× and the NA was 0.186. The resolving power was again 2.75μm. The spherical correction was good but coma was still present strongly.

5.3.2 *Smith (Wellcome Collection A54204)*

Table 70: Smith, triplet (A54204)

srf	radius	dst	N	ΔN
1	13.44	4.115	1.53	0.01
2	-19.29	0.42	1	0
3	-12.66	0.683	1.59	0.0147
4	12.70	0.2	1	0
5	15.36	4.175	1.515	0.0088
6	-14.13		1	0

The data of this triplet show that the lenses have been shifted, the front and the back lenses have been changed. The objective was measured and calculated as it was found. The focal length was 22.78mm, with a body tube of 200mm the magnification was 7.7× and the NA was 0.17. The resolving power was 4.75μm. There was not much spherical correction but there was a lot of coma, possibly caused by bad centering of the lenses in their mount. The computer simulation gives a focal length of 23.2mm for the above data, a NA of 0.16, and a spherical over-correction of about twice its optical tolerance.

5.3.3 *Lister Lenses no. 44, back triplet*

Like Tulley's triplet (section 5.3.1) this one forms the back component of a compound objective. The measured focal length was 25.2mm. The calculated NA of this triplet with its diaphragm is 0.14 for a tube length of 160mm. There is a small amount of spherical over-correction for the marginal rays, and the zonal rays are slightly under-corrected, but the amount of this is below its optical tolerances. When stopped down to NA=0.137 the focus for the zonal and the marginal rays coincides. The OPD between the marginal and the axial rays is 0.55μm, which

Table 71: Lister lenses, no.44

srf	radius	dst	N	ΔN
1	14.96	3.83	1.515	0.0088
2	-13.60	0.14	1	0
3	-12.26	0.483	1.59	0.0147
4	12.3	0.14	1	0
5	13.37	3.59	1.52	0.0092
6	-20.65		1	0

is below the 1.08μm given by Zernike as the maximum allowable value in this situation. An analysis of the complete objective is given in section 5.4.3.

5.4 COMBINATIONS OF TRIPLET LENSES, COMPOUND OBJECTIVES

The last stage in this series of experiments was the combination from two triplets to a compound objective. The back triplet in this combination is the usual 9/10in. The drawings in the Lister Archive show a number of trials for front triplets. Of these two are of interest. One as it is the forerunner of the triplet fronts which were widely used in English objectives until they were superseded by the single hemispherical front lens. The other as it closely resembles the front triplet in an objective in the collection of the Royal Microscopical Society (Turner [107], cat. no. 382.44), of which the back triplet was analysed in section 5.3.3. The objective was calculated for a body tube of 160mm and a tangent of the field angle of -0.05.

Table 72: Lister's first compound objectives

	L64/1	L64/2	382/44
ef	10	10	10
efl	10.027	10.025	10.013
efs	9.973	9.979	9.979
efs-efl	-0.053	-0.047	-0.034
msA	-0.019	-0.017	-0.0156
NA	0.23	0.25	0.283
OSC′	0.00057	0.00008	0.0071
Petz	0.0814	0.1038	0.0873
OT	0.0095	0.0087	0.0078
zoC	-0.0318	-0.024	-0.026

5.4.1 *Lister Archive folio L64, objective drawing 1*

Table 73: Lister lenses, folio L62, dwg.1

srf	radius	dst	N	ΔN
1	14.48	3.8	1.53	0.01
2	-14.48	0.13	1	0
3	-13.21	1.28	1.6	0.017
4	13.21	0.16	1	0
5	13.97	3.8	1.53	0.01
6	-21.34	1.8	1	0
7	6.86	3.12	1.53	0.01
8	-27.94	0.08	1	0
9	-25.4	1	1.6	0.016
10	5.08	3.12	1.53	0.01
11	∞		1	0

The first combination of two triplets is dated 6 December 1827. The back triplet is the 9/10in. analysed above. The front triplet has a focal length of 16mm. Lister writes about this combination:[10]

> This projection for the small Object-Glass to go in front of the 9/10 is on the principle that the ray should form nearly the same angles on the different surfaces as in the 9/10th.- It is made thicker than requisite for the purpose of comparison with a triple 6/10 lately made. The effect of this combination will it is hoped be very fine as it will admit a pencil of rays of nearly 50° performing [unreadable] the image which will be subjected to only the same angles of refraction as in the 9/10th which admits but 23° of the pencil.

The dispersion of the front triplet was calculated in the usual way, using a ratio of the focal lengths of the crown and the flint component of 0.707. This resulted in a dispersion of 0.016, compared to 0.01694 for the back triplet. The focal length of the compound objective is 10.9mm. The objective was calculated for a numerical aperture of 0.23 for which the spherical aberration equalled twice its optical tolerance.

5.4.2 *Lister Archive folio L64, objective drawing 2*

Table 74: Lister lenses, folio L62, dwg.2

srf	radius	dst	N	ΔN
1	14.48	3.8	1.53	0.01
2	-14.48	0.13	1	0
3	-13.21	1.28	1.6	0.0167
4	13.21	0.16	1	0
5	13.97	3.8	1.53	0.01
6	-21.34	7.36	1	0
7	4.7	2	1.53	0.01
8	-25.4	0.1	1	0
9	-17.78	0.9	1.6	0.016
10	3.73	0.1	1	1
11	3.96	2	1.53	0.01
12	-66.04		1	0

A small inserted drawing, dated '11 mo. 1829' (November 1829) shows two drawings of triplet fronts for combinations with the 0.933in.[sic] triplet. Lister writes the following:[11]

> W. Tulley's first trial of the front triple came out by measurement. [Here follows the drawing of a triplet, radii from back to front +0.31, -1.25, -0.9, 0.22, 0.23, 2in. respectively.] It gave fine performance but

10 Lister Archive, folio L64.
11 Lister Archive, folio L64.

> a deeper front object glass being thought preferable by him for the sake of obtaining higher power he produced the following which has been his standard since [Here follows the drawing of the triplet which is analysed below, the thickness is 0.2in. and the diameter is 0.26in.]

The dispersion of the flint glass of the front component was calculated using a ratio of the focal lengths between the crown and the flint components of 0.706. The distance between the two components of this combination was unknown. It was calculated such as to minimise the OSC′ and the lateral spherical aberration. The objective appeared to be very sensitive to changes in the distance between the two components. Applied to L64.1 a similar approach did not result in such an improvement. As a result the numerical aperture of L64.2 could be increased to a higher value than that of L64.1.

5.4.3 *Lister Lenses no. 44, total objective*

The data and a description of this objective are given in appendix 3.6. The focal length of the calculated objective was 10.75mm. Using a body of 160mm, a tangent of the field angle of -0.05 and a NA of 0.34 the spherical under-correction of -0.017 was about three times its optical tolerance. The OSC′ was 0.013, which is too high. Stopped down to a NA of 0.275 the spherical aberration of -0.016 equalled twice its optical tolerance. The OSC′ was still too high. When the distance between the triplets was increased this resulted in a decrease of the OSC′ but not in such a measure as to justify a recalculation with a larger distance.

5.5 CHEVALIER'S DOUBLETS, 1826–1827

The microscope 'Selon Euler, Perfectionné par Vincent Chevalier ainé et fils', caused a lot of sensation when it appeared on the market, somewhere in 1825. The controversy between Chevalier, the maker, and M. Selligue, the inventor, about the priority and the rights contributed to this in no small measure. The name Selligue is an inversion for A.F. Gilles (1784-1845).[12] To give the construction of his achromatic doublets even more standing Chevalier stated that they were constructed according to the prescriptions of the great Euler. This is even emphasized by Chevalier's publication in 1825, of a translation of Fuss's book, which gave some practical applications of Euler's rather mathematical theories. Reading Fuss's book carefully, it appears that Chevalier's achromats have nothing to do with Euler. In the *Instruction Détaillée* Fuss gives the construction of a number of triplet lenses for telescopes; one doublet lens for a telescope which is completely different from the type of doublets used by Chevalier; and the design of a microscope with an achromatic triplet. This triplet was analysed in section 4.4.1, and bears no relation whatsoever with Chevalier's doublets.

As might be expected, Lister was interested in this famous microscope. He saw one which belonged to a Mr. Bauer and looked 'cursorily at it with Mr. Dollond'. Obviously Lister was rich enough to buy one. For the actual instrument see section 3.5.11. According to Goring this was done indirectly:[13]

> Mr. J. Lister, actuated by a most laudable zeal for the prosecution and advancement of optical science, as it concerns microscopes, caused me to order him one of Messrs. Chevalier's instruments, in Mr. W. Tulley's name; for, as Mr. L. wished that Messrs. C's pretensions should be fairly and thoroughly scrutinized, it was but fair that the latter gentlemen should be stimulated to do their utmost, by a consideration of the science of their customer.

In the Lister Archive of the Royal Microscopical Society there are two double sheets with notes of Lister's experiments with the doublets of this microscope.[14] They can be dated fairly accurately as Lister notes the date of payment of the microscope as 16 December 1826. So these experiments were conducted from the end of 1826 onwards and must have coincided partly with the experiments with Tulley's triplets treated above.

The experiments with these doublets led Lister to his most important discoveries. The first one being the possibility to use a combination of two or even three cemented doublets to assemble a compound objective of increased aperture, instead of muddling with too complicated triplets or combinations of those. The second one being the way how to do this most effectively. These experiments resulted in the paper which was published partly in 1830 in the Philosophical Transactions. It led to his election as a fellow of the Royal Society.

When reading Lister's notes on his experiments with Chevalier's microscope it is rather amazing that he ever bought it. He writes:[15]

12 Archinard [4], 31.
13 Goring [55], 248-258, (248-249).
14 Lister Archive, folio L19-L25.
15 Lister Archive, folio L19.

> I have been wholly mistaken in the very low opinion I had formed of Chevalier's object glasses, & freely & gladly retract it. I was deceived by observing the very indifferent performance of his two glasses numbered 10 & 14 as they were sent out by their maker – for they showed little more than single lenses of the same focus and aperture though they appeared to be got up in his best style.

Lister writes:[16]

> The french optician (as D[r.] G[oring] suspected) knows nothing of the value of aperture but he has shown us that fine performance is not confined to triple object glasses and in successfully combining two achromatics he has given an important hint probably without being himself acquainted with [unreadable] that I hope will lead to the acquisition of a penetrating power greater than could ever be reached with one alone.

5.5.1 *Investigation of Chevalier's doublets and microscopes*

Not many of Chevalier's doublets have survived the ravages of time. Of the few I could investigate the cement was strongly yellowed or cracked. In a recent article in *Annals of Science* Mills traces the history of the use of this cement, usually Canada Balsam.[17] The data of five doublets, originating from two microscopes could be measured.

5.5.2 *Microscope A54219*

Wellcome Collection, signed 'Selon Euler / Perfectionnée / Par Vinc.t Chevalier ainé et fils, / Ing.rs Opt.ns Brevetes / quai de l'horloge n.69 à Paris'. This was Lister's own microscope.[18] Only one doublet, size 2, accompanies the instrument. Its data could not be measured accurately. Those given in Table 19 were obtained assuming that its construction was similar to that of the other doublets. The refractive indices were assumed to be equal to those of number 9 of the Lister Lenses which originates from the same instrument. The thicknesses were chosen accordingly. Another doublet, which originally belonged to this instrument, is now in the collection of the Royal Microscopical Society (Turner cat. no. 382.9). It was investigated by Bracegirdle who incorrectly gives a focal length of 28.6mm.[19] Comparing it with the other doublets this obviously is a size 14, the 1.5in. doublet.

5.5.3 *Microscope 1921-746*

Science Museum London. Signed 'Selon Euler / Perfectionnée / Par Vinc.t Chevalier ainé et fils, / Ing.rs Opt.ns Brevetes / quai de l'horloge n.69 à Paris'. Four doublets, sizes 14, 10, 4, and 2 belong to this microscope. Size 2 is damaged beyond

16 Lister Archive, folio L20.
17 Mills [83], 173–185.
18 Bracegirdle [16], 273–297, (278–280).
19 Bracegirdle [16], 273–297, (280, 295).

repair, the others could be measured. The lenses are kept together in a can which bears the number '896', indicating that they once formed part of the Crisp Collection. The construction of Chevalier's doublets is very simple. The crown lens is equally convex and the front of the flint lens is flat. All their external surfaces and internal reflexes were measured using the method described in section 2.5.

Table 75: Chevalier's doublet lenses

	size 2 A54219	size 4 1921-746	size 10 1921-746	size 14 1921-746	size 14 RMS 382.9
ef	11.08	11.54	24.3	38.11	38.11
rds 1	4.67	4.9	10.135	15.66	15.61
dst 1	2	1.98	1.9	1.7	1.81
N 1	1.51	1.53	1.52	1.52	1.51
rds 2	−4.67	−4.5	−10.13	−15.66	−15.61
dst 2	1.1	0.55	0.97	2.15	1.24
N 2	1.614	1.637	1.633	1.638	1.614

Table 76: Measurements of Chevalier objectives, body 185mm:

doublet:	NA	d (μm)	MRP (μm)
size 2	0.215	1.5	2.75
size 10	0.05	6.5	7
size 14	0.036	9	9
size 14	0.069	4.75	5.5

5.5.4 *Chevalier doublet size 2 (A54219)*

Objective size 2 could only be used by screwing it onto the empty body of objective size 4. Its cemented surface was in a bad condition. As a consequence the image was hazy. Thus it was not surprising that the resolving power was worse than the smallest resolvable detail of 1.5μm. A computer simulation of this doublet, using the approximate data of table 75, showed for a NA of 0.215 a spherical under-correction of 4x its optical tolerance. Stopping down to a NA of 0.15 gave an acceptable result as far as spherical aberration is concerned, the under-correction being twice its optical tolerance. The OSC′ being −0.016 was still too large. Stopping down to a NA of 0.092 resulted in an OSC′ of −0.006. This value is similar to the one which results when the correction of an objective was acceptable in Lister's opinion.

5.5.5 *Chevalier doublet size 4 (1921-746)*

A computer simulation of size 4, with a calculated focal length of 11.56mm, gave the following results with a body of 185 mm. The NA was 0.18, the marginal and the axial ray come to the same focus, the zonal spherical aberration is smaller than its optical tolerance. The OPD between the marginal and the axial rays is smaller than 1.08μm. Only the OSC′ is about ten times as large as allowed. When the objective was stopped down to a NA of 0.09 the OSC′ was reduced to −0.006. The spherical aberration was below its optical tolerance. Lister wrote that he:[20]

> Opened the cell & tried a stop of the same aperture as that applied to Glass 10 & it will do though rather too large.

Applying this aperture of 0.16in. gave the following results with a body of 250mm: spherical under-correction, however both marginal and zonal well below the optical tolerance. The OSC′ was −0.022, this is too much. The objective must have shown a lot of coma.

5.5.6 *Chevalier doublet size 10 (1921-746)*

A computer simulation of size 10, with a calculated focal length of 24.13mm, gave the following results with a body of 185 mm. Assuming a NA of 0.05 the spherical aberration was about 1/10 of its optical tolerance. The OSC′ was −0.0028, a reasonable value. During his experiments Lister increased the aperture from the original 0.09in. to 0.16in. (4.1mm). Using this value the NA increased to 0.074. This resulted in spherical under-correction, but this was smaller than its optical tolerance. The OSC′ was −0.006.

5.5.7 *Chevalier doublet size 14 (1921-746)*

It was possible to repeat Lister's experiments with doublet size 14. The third row in table 77 gives its normal data, the last row gives its data with an increased aperture. With the increased aperture it shows under-correction.

A computer simulation of size 14 (the Science Museum one), with a calculated focal length of 38.17mm, gave the following results with a body of 185 mm.

The NA of 0.036 resulted in spherical under-correction but this was smaller than its optical tolerance. The OSC′ of −0.0021 was also small. When used with an aperture of 0.1in. as indicated by Lister, the Numerical aperture was even lower, namely 0.026. Lister increased the aperture of this doublet to 0.23in. In the computer simulation this resulted in a NA of 0.061. The spherical under-correction of −0.015 is still smaller than its optical tolerance of 0.035. The OSC′ was −0.0062.

A computer simulation of size 14 (Turner cat. no. 382.9), with a calculated focal length of 38.11mm, gave the following results, with a body of 185 mm.

For the small original values of the aperture the spherical aberration and the OSC′ were smaller than their respective optical tolerances. When the aperture was increased to 0.23in., as Lister did, the NA increased to 0.061. The spherical under-correction was then −0.019 and the optical tolerance was 0.035. The OSC′ was −0.006.

Lister probably used a longer body. For this reason a second calculation was made for a body of 250mm. The results were as follows: All computer simulations of Chevalier's doublets show chromatic under-correction, which is not surprising.

20 Lister Archive, folio L21.

NA	msA	OT	OSC′
0.065	−0.013	0.035	−0.0056

As there is only one radius the ratio of the focal lengths of the two glasses will be independent of the radius in a thin-lens approximation:

$$\frac{f_{crown}}{f_{flint}} = \frac{N_{flint} - 1}{2\,(N_{crown} - 1)}. \tag{38}$$

For all five doublets this ratio has a value of ca. 0.6 while the dispersive ratio of crown- and flint glass as calculated using the formulae for old glass has a value of ca. 0.62.

5.5.8 *Compound objectives*

Table 77: Chevalier's compound objectives, data for a tangent of the field angle of −0.05

	size 4 + 2 (250mm)	size 4 + 2 (160mm)	0.933 + 10 (250mm)	0.933 + 10 (160mm)
ef	7.36	10	14.68	10
efl	7.365		14.698	
efs	7.338		14.649	
efs−efl	−0.028		−0.049	
NA	0.27	0.27	0.27	0.27
msA	−0.005	−0.017	+0.022	+0.016
OT	0.008	0.008	0.008	0.008
OSC′	-0.013	-0.0148	0.019	0.019
zoC		−0.034		−0.024
Petz(10mm)		0.0911		0.087

After experimenting with these single doublets Lister started combining them. Only the combinations of Chevalier's size 4 + size 2 and that of Lister's 9/10in. with Chevalier's size 10 were analysed. The distance between the two components was in both cases taken as 3.6mm. The combinations were computed for two body tube lengths, one of 250mm and one of 160mm. For this latter value the focal length was scaled to 10mm. The results are assembled in table 77.

Lister mentioned some other combinations too but their components could not be identified. For this reason no simulation of these combinations was performed.

5.6 APLANATIC FOCI, 1830-1831

In Lister's papers the aplanatic foci of an achromat are mentioned for the first time in his notes related to the investigation of Fraunhofer's doublets. At the end of 1829 Lister was lent by 'Mr. Brown' (the botanist Robert Brown) a series of doublets made by Fraunhofer. Lister carefully noted their focal lengths and apertures and whether they showed spherical and chromatic under or over-correction. One Fraunhofer doublet, size 3, was even taken apart and an accurate drawing of it was made, showing the path of a marginal ray. Lister combined Fraunhofer's plano-concave flint lens later with a plano-convex crown lens. This latter lens is still in the collection of the Royal Microscopical Society (Appendix 3.1, no. 59). For this combination he determined the longer and the shorter aplanatic foci.[21] In a small insert in his original notes he made a table of the aplanatic foci of the other doublets (sizes 1, 2, and 4).[22]

The use of this theory becomes clear immediately when we realise the much higher aperture that the doublet has when the object is in its shorter aplanatic focus. There it is larger than 0.23, compared to 0.1 when used in the original way. Besides, the spherical aberration is so small that it is not longer of account. The sign of the OSC′ is reversed. This means that the coma of a compound objective constructed according to this principle can be compensated to a certain extent. Lister correctly observed that the direction of his 'burr' changed 180°, from upwards to downwards.

This will be analysed in more detail in the next paragraphs, using Lister's experimental data and the data of the lenses which still survive.

5.6.1 *Fraunhofer's doublet, size 3*

It was possible to simulate Lister's experiment with Fraunhofer's objective in a computer simulation. In the Science Museum I found a microscope made by Fraunhofer (inv. no. 1921–741) which had a doublet size 3. Its focal length, being 24.23mm (0.954in.), was close to Lister's 0.95in. The outer radius of the convex crown lens was 10.3mm (0.4in.), compared to 0.43in. for Lister's specimen. Lister assumes the refractive indices to be 1.5 for crown and 1.6 for flint glass. Using these values the internal radius of the flint lens was calculated. The value I found was 9.652mm (0.38in.) which was measured by Lister too.

The focal length of the combination of the flint lens of size 3 and the plano-convex lens number 59 of the Lister Lenses is 77.6mm. The spherical aberration is strongly under-corrected for an object point at infinity.

One aplanatic focus was calculated for a height 2mm of the marginal ray in the entrance pupil plane figure 36. The pencil of rays radiates from a point 9.25mm to the left of the doublet. The diverging pencil seems to radiate from a point 6.1mm to the left of the doublet. For these two points both the marginal and the axial ray come to the same focus. There remains a small amount of zonal

21 Lister [75], 187–200, (195).
22 Lister Archive, folio L104

Table 78: Data of Fraunhofer size 3 flint lens with plano-convex lens RMS 382.59

srf	radius	distance	N	ΔN
1	7.828	2.33	1.509	0.0084
2	∞	1.5	1.6	0.0154
3	9.652		1	0
Fraunhofer's original biconvex crown lens:				
1	10.922	2.95	1.53	0.01
2	−10.16		1	0

under-correction. This situation differs considerably from the one Lister shows in his drawings.[23]

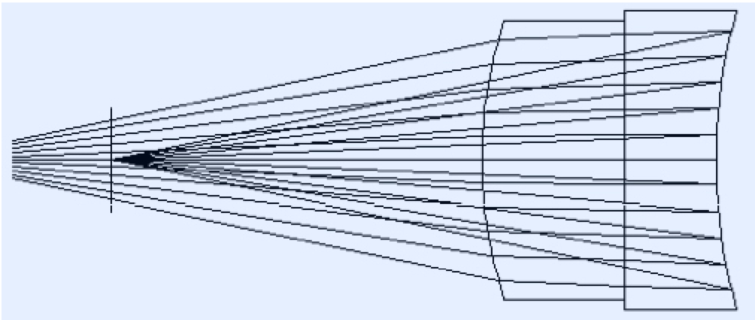


Figure 36: Aplanatic foci, I

The other aplanatic focus was calculated for a height of the marginal ray of 5mm in the entrance pupil plane of figure 36. The pencil is convergent and focuses to a point 12.5mm (0.5in.) to the right of the doublet. This is the 'longer' focus indicated by Lister in the original drawing. The marginal and the axial day come again to the same focus. There remains a small amount of zonal under-correction.

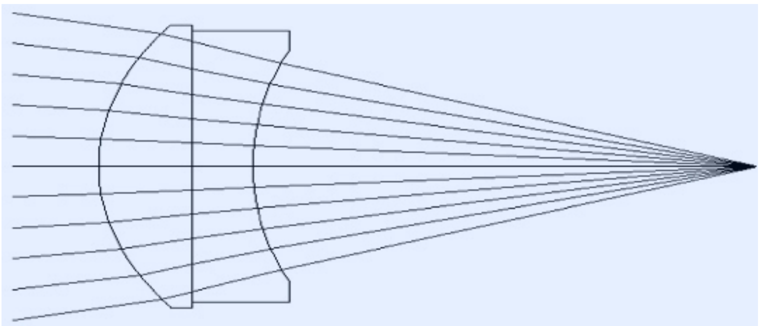


Figure 37: Aplanatic foci, II

The aplanatic foci of Fraunhofer's doublet were computed too, though the system data had to be adapted slightly. The values which Lister assumes for the refractive indices result in a focal length which is considerably larger than the

23 Lister Archive, folio L104a, Lister [75], 187–200, (195).

one Lister gives (0.95in.). This latter coincides with the one I measured myself on another doublet size 3 by Fraunhofer, namely 24.23mm (0.954in.). To bring the focal length to this value N_{crown} had to be increased to 1.53 and N_{flint} was decreased to 1.59. The resulting focal length now was 24.4mm, the back focus being 21mm to the right of the plane surface.

Lister measured a pencil of 11.5°, which is equivalent to a NA of 0.1 with a body of 12in. The incident height of the marginal ray was 2.65mm. The doublet shows some over-correction for a body of infinite length. Shortening this to 256.4 mm the marginal and axial rays came to the same focus. Using the same marginal height the NA was 0.23. Some zonal under-correction remained. The position of Lister's longer aplanatic focus is now 23.6mm to the right of the plane front. The shorter aplanatic focus was found to be at a position of 8.3mm to the right of the plane front.

5.6.2 *Experiments with a combination of doublets*

In the first series of experiments, dated 11 November 1830, Lister determined the most favourable curvatures for the doublets he wanted to investigate. He started with three plano-concave lenses, two of common flint and one of Swiss flint. Their radii were 0.6in. (15.24mm). The biconvex lens was made of plate glass and its radii were 0.6in. and 0.7in.[24] These values were not computed beforehand but they were chosen for the sake of convenience. A very small or a very large radius was more difficult to realise. These lenses he made himself as Tulley was too busy for some reason.[25] The plano-concave lenses could be identified as the numbers 6 and 8 (common flint, refractive index ≈1.58) and 7 (Swiss flint, refractive index ≈1.60) from the Lister Lenses. A description can be found in Appendix 10.2. The biconvex lens is either number 25 (refractive index ≈1.5) or number 53 (refractive index also ≈1.5) of the Lister Lenses, see Appendix 10.3.

Later Lister made a second biconvex lens. Apparently it was his purpose to combine two doublets to a compound objective. This lens was 'very veiny' and made of plate glass. This description fits number 58 of the Lister Lenses. It is wrapped in a piece of paper stating that it is veiny (refractive index ≈1.5), see Appendix 10.3.

Lister subsequently combined the biconvex lens with all three flint lenses, both with and without cementing them together. For all these combinations he wrote down whether he observed spherical and chromatic aberration, using two different tube lengths (9in. and 20in.). The two lenses of common flint combined with the crown lens both showed chromatic under-correction. The one of Swiss flint, with its higher refractive index and dispersion, showed over-correction when combined with the crown lens. The lens of veiny plate showed the same effects. This led him to the conclusion that the back radius of the biconvex lens had to be made slightly larger for the combination with the common flint lens and slightly smaller for the one with the lens of dense flint. This is sound reasoning, knowing that Lister was familiar with the article Herschel wrote about achromatic objectives in 1821. Herschel states that for an achromatic doublet f:f' :: d:d'.[26] Increasing the radius of the lens f leads to increasing its focus and hence to less under-correction (even over-correction if the radius is made too large).

For a second series of experiments in which he wanted to investigate the application of the principle of the aplanatic foci for making a compound objective, two new biconvex lenses were made. One had radii of 0.75in. and 0.6in. and the other had radii of 0.65in. and 0.6in. Unfortunately these two biconvex lenses could not be found in the collection of the Royal Microscopical Society.

For a computer simulation I used the radii as Lister gives them, not the slightly different values I measured. All thicknesses were unknown, either because the lenses were lost or because it was not known which of two different lenses Lister actually used. So the values I use in the model are guesses, though they come close to the actual ones. This also holds for the refractive indices.

24 Lister Archive, folio L28.
25 Lister Archive, folio L43 [original draft] and L70 [a copy, made on paper with watermark 1866], a letter to J.F.W. Herschel, dated 24 February 1831.
26 Herschel [61], 222–267.

Table 79: Combination '1' with Swiss flint

srf	radius (inch)	radius (mm)	distance (mm)	N	ΔN
1	0.65	16.51	3.2	1.5	0.0077
2	−0.6	−15.24	1.8	1.6	0.0155
3	∞	∞		1	0

Table 80: Combination '2' with common flint

srf	radius (inch)	radius (mm)	distance (mm)	N	ΔN
1	0.7	17.78	2.8	1.5	0.0077
2	−0.6	−15.24	1.2	1.585	0.0143
3	∞	∞		1	0

The first objective had two doublets, combination '1' at the back and combination '2' at the front. The longer aplanatic focus of combination '1' and the shorter aplanatic focus of combination '2' were calculated. Using these data the distance between the two doublets was calculated as 15.42mm. The data of this combination are to be found in column '1'+ '2', distance 1. As the marginal incident height of the front doublet is smaller than that of the back doublet, the shorter aplanatic focus of the front was calculated assuming a smaller marginal incident height.

When this was checked in the complete compound objective the assumed and the actual values were close. The column '1'+ '2', distance 2, gives the data for a body of 250mm. For this body length the distance between the two components had to be decreased to 9.6mm.

For a body of 9in. the corresponding combination in Lister's experiment has a distance between the two components of 0.3in. [27] When the computer model was used with this body a value of 0.34in. was found. This shows how careful Lister executed his experiments. The 'pencil' he found was 23°, which corresponds with a NA of 0.2. The OSC′ of this objective is higher than we would allow. Lister remarks himself: 'coma out'.

27 Lister Archive L29

Table 81: Combination '3' with common flint:

srf	radius (inch)	radius (mm)	distance (mm)	N	ΔN
1	0.75	19.05	3	1.5	0.0077
2	−0.6	−15.24	1.8	1.585	0.0143
3	∞	∞		1	0

Table 82: Lister's combinations of doublets Compound achromatic objective, combinations '1' and '2'

	'1' body 250mm	'1', longer apl.focus	'2' shorter apl.focus	'1'+'2', distance 1	'1'+'2', distance 2
ef	41.413		43.789	27.295	25.097
efl	41.425		43.818	27.307	25.108
efs	41.443		43.777	27.296	25.098
efs–efl	+0.018		−0.041	−0.011	−0.010
bp	−250	−444	+26.45	−444	−250
bkf	+45.86	+41.87	+13.61	13.61	16.9
NA	0.12	0.13	0.21	0.21	0.22
msA	−0.046	0	0	−0.0001	−0.0001
OT	0.018			0.01	0.01
OSC′	−0.02	−0.019	+0.0087	−0.01	−0.01
zoC	0.05	0.041	−0.005	0.01	0.007
Petz(10mm)	0.0723		0.0718	0.0924	0.0850

5.6.3 *Experiments with combinations of doublets and triplets*

Lister started a second series of experiments in 1831, the purpose being:[28]

> .... a construction fitted to obtain the largest pencil with good front space & without coma.

In a letter to J.F.W. Herschel, dated 24 February 1831, Lister writes:[29]

> All about three weeks ago, when I made a second and more complicated trial, projected for obtaining the same effect with a much larger pencil. This is just finished, but not without altering one of the original curves, and its plan might be improved if I could spare time to make another set.

The object glass to which Lister refers in this letter consisted of three components. The back component was a normal achromatic doublet. The middle component was a triplet of the design which was to become the standard front for English objectives for about forty years, after Andrew Ross started making objectives after Lister's design in 1837. The front component was the combination Lister experimented with when he investigated the Fraunhofer doublets: a concave-plano front of flint glass and a plano-convex crown back glass. This combination became the middle component in the designs for Ross. Of the refractive indices not much is known. It is only mentioned that the negative lenses are of dense flint and that the crown lenses were of English plate, for which I assumed N=1.5.

When calculated for the values of the refractive indices indicated above the objective was much under-corrected, both spherically and chromatically. To correct this the refractive index of the flint lenses was increased to 1.63. The object

28 Lister Archive, folio L30.

29 Lister Archive, letter to J.F.W. Herschel, dated 24 February 1831, folio L43 [original draft], L70 [copy, made on paper with watermark 1866].

Table 83: Object glass, three components (L32), dimensions

srf	radius (inch)	radius (mm)	distance (mm)	N	ΔN
1	0.46	11.684	2.95	1.5	0.0077
2	−0.4	−10.16	1.1	1.6	0.0155
3	∞	∞	0.2	1	0
4	0.4	10.16	2	1.5	0.0077
5	∞	∞	1.2	1.6	0.0155
6	0.4	10.16	2	1.5	0.0077
7	∞	∞	0.81	1	0
8	0.19	4.826	2.3	1.5	0.0077
9	∞	∞	0.8	1.6	0.0155
10	0.3	7.62		1	0

glass was analysed for three different values of the refractive index of the flint glass, with and without a cover glass. The cover glass had a refractive index of 1.5.

Table 84: Object glass, three components (L32)

Nf=1.6	Nf=1.6	Nf=1.62	Nf=1.62	Nf=1.63	Nf=1.63	
cover glass	no	1.99	no	0.24	no	0.2
ef	9.5	9.5	9.88	9.88	10.09	10.09
ef, back	29.6		31.27		32.18	
ef, middle	24.8		25.9		26.5	
ef, front	24.12		25.43		26.13	
efs−efl	−0.031	−0.031	−0.0004	−0.0004	+0.017	0.016
zoC	−0.014	−0.0074	0.012	0.013	0.027	0.031
NA	0.44	0.44	0.44	0.44	0.44	0.44
msA	−0.04	0	−0.0047	0	0.0167	0.011
OT	0.0052	-	0.0052	-	0.0052	0.0052
OSC′	0.013	0.0067	0.0058	0.0051	0.0011	0.018
Petz(10mm)	0.0693	0.0693	0.0696	0.0696	0.0699	0.0717

The objective is strongly under-corrected for $N_{flint} = 1.60$. This did not improve much when the distances between the components were changed. When a cover glass of 1.99mm was inserted the marginal and axial rays came to the same focus. The remaining zonal under-correction was smaller than the OTz. The OPD between the marginal and the axial ray was 0.7μm, which is maller than the maximum value of 1.08μm. However, as a cover glass of this thickness is unusual the objective is under-corrected for normal purposes.

Increasing the refractive index of all the flint lenses to 1.62 gave a much better correction. Without a cover glass there was still a considerable zonal under-correction (−0.086 at 0.875 pupil height). With a 0.24mm cover glass (a realistic value) the axial and marginal rays came to the same focus. The remaining zonal under-correction of −0.0052 equalled the optical tolerance for zonal spherical aberration. The OPD between the marginal and the axial ray was 1.1μm, about its maximum allowable value. For short wavelengths the spherical aberration was very small for the centre of the pupil but over-corrected for the outer zone.

When the refractive index of the flint lenses was increased to 1.63 the objective was over-corrected. For a cover glass of 0.2mm the distance between the middle and front components had to be increased from 0.81 to 1.85mm to get an acceptable spherical correction. A considerable zonal under-correction remained, which had its maximum of −0.043 at 0.75 pupil height.

The table which Lister made of the magnifications which he measured with this objective show that he used strong eyepieces. For a body of 11in. as mentioned by Lister the objective magnifies 26 diameters. For a total magnification of 280 diameters this means that Lister's eyepiece size 1 magnified 11 diameters; his size 2 magnified 20 diameters; and his size 3 magnified 30 diameters.

It is very probable that this objective survives partly. The data of the back and middle components of number 41 of the Lister Lenses correspond with those of Lister's design (L32). Only the front component of number 41 – a triplet – differs. The thread of this objective is characteristic for Tulley. It is marked 'II'. See Appendix 10.6 for more details on this objective.

5.7 CONCLUSIONS

Lister started his experiments with combinations of two triplets. They allow for an increase of the Numerical aperture from ca. 0.15 for the single triplet lenses to ca. 0.25 for the compound objectives of two triplets. However, these double triplets have some serious drawbacks. Firstly the number of twelve glass to air surfaces is too large, the decrease of contrast was already mentioned for Lister Lens number 44. Their behaviour in respect to aberrations is not easy understood when experimenting in the way Lister and Tulley obviously did.

It is remarkable that none of Lister's papers shows the least sign of any serious calculation. Sometimes he calculated the ratio of the focal length of the crown components to that of flint components, using thin lens formuae. In these instances he even did not apply these formulae correctly, using the same refractive index for both crown and flint glass. In general one marginal ray is drawn. The method of construction is not clear as no traces of guide lines remain. The design of the triplets remains enigmatic. One of them, the early 9/10in. which Lister designed for Tulley, shows a striking resemblance to the Euler/Fuss triplet, but the other ones could not be traced as yet. The construction of Tulley's triplets – loose lenses screwed together in a mount – makes them very vulnerable. They can be taken out easy and be shifted. For the same reason their centring can be disturbed easy, giving rise to axial coma.

It appears that George Dollond (1774–1832) also made such triplets. Goring wrote in 1827:[30]

> He has, without effort or difficulty, and with the same precision and certainty which he has attained to in the manufacture of the larger glasses, produced three triple small ones, of somewhat less than an inch focus.

It is very probable that a Dollond microscope in the Science Museum (inv.no. 1928-860) is provided with such a triplet. This microscope was bought in 1886 by Sir Frank Crisp from Professor Hubrecht, Harting's successor in Utrecht. In a footnote of *Das Mikroskop* Harting writes:[31]

> Da die Beschreibung der Tulley'schen Linsen ziemlich auf sie passt, und da Pritchard wie Queckett bezeugen, Tulley habe zuerst in England solche Linsen angefertigt, so vermuthe ich, dass sie nicht von Dollond selbst kommen, sondern von Tulley, zumal bekanntlich Dollond in der späteren Zeit keine mikroskope mehr gearbeitet hat.

Harting obviously did not know that Tulley's triplets were mounted in a cell with a little cap to fix them. According to Goring, Dollond made them much better by burnishing them in their cells, which was done with the remaining lens of this microscope. The aperture of Dollond's lenses, which is given by Goring as 0.45in. fits this lens well. I measured a value of 11.6mm (0.457in.). The focal length was 26.7mm, the NA was 0.116 and the resolving power was 2.25μm. The internal construction could not be investigated, moisture between the lenses prevented this.

30 Goring [56], 410–434, (410).
31 Harting [59], 137.

From some remarks made by Brewster (1781–1868) in his Treatise on Optics it becomes clear that the development of the microscope and the way in which it was going to be used over the coming decades was still not clearly defined. Brewster still strongly recommends the use of simple microscopes and especially those with precious stones, like diamonds and garnets. According to Brewster these simple microscopes perform very well with homogeneous light. When this 'monochromatic' light is used, achromatic object glasses are even completely unnecessary. Herschel's doublets are entirely free from spherical aberration and can be used if a simple microscope is not convenient enough. Compared to all these other possibilities achromats, whether they be doublets, triplets or combinations of them, are very expensive and by no means superior.[32]

After the experiments with triplets Lister discovered the simpler combinations of Chevalier, consisting of two or more doublet lenses.

His first experiments with single doublets show one common factor: the OSC′ is always limited to a value of about 0.006. As far as spherical aberration is concerned Lister could have increased the apertures even more but the increase of coma opposed this.

The experiments with combinations of achromats all show that Lister's criteria for judging whether a lens was well corrected or not were much less severe than ours. The large 'burrs' caused by coma, which he draws, confirm this.

The result of these researches was that Lister became convinced it might be worth while to investigate the behaviour of combinations of doublet lenses more closely. He then temporarily left his original research programme in which the triplet played a major role.

His own conclusions from these experiments were:[33]

- That a penetrating & defining power may be got by combining two achromatic Glasses, which we cannot obtain from one except it be of much deeper focus than the virtual of the compound.
- That the front Glass ought to be made expressly to be put before the other – thin and small and such as would if used alone be somewhat over corrected for both aberrations.
- The rays take the same course in passing through the back object glass as if it were used singly.
- The thinner both glasses & the closer together, the greater will be the power, the greater the distance of the front from the object & of course the better the light for an opaque one.
- The front Glass however requires particularly to be thin & small.
- The back one requires greater size for the sake of aperture and I have no doubt that a very beautiful thing may be made by applying a double glass something like Chevalier's 9/10th (Glass 10) to be slid when wanted over M. Tulley's new 9/10 triple object glasses, and a still finer by applying in the same way a little doublet 4/10 or 3/10 if it can be manufactured in front of a triple 3/10. Probably a triple 5/10 inch on the model of the 9/10 & a double 5/10 in front of it would be less difficult.

32 Brewster [20], 342–343.
33 Lister Archive, folio L24.

Defining power was defined by Goring as:[34]

> a destitution of both kinds of aberration, considered independently of the aperture of the microscope or engiscope.

The aberrations Goring refers to are spherical and chromatic aberration. A microscope in Goring's terminology is a simple microscope, an engiscope is a compound microscope. Penetrating power is 'a large angle of aperture'.

The conclusions formulated above led Lister to propose the following research programme:[35]

> How much of the inferiority of Chevalier's object glasses when used single is to be attributed to their want of correction for the ray of the circumference (we must remember we use them with an aperture for which they were not intended) and how much if any to their being double instead of triple & to their being cemented with varnish. If we had reason to support the latter circumstance to be no disadvantage to performance it would clearly be a benefit in regard to light & would be a great advantage in setting the glasses, for the varnish being put between them the central adjustment might be made while it is fluid & after it has been left to dry, the compound glass might be burnished in without fear of disarranging it. When I observe the extraordinary beauty of performance of Chevaliers Glass 10 combined with my 9/10 it gives me strong doubts of the figure of these small achromats being injured by varnish.

This research programme proved to be so successful that Lister was allowed to publish a report of his discoveries in the *Philosophical Transactions* of 1830. In this paper Lister gave an account of his researches, starting with the improvement of Tulley's triplets, the investigation of the Chevalier and Fraunhofer doublets, his modifications of them and the principle of the aplanatic foci of an achromatic doublet.[36]

It is obvious that Lister's work is mainly experimental. Mathematical analysis along the lines set by Fraunhofer in Germany was clearly beyond his scope, or anybody else's, as the decline of Fraunhofer's workshop after his early death in 1826 shows.[37] The choice to start working on doublets is only logical from this point of view, as they are much more suitable for experimental work than triplets. The number of curvatures is small, in general only two, and chromatic and spherical aberrations for each doublet can be diminished to a great extent. As was shown in section 5.6, some doublets have the favourable property that their marginal spherical aberration for two object points can be annulled. These points are Lister's aplanatic foci. Using this knowledge the distance between the components of a compound objective giving the best correction of the spherical and chromatic aberration could be determined.

34 Goring [57], 173.
35 Lister Archive, folio L25.
36 Lister [75], 187–200.
37 Rohr [91], 277–294.

The design of the objective analysed in section 5.6.3 is interesting in that it shows that Lister only tried to assemble a compound objective of both spherically and chromatically corrected parts during his first experiments. This idea is already given up during his later experiments. The under-correction of one part is then compensated by the over-correction of another part. The principle of the aplanatic foci was used for quantitative reasoning, but as Lister never performed lengthy calculations it was not used as a starting point for a design, and it was at most measured on a trial combination.

His designs are empirical, i.e. not based upon fundamental mathematical analysis. He must have been a very intelligent man and a keen and patient observer. His reasoning is generally sound and of a very qualitative nature, e.g. 'increasing this radius will have that effect'. As a result a lot of experiments had to be performed and when someone else wanted to execute his designs they had to be adapted to the kind of glass which was used, a rather time-consuming and boring work. This can very well explain why Lister?s ideas were not taken up immediately and why he had to make the first designs for Ross and Smith himself.

6 THE COMMERCIAL EXPLOITATION OF LISTER'S DISCOVERIES

6.1 ANDREW ROSS

6.1.1 *High power lenses*

As was mentioned at the end of chapter five, Lister left the subject of improving the achromatic objective in 1831 for some time:[1]

> hoping it would be persued by opticians, but the glasses produced by the makers continued to be on the first simple construction of 2 or 3 plano-convex compound lenses till the beginning of 1837. At that time I called on Andrew Ross regarding some object glasses he had made for a microscope for Richard Owen; when he told me he had been long engaged in unsuccessful trials for a new construction & at his request I gave him a projection for an 1/8 inch objective of 3 compound lenses, the first one a triple, which he soon worked out successfully – & it became the standard form for high powers for many years.

Later on Richard Owen (1804–1892), a well known anatomist and the first President of the Microscopical Society of London (1840–1842), is not mentioned anymore, and Lister explicitly states that the first 1/8 inch objective Ross made was bought by himself on 24 April 1837.[2] He used it with and without a cover glass. From a note he made on 4 July 1837 it appears that this objective was not yet provided with the correction collar Ross described in 1839 in the Penny Cyclopædia.[3] Lister loosened the screws that fixed the distance between the front and the middle component to push the front closer to the middle glass. He did this to change the spherical correction and thereby cracked one of the lenses. It was not an uncommon problem. In a number of objectives which I investigated the very thin negative front lens of the middle triplet had been cracked by the back lens of the front triplet. Especially in high power lenses the distance between the two front components is so small that the lenses can touch and be cracked easily.

Ross must have made a 1/4 inch objective of the same construction. Lister also examined this one and found that it was spherically considerably over-corrected. He also loosened the screws of this objective and pushed the front closer to the middle glass, then it was well corrected. The day after he discovered that the front and middle components actually touched each other, but they had not been damaged yet.

1 Lister Archive, L76 (see Appendix 4); Conradi [28], 27–55 (27–28).
2 Lister Archive, L100b.
3 Lister Archive, L100b; Ross [94], 177–188, (185); idem, (1837–1838), 99–107.

A reconstruction of these first objectives is only partly possible. Lister's notes on his contacts with Ross are very incomplete and no surviving objectives were found as yet. This is not surprising for Ross soon changed Lister's original construction slightly.[4] In a note written for James Smith the curvatures of the surfaces of both Lister's original and Ross's modification are given.[5] Of both objectives the construction is derived from the last one analysed in chapter five (L32). The most important change is the transposition of the middle and the front components. In (L32) the middle component was a triplet of two plano-convex crown lenses with a plano-concave flint lens between them. This triplet became the front component of the objective for Ross and was widely used in most English objectives until it was superseded by the single hemispherical front of Amici's design. The concave front of (L62) became the middle component of the new objective. When Ross started providing objectives with a correction collar, which he must have done when he started producing them in greater quantities, this collar moved the front component inwards or outwards. A drawback of this arrangement, especially in high power objectives where the distance between the front and the object can be very small, is that the object and/or the front can easily be damaged when the correction collar is readjusted. I had to be very careful not to damage the precious diatom test plate I used to judge the general performance of these lenses.

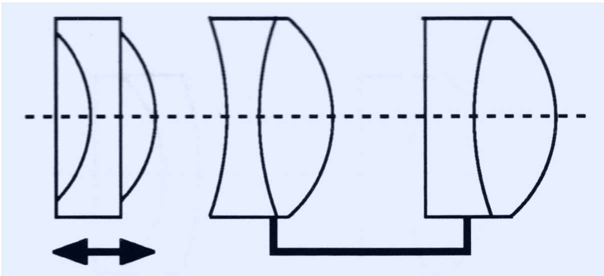


Figure 38: Lister/Ross compound objective, 1/8, 1/4 and 1/2 inch,1837

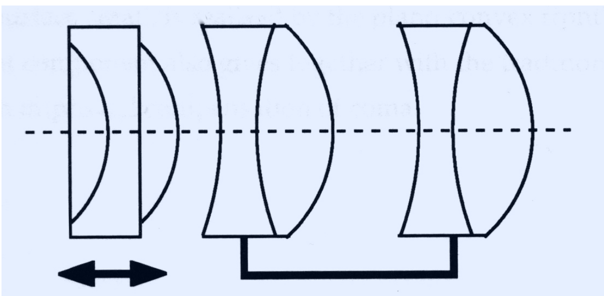


Figure 39: Ross's compound objective,1/8, 1/4 and 1/2 inch, 1838

4 Lister Archive, L97.
5 Lister Archive, F45.

6.1.2 *Low power lenses*

The low power lenses designed by Lister were a combination of two doublets:[6]

> On my suggesting the above form to A.R. he looked out one from a number of old glasses he had made for trials, which I took home & found my hopes justified on putting it in front of my old back glass.

The design is such that the shorter aplanatic focus of the front and the longer aplanatic focus of the back coincide, in this way destroying spherical aberration and compensating most of the coma. Though Lister wrote a number of notes about this design, he mentioned no curvatures and the focal length is not given either. The optical construction of these 1in. and 2in. objectives is sketched in figure 40. The front is to the left.

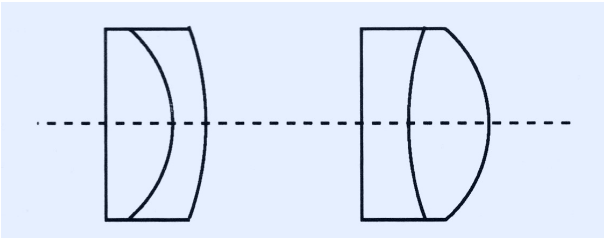


Figure 40: Lister/Ross low power objective, 1 and 2 inch, 1837

In this design Lister's aim to keep the angles between the rays and the normal of the surface small, is realised by the plano-convex front of crown glass. The combination of the traditional back doublet and this front component results in a much improved compensation of coma.

6 Lister Archive, L100a and L76.

6.2 JAMES SMITH

6.2.1 *Introduction*

It is still not clearly understood from the documents in the Lister Archive which designs James Smith received from Lister. There is one double folio page with drawings of simple doublets (i.e. a plano-concave flint and a biconvex crown lens) which were tried in various combinations. It does not explicitly state which were the combinations Smith was going to make.[7] The accompanying text on the back of this double folio leaf states:

> The constructions both for the double & triple combinations were given him in the hope that they might answer his purpose without interfering with the better forms which A. Ross had adopted at my suggestion two years before (i.e. spring 1837). The convex fronts to the back & front glasses of the double were tried for the object of getting rid of outward coma. But the disadvantage of the great angles of the rays at the interior refraction &c was so evident that the construction which had been given to Ross both for double & triple combinations were afterwards taken for Smith's as being really necessary. I previously had A. R's assent for doing so.

Lister added later:

> This was in 1840. The double combination first, then the triple 1/2 inch. But the triple 1/4 inch on the better construction was not executed till 1842.

I have never seen the double combinations Lister mentions. Judging from his drawings they were comparable with the ones that were used in the experiments of 1830/1831. The triple 1/4 inch must have been made on the same pattern, i.e. three simple doublets. A small drawing on a piece of paper dated December 1840 gives the curvatures of the three components of this objective, but none of these could be traced on the earlier double folio.[8] I give them as a reference in the following table. No calculations were made because it did not make much sense here.

Table 85: Radii for early 1/4 inch objective for James Smith, 1840

back component		middle component		front component	
srf	rds (inch)	srf	rds (inch)	srf	rds (inch)
1	0.28	4	0.24	7	0.22
2	−0.28	5	−0.24	8	−0.25
3	∞	6	∞	9	∞

7 Lister Archive, H2.
8 Lister Archive, F45.

Another piece of paper, dated 11 January 1842, gives details of the construction of objectives of 1 1/4 inch, 2/3 inch and 4/10 inch.[9] I found some examples of them in the Science Museum and in the RMS collection. Using both the original data from Lister's paper and the measured data, I made a computer simulation of these objectives. The results are given in section 6.2.2.

The three objectives Lister describes here are of the same pattern as the ones Ross made. The 1 1/4 and 2/3 inch objective form a combination. When only the back doublet is used the focal length is 1 1/4 inch; when a front is added the focal length is 2/3 inch. The 4/10 inch is an objective on its own, is uses an identical back doublet as the other objective. The middle doublet has a concave flint front and the front triplet is of Lister's well tried recipe. This is to say it has a plano-concave flint lens in the middle with two plano-convex crown lenses on either side of it, which is shown in figure 39.

6.2.2 *Measurements*

Table 86: Objectives by James Smith

inv. no.	year	thread	dwg	F (mm)	mgn	NA	rp (μm)
RMS15.2	<1847	0; 20.3; 36tpi		31.76	7.01	0.108	3.75
SM1891-19.3		0; 20.3; 36tpi		32.64	6.92	0.112	3.25
RMS15.2a	<1847	0; 20.3; 36tpi		16.02	15.02	0.232	1.5
SM1891-19.3a		0; 20.3; 36tpi		16.62	14.82	0.239	1.75
RMS15.3	<1847	0; 20.3; 36tpi	31	9.79	26.08	0.421	1.2
SM1891-19.1		0; 20.3; 36tpi		9.23	19.10	0.435	1.25

inv. no.	signature
RMS15.2	on can: 1 1/4 & 2/3 Ja.s Smith LONDON [combination]
SM1891-19.3	microscope: James Smith London '76' [1 1/4"+ 2/3" combination]
RMS15.2a	on can: 1 1/4 & 2/3 Ja.s Smith LONDON [combination]
SM1891-19.3a	microscope: James Smith London '76' [1 1/4" + 2/3" combination]
RMS15.3	on can: Ja.s Smith LONDON [4/10" objective]
SM1891-19.1	microscope: James Smith London '76'. [4/10" objective]

As mentioned in section 6.2.1 the 1 1/2in., the 2/3in. and the 4/10in. objectives all use an identical back component. On three of those back components additional measurements were made. The front doublets of two 1 1/2 and 2/3in. combinations were measured and of one 4/10in. objective the middle and the front components were measured.

Back doublets for all combinations:

9 Lister Archive, F84.

inv. no.	f (mm)	thickness	aperture	back radius
RMS15.2	31.76	4.34 mm	ø 7.3 mm	0.5 inch
SM1891-19.2	32.64	-	-	
RMS15.3	31.07	4.31 mm	-	0.49 inch

Front doublets of 2/3 inch combinations:

inv. no.	f (mm)	thickness	aperture	back radius
RMS15, 2/3in.	29	3.9	ø 7.6 mm	0.46 inch
SM1891-19.3	27.69	-	-	-

Middle and front of 4/10 inch, RMS 15.3:

	f (mm)	thickness
middle	24.85	3.78
front	14.42	5

Lister gives specific gravities for the flint glasses. Using a catalogue of Chance Brothers the following glasses which come close to Lister's were selected:

component	spec. grav.	glass	Nd	ΔN
back glass	3.556	Chance, DF	1.61323	0.01661
front double	3.613	Chance, DF	1.61676	0.01686
middle of triple	3.655	Chance, DF	1.62046	0.01718
front of triple	3.678	Chance, DF	1.62258	0.01727
all crown glasses		Chance, BSC	1.5097	0.00791

This resulted in the following combinations (1 1/4 and 2/3 inch)

srf	radius (mm)	distance (mm)	Nd	ΔN
1	12.7	3.1	1.5097	0.00791
2	−10.922	1.2	1.61323	0.01661
3	∞	two values *	1	0
4	10.922	1.6	1.61676	0.01686
5	5.588	2.3	1.5097	0.00791
6	∞		1	0

Two distances between the components were used, one of 1.372mm, for this value OSC′=0; the other one (0.3mm) was the measured one. In Table 23 these are the colums 2/3 (1.372) and 2/3 (0.3) respectively.

Data used for simulation of a 4/10 inch objective:

srf	rds (mm)	dst (mm)	N_d	ΔN
1	12.7	3.1	1.5097	0.00791
2	−10.922	1.2	1.61323	0.01661
3	∞	0.8	1	0
4	9.652	2.3	1.5097	0.00791
5	−12.192	1.5	1.62046	0.01718
6	127	2.875	1	0
7	6.35	1.8	1.5097	0.00791
8	∞	1.4	1.62258	0.01727
9	6.35	1.8	1.5097	0.00791
10	∞		1	0

Data used for simulation of an 0.55 inch (13.97 mm) objective:

srf	rds (mm)	dst (mm)	N_d	ΔN
1	17.78	3.72	1.5097	0.00791
2	−15.24	2.63	1.62046	0.01718
3	∞	0.3	1	0
4	13.97	3.6	1.5097	0.00791
5	−18.034	1.48	1.62046	0.01718
6	127	3.11	1	0
7	10.16	1.77	1.5097	0.00791
8	∞	1.032	1.62046	0.01718
9	10.16	1.77	1.5097	0.00791
10	∞		1	0

Table 87: Results of simulations of objectives for James Smith

	1 1/4	2/3 (1.372)	2/3 (0.3)	4/10 inch	0.55 inch
ef	31.81	15.464	15.16	9.825	14.294
efl	31.80	15.469	15.165	9.832	14.295
efs	31.90	15.476	15.173	9.818	14.309
efs–efl	0.10	0.0073	0.0076	0.0137	0.008
NA	0.1	0.224	0.228	0.422	0.39
OSC′	−0.013	0	0.001	−0.0022	0.01
zoC	0.13	0.0096	0.0083	0.013	0.027
Petz(10mm)	0.0722	0.0770	0.0755	0.0952	0.0907
msA	0.0027	−0.018	−0.018	0	0
OT	0.021	0.01	0.01		
mgn	6.9	15.3	15.6	25	18

The design of this objective, which is dated 15 December 1840, is accompanied by the following remarks by Lister:[10]

> Rough trial towards enabling Smith to obtain a large pencil without coma on the principle suggested to A. Ross in 1837 & adopted

10 Lister Archive, F44.

with modifications by him for his 1/8th. Used for back glass the back plano-convex of my original combination. For the middle a glass made for experiment by Smith some months ago. For front glass the triple glass that formed the middle of my trial combination of 1831.

1 1/4 inch: The offence against the sine-condition OSC′ of this doublet, when used on its own is too high. This results in coma. There is zonal spherical under-correction and marginal over-correction. Both are smaller than their optical tolerances. The red rays are stronger under-corrected and the blue rays are stronger over-corrected than the green rays.

2/3 inch: The red and green rays are spherically under-corrected to the same measure, the blue rays are slightly less under-corrected. The spherical under-correction is not very sensitive to changes in the distance between the components, a cover glass has not much influence too. I tried to improve the objective by making small changes in the curvatures. This improved the spherical correction but the chromatic correction got worse. Other types of glass would have been necessary to counteract this. A total redesign of the objective would result.

4/10 inch: There is some zonal spherical under-correction, zsA = −0.0037, while the zonal Optical Tolerance equals 0.005. The OPD between the marginal and axial rays is 0.7μm, which is smaller than the value of 1.08μm given by Zernike. The red and mean rays are equally under-corrected, the blue rays are over-corrected.

0.55 inch: The OSC′ is about four times as large as its tolerance allows, and as a result the objective shows a lot of coma. The zonal spherical aberration zsA= −0.0037, which is much smaller than its tolerance (OTz = 0.006). The OPD between the axial and the marginal rays is −0.7μm, the maximum value is 1.08μm. The long wavelength is more under-corrected than the mid-wavelength; for the short wavelength the objective is over-corrected.

6.3 POWELL & LEALAND

There is no evidence of any connection between Lister and Powell in the papers bequeathed to the Royal Microscopical Society by Lister's son. Only Ross in his article in the Penny Cyclopædia writes:[11]

> The new principles were applied and exhibited by Mr. Hugh Powell and Mr. Andrew Ross with a degree of success which had never been anticipated....

To investigate this a number of objectives by Powell and later ones by Powell & Lealand (partners from 1842 onwards) were measured. The number of objectives is large, Powell & Lealand objectives being still most abundant. In many cases the construction is such as to make it impossible to take the objectives apart. For this reason it was possible to measure the construction for a limited number of objectives only.

A very characteristic feature of Powell's objective is his triple front, which was described by Fletcher.[12]

Powell made a number of lenses with very small focal lengths of 1/25, 1/26, 1/50, and 1/60 inch. I investigated the ones I found but these were either damaged too much or made for a thinner cover glass than the usual 0.17mm. Therefore the number of results is too small to justify their inclusion.

6.4 CONTINENTAL OBJECTIVES

Lister's designs gave Ross, Smith and Powell a great advantage over their competitors, especially during the period 1837–1850. In this period they used Lister's original designs and adaptations to increase the NA of their objectives.

The jury of the Great Exhibition of 1851 rewarded both Ross and Smith & Beck with the Council Medal; Powell & Lealand did not exhibit, otherwise they certainly would also have won one. Of the Continental makers only Nachet was thought acceptable.[13]

After 140 years it is still a difficult task to compare the English objectives from the period 1835–1850 with those from the Continent. From a mechanical point of view the English were definitely better. It was not necessary to screw and unscrew a number of components to assemble the objective that was required. This assembling and disassembling was a great drawback of many Continental objectives, like those of Schiek, Plössl and Amici. It was cheaper only: one doublet lens could be used in more than one combination.

Comparing English objectives with each other was easier. They were made in a reasonably well defined range of focal lengths. They even had a name like a '1/8in.'. A continental objective on the other hand had to be assembled from a number of doublets according to the directions of its maker.

The number of English objectives is larger and many of them can be dated fairly accurately. Only in the Utrecht collection I had a number of well dated

11 Ross [94], 177–188, (184).
12 Fletcher [45], 514–520.
13 Various [117], 265–269.

continental objectives at my disposal. The microscopes from the former Physical Laboratory and the instruments from the Zoological Laboratory bought by Pieter Harting (1812–1885) have a good provenance (see Appendix 3 for a list of the Utrecht microscopes). Though there are at least fifteen microscopes by Nachet in the Utrecht collection I do not include any of them in this comparative examination; Harting bought them after 1850 and they are difficult to date exactly. Apart from the Utrecht microscopes with their UM and Li inventory numbers I included a number of microscopes from the Science Museum (SM inventory numbers) which could be dated with some accuracy.

The microscopes by Schieck were dated by using the information provided by Weil und Baden.[14] Both were signed 'Schiek in Berlin'.

According to the technical file in the Science Museum the Plössl microscope SM1928–801 was made in 1835 for the physiologist Schwann (1810–1882). A similar one in Utrecht (UM296) has a note by Harting dated '1843', giving the combinations of its doublet lenses. So it can be dated somewhere between 1835 and 1843. The third one, SM1925–149 is a simpler and much smaller model. It might be a little older.

The Amici microscopes SM1954–287 and SM1938–688 are similar to the one Harting bought in 1848 (UM351). The objective of SM1938–688 is a very special one, a water-immersion with a single lens ruby front. It showed the lines on Pleurosigma angulatum. Harting mentions that Amici made water-immersion objectives from ca. 1850 onwards, when professor F.C. Donders (1818–1889) from Utrecht bought one.[15]

When we form groups of objectives with a comparable focal length from table 88 and try to find some common characteristics with the English objectives (Appendix 8) from the same period the supposed superiority of the English ones is not very obvious. In the group 2mm–2.7mm, which can be well compared with the English 1/8in. objectives, the NA seems to increase from 0.43 in 1838 to 0.7 in 1849. A similar trend is found for the 1/8in. Ross objectives, while the NA of Powell & Lealand might have been slightly higher. In the group 5mm–7mm, equivalent to the English 1/4in. objectives, the NA varies between 0.45 and 0.53. An obvious trend is lacking. The comparable 1/4in. objectives by Ross and Powell & Lealand (Appendix 8) have similar values of the NA. Lastly, the two objectives of 9.1mm and 10.3mm focal length compare well with the 0.5in. objectives by Ross and Powell & Lealand. In both groups we find similar values of the NA.

I found some data of Ross's objectives in Queckett's *Practical Treatise* of 1848.[16] Harting copied this and later added the data of the objectives belonging to the microscope which Ross sent to the Great Exhibition.[17] In table 89 the the numerical aperture of Ross's objectives as given by Queckett and Harting are listed.

Comparing the numerical apertures of table 89 and those of Appendix 8 shows that the values I actually measured are lower. There are two possible explanations for this discrepancy. The first is that Ross's measurements of the angular aperture–which Quekett used–were inaccurate. The second possibility is that his values are those of the best objectives he had made. My tables in Appendix 8 show

14 Weil and Baden [119], 9–12.
15 Harting [59], 174.
16 Queckett [89], 430–431.
17 Harting [59], 203.

Table 88: Continental objectives, 1830–1850

Invent no.	Made by	date	name	f (mm)	NA	d(μm)	MRP (μm)
SM1921-754	Amici/Modena	1830, c.	.../../.	6.78	0.45	0.71	1
Li116	Ch. Chevalier	1835	'3'	5.12	0.23	1.4	3.2
Li116	Ch. Chevalier	1835	'5'	0.9	0.47	0.68	1.3
UM296	Plössl	1835–1843	4/5/6	8.1	0.45	0.71	1.3
UM296	Plössl	1835–1843	5/6/7	4.23	0.69	0.46	0.7
SM1925-149	Plössl	1835, c.	4/5/6	6.87	0.49	0.65	1
SM1928-801	Plössl	1835	4/5/6	7.69	0.48	0.67	1.5
SM1928-801	Plössl	1835	5/6/7	4.39	0.59	0.54	<1
SM1928-801	Plössl	1835	3/6/7	4.2	0.6	0.53	<1
Li118	Amici/Firenze	1836	U7	6.92	0.45	0.71	0.8
Li118	Amici/Firenze	1836	U8	3.86	0.57	0.56	0.7
UM230	Ch. Chevalier	1838	./../...	9.1	0.44	0.73	1.3
UM230	Ch. Chevalier	1838	1/2/3	4.2	0.47	0.68	1
UM230	Ch. Chevalier	1838	+/++/+++	2	0.43	0.75	0.8
SM1921-250	Schiek No.32	1838, c.	4	6.23	0.53	0.6	<1
SM1921-250	Schiek No.32	1838, c.	5	7.55	0.56	0.57	<1
UM31	Schiek No.135	1839-40	1/2/3	10.3	0.25	1.28	1.6
UM31	Schiek No.135	1839-40	2/3/4	5.7	0.51	0.63	1
UM76	Lerebours	1844-1854	2	4.06	0.36	0.89	1.6
	Secretan		3	2.28	0.49	0.66	0.8
SM1921-750	Nobert	1845-1855	4	5.16	0.45	0.71	1
SM1921-750	Nobert	1845-1855	5	2.3	0.68	0.54	<1
UM27	Oberhaüser	1848	IX	8.44	0.28	1.15	1.6
UM351	Amici	1849	L2	8.46	0.61	0.53	<0.8
UM351	Amici	1849	L8	3.95	0.58	0.55	0.7
UM351	Amici	1849	L10	2.71	0.7	0.46	0.7
SM1954-287	Amici	1850, c.	./../.../....	4.32	0.57	0.64	<1
SM1938-688	Amici	1850, c.	10	1.73	1.04	0.35	0.55

that there were considerable differences between individual objectives. It is not impossible that a specially made 1/4in. had a higher numerical aperture than one which was not made for a particular customer.

Table 89: Numerical aperture of Ross's objectives, 1832–1851

date	1 in.	1/2 in.	1/4 in.	1/8 in.	1/12 in.
1832	0.12	-	-	-	-
1833	0.16	-	-	-	-
1834	-	-	0.46	-	-
1836	0.19	-	-	0.5	0.59 (1/10 in.)
1838	-	-	-	0.53	-
1842	-	0.37	0.52	0.6	-
1844	-	-	-	0.67	0.92
1851	0.23	0.5	0.83 (1/5 in.)	0.8	0.92

6.5 CONCLUDING REMARKS

It was hoped that the investigation of a large number of objectives from the period 1830–1850 might enable us to draw a much better founded and more precise picture of the increase in numerical aperture related to the date of manufacture of the objectives.

The graph published by Van Cittert in 1951 – showing the increase of the numerical aperture over the period 1790–1920 – was based upon the measured values of only thirteen objectives.[18] In 1966 Turner published a comparable graph, also based upon a small number of objectives.[19] A complicating factor is that Turner uses secondary sources on top of that, one of them being John Quekett (who for his part got his data from Ross). As I showed in the previous paragraph Quekett's (i.e. Ross's) data are perhaps a bit too optimistic. This does not mean I disagree with the general point of both Van Cittert and Turner – the dramatic increase of the numerical aperture between 1830–1850 – but I should like to emphasise that the character of their graphs is only schematic. In Figure 20 I collected the Numerical apertures and dates of manufacture of Van Cittert's Continental objectives listed in 1951, Turners English objectives of 1966, my own measurements of Continental objectives and my measured values of English objectives. The trend is obvious, the Numerical aperture doubled between 1835 and 1850. Continental objectives seem to lag behind, but as the number of investigated Continental objectives is so low that I hesitate to state as self-confident as my predecessors that they were inferior.

I would like to stress that we must be careful not to pay too much attention on the numerical aperture alone. The numerical aperture is a measurable and important quantity indeed, but it is good to realise that above a certain value a further increase is of interest for 'diatom hunters' only. It has a limited value for everyday microscopy. In this respect the Dutch histologist professor Dr. J.

18 van Cittert and van Cittert-Eymers [114] 73–80, (77).
19 Turner [103], 175–199, (188–190).

James compares the Numerical aperture with a double-edged sword.[20] Increasing the Numerical aperture also increases the transversal resolving power, but the simultaneous decrease of the axial depth of field undoes much of this advantage.

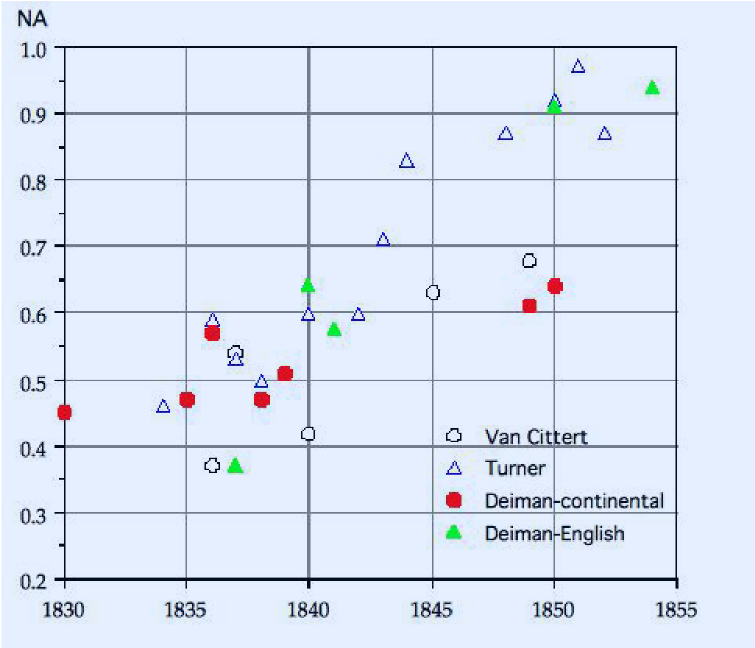


Figure 41: NA and date of achromatic objectives, 1830–1855

Similar remarks are found in the 1852 Reports by the Juries of the Great Exhibition:[21]

> ... as in all lenses of large aperture, the image becomes indistinct from the slightest change of focus: –and so, unless an object be an absolute plane, it is impossible to see the whole field tolerably distinct at once with an object-glass of large aperture. In the set examined, the inch, the half-inch, and the one-eighth of an inch, are intended for the general examination of objects; and the one-fourth and one-twelfth of an inch for the examination of minute structures.

My original hope to be able to trace the development of the achromatic objective between 1835 and 1850 much more accurately could not be fulfilled. The number of dated objectives was lower than I thought, and though Powell's microscopes are all dated their objectives are not. One can never be sure whether the objectives were bought later than the microscope. Of a number of objectives the optical construction could be found out (Appendix 8.2) but this did not allow me to show a line of development either. The combination of a triple back, a double middle, and a triple front element as mentioned by Carpenter and attributed by him to Lister or Amici was found in a number of objectives made after 1850 by Powell and Lealand.[22] However, the spread in numerical aperture was considerable and many slightly different constructions were found. As a result it was

20 James [69], 68–71.
21 Various [117], 266.
22 Carpenter [23], 310.

impossible to tell which were earlier and which were later forms. They might as well have been produced in the same period.

It is obvious Lister's designs gave Ross, Smith and Powell & Lealand an advantage over their competitors, especially between 1837 and 1850. Important aspects are that a range of objectives was produced and that the instrument makers started realising the importance of a large angular aperture.

7 CONCLUSIONS AND SUBJECTS FOR FURTHER RESEARCH

7.1 CONCLUSIONS

The purpose of this thesis was to investigate whether there were 'internal' technological reasons for the slow development of the optical system of the microscope, compared to the telescope, especially in the period from ca. 1750 to ca. 1850.

It was thought absolutely necessary to go back to primary sources as much as was possible and practicable. To this end a representative selection was made of microscopes in the Utrecht, the London, and the Oxford collections.

About sixty microscopes from the eighteenth century were investigated to obtain an overall view of their quality and assembly. The same was done with a hundred microscopes from the nineteenth century to see which were the problems encountered and how their designers solved them.

The study of eighteenth-century microscopes revealed that they were not as bad as many authors assume. Spherical aberration, often mentioned as a cause for this bad quality, was nearly always smaller than the optical tolerance according to Zernike's modified Rayleigh–Conrady criterion, as can be seen from Figure 9.

In single lens microscopes chromatic aberration is relatively harmless. The eyepieces of compound microscopes were found to be of acceptable quality. Their magnification was always low, four to eight diameters at most. Only in late eighteenth-century microscopes does the abundance of lenses cause loss of contrast and their large field of view gives occasion to distortion of the image. The claim that the image of these microscopes was degraded by spherical and chromatic aberration is in my view an oversimplification.

In my opinion it would be better to claim that the usefulness of non-achromatic miscroscopes is limited by empty magnification. As I showed in §3.2 that the numerical aperture–and as a consequence the magnification–of these microscopes cannot be increased beyond certain limits.

A precise limit of the magnification is difficult to give, but a value of 150 diameters with a 5mm objective lens and a x5 eyepiece is about the maximum value to be attained. The numerical aperture is in this case limited to ca. 0.15; the resolving power could be 2.4μm. It is shown in §3.2 that 17% of the 243 single lens objectives that I investigated have a focal length smaller than 5mm. When they are used in a compound microscope this will inevitably lead to empty magnification. That many of these strong objectives were used in this (wrong) way is proved by the globular structures which were observed by many microscopists of the period. Globular structures are a typical by-product of empty magnification.

A second cause for a bad quality of the image was the very primitive way in which the lenses were ground and polished. In telescopes, eyepieces, and low-magnification object glasses this is relatively harmless. However, high-magnification lenses of microscopes the smallest irregularities in the structure of the surface, caused by imperfect polishing, deteriorate the image considerably. In star tests performed with these lenses this was confirmed by the irregular and spiky form of the diffraction rings. This, and bad centering of the lenses, which are generally fitting very loosely in their mounts, limits the quality of eighteenth and early nineteenth-century microscopes. It explains why blown lenses were preferred for high-magnification single lens microscopes, since they do not have these surface irregularities.

In the nineteenth century the technology of making lenses advanced gradually and it became possible to make achromatic doublets and triplets for microscopes in the same way as this was done for telescopes. In the 1820s and 1830s, a period of transition, the old-fashioned non-achromatic microscope, the single lens microscope, and the jewel microscope were serious competitors of the achromatic doublet and triplet microscope.

It is in this period that people started to stress how bad the old eighteenth-century microscopes were. Analogies with our own time are abundant. The fact that the old non-achromatic microscope–if properly used–was not so bad explains why it took a relatively long period before the compound achromatic microscope completely dominated the market. An important difference with telescopes becomes manifest in this period. The objective of a telescope can be designed using simplified thin-lens approximations which allow for a considerable spread in the optical properties of the glass and accuracy of the curvatures of the surfaces. Making a number of lenses the best combinations can be selected and residual aberrations can be annulled by zoning. This does not work very well with microscope objectives as the tiny lenses are too small for zoning. As a result a much more rigorous control of all the relevant parameters, especially the optical parameters of the glass, is much more vital for microscopes.

A second difference is that the power of a telescope can be increased by making the diameter of its objective larger, so that it will collect more light. A microscope needs a higher numerical aperture, which cannot be attained by decreasing the dimensions alone. A simple achromatic doublet or triplet of the early nineteenth century is limited to a NA of ca. 0.2. The only way to increase the NA beyond this value is to employ the compound achromatic objective, a combination of doublets and triplets.

In France they were invented by Selligue and Chevalier but their full potential was realised by Lister in 1829–1830. His major contribution to the development of the compound achromatic objective was the discovery of some of the laws which govern the behaviour of achromatic doublets and triplets. This allowed him to combine them in a rational way. His systematic investigations showed him which combinations of biconvex, biconcave, and plano-convex or plano-concave lenses could be used to assemble a compound objective. The first compound systems were individually made using a mixture of scientific reasoning and much trial and error. As a result they were expensive, their number was relatively small, and only very few people were able to make them.

The gradual increase of the numerical aperture of objectives of a particular focal length by Ross, Smith, Smith & Beck, and Powell & Lealand over the period 183–1850 proves the success of Lister's methods. In 1851, the year of the Great

Exhibition, the dry achromatic objective of short focal lenght had reached its maximum aperture.

After the initial success of Lister's designs and the gradual improvements on them by the leading British instrument makers, the fact that Lister had no scientific successors proved to be fatal. Continental 'entrepreneurs', like Oberhaüser, Hartnack, and later Zeiss and Leitz could easily take over the initiative. Employing a scientist like Ernst Abbe, Zeiss could improve the optical designs and also rationalise the production of the objectives. This enabled Zeiss to produce objectives in much larger quantities and at a much lower price.

7.2 SUBJECTS FOR FURTHER RESEARCH

In my opinion one of the limitations of the eighteenth-century microscope is the insufficient quality of the optical surfaces of the objective glass. Quantitative research with a micro-interferometer must be performed to reveal the seriousness of these defects.

The main cause for the surface irregularities is the way the lenses were polished, on cloth or on paper. More research should be done in historical aspects of the technology of lens grinding and polishing.

When instrument makers started making achromatic doublets, optical glass with accurately defined properties did not exist. Virtually nothing is known of the sources of glass in eighteenth-century instruments. More research should be carried out on the optical properties and chemical composition of glass. In a few cases the source of the glass of nineteenth-century instruments is known, but more research should be done in this field. The optical properties of glass made in this period are virtually unknown, so it might be useful to investigate optical instruments from this period to find out what kind of glass was used.

The photographic lens, being more complex than the telescope lens because of the flat field which is required and the greater relative aperture which was needed as long as photographic plates were very insensitive, had a profound impact on optical technology. Photographic objectives were required in great quantities and had to be produced at low prices. This forced instrument makers to employ scientists to design them and to adopt methods of accurate production. Not much is known about this, and the influence it must have had on the design and production of microscope objectives. Detailed research in this field might give us a better idea of the development of optical technology.

In this thesis I limited myself to the influence of Lister on the development of the achromatic compound microscope objective. Similar developments took place in France (Chevalier, Oberhaüser–Hartnack, Nachet), in Italy (Amici), in Germany (Schiek, Kellner–Leitz, Zeiss), and in Austria (Plössl). Further research should be done to investigate these developments and the way scientists influenced them.

Not much is known of the profitability of the trade. Again, more research should be done.

8 APPENDIX 1: OPTICAL GLASS

This is the list of 21 'old' glasses from the list of 44 glasses, produced by Schott in Jena in 1886. Hovestadt used these glass types to derive his formula, see section 2.2.4, formula 6.
Legends:

- The first column, headed 'no.' is the current number from Czapski's list in the Zeitschrift für Instrumentenkunde of 1886.
- The second column, headed 'German name', gives Czapski's name for the glass.
- The third column, headed 'Schott' gives the corresponding glass type (if available) from the 1923 catalogue of Schott & Gen. in Jena.
- N_D, ΔN, and N_F are the refractive index for the D-line, the dispersion $N_F - N_C$ and the refractive index for the F-line respectively.

Table 90: Optical glass

no.	German name	Schott	N_D	ΔN	N_F
6	Leichtes Silikat-Crown	K1	1.5086	0.00823	1.51438
7	Silikat-Crown	K9	1.5166	0.00849	1.52256
8	Calcium-Silikat-Crown	-	1.5179	0.00860	1.52395
13	Gewöhnl. Silikat-Crown	K3	1.5175	0.00877	1.52366
14	Kalium-Silikat-Crown	-	1.5228	0.00901	1.52917
17	Silikat-Crownglas	-	1.5160	0.00904	1.52237
18	Weiches Silikat-Crown	-	1.5151	0.00910	1.52152
23	Silicat Glas	-	1.5368	0.01049	1.54423
26	Silikat-Glas	-	1.5366	0.01102	1.54441
29	Leichtes Silicat-Flint	LF1	1.5710	0.01327	1.58043
31	Leichtes Silicat-Flint	LF2	1.5900	0.01438	1.60022
34	Gewöhnl. Silicat-Flint	F3	1.6129	0.01660	1.62474
35	Gewöhnl. Silicat-Flint	F4	1.6169	0.01691	1.62896
36	Gewöhnl. Silicat-Flint	F2	1.6202	0.01709	1.63240
37	Gewöhnl. Silicat-Flint	F1	1.6245	0.01743	1.63693
38	Schweres Silicat-Flint	SF2	1.6489	0.01919	1.66262
39	Schweres Silicat-Flint	SF5	1.6734	0.02104	1.68847
40	Schweres Silicat-Flint	SF1	1.7174	0.02434	1.73489
41	Schweres Silicat-Flint	SF3	1.7371	0.02600	1.75580
42	Schweres Silicat-Flint	SF4	1.7541	0.02743	1.77384
43	Sehr schw. Silicat-Flint	-	1.7782	0.02941	1.79940

9

APPENDIX 2: SINGLE LENS OBJECTIVES

Single lens objectives of compound microscopes in the Science Museum, the Wellcome Collection, and the Utrecht University Museum.
Legends:

- invent. no.:
  - UM and Li inventory numbers: Utrecht University Museum
  - SM: private collection, Utrecht University Museum
  - Chrs: Christies, London
  - year-number: Science Museum London
  - 'A' inventory numbers: Wellcome Collection London
- f: focal length in mm
- d(μm): the smallest resolvable distance, calculated from the NA.
- MRP: the measured resolving power(μm), measured with the line test plate.

Table 91: Single lens objectives

invent.no.	made by	type	f	NA	d(μm)	MRP
A159192.01	Adams	1	5.47	0.116	3.16	3
A159192.02	Adams	2	9	0.087	4.21	6.25
A159192.03	Adams	3	24.1	0.037	9.89	9.5
A159192.04	Adams	4	31.07	0.033	11.12	10.5
A159192.05	Adams	5	48.52	0.021	17.61	15
A159473.01	Adams	1	10.39	0.05	7.41	7
A159473.02	Adams	2	20.08	0.024	15.29	14
A159473.03	Adams	4	42.93	0.015	24.34	22
A159473.04	Adams	5	56.33	0.012	31.6	30
A159980.01	Adams	1	7.31	0.068	5.42	5.25
A159980.02	Adams	2	11.96	0.051	7.13	6.25
A159980.03	Adams	3	18.69	0.035	10.62	10
A159980.04	Adams	4	23.54	0.027	13.38	11.5
A159980.05	Adams	5	28.56	0.028	13.06	12
A56523.01	Adams	1	10.65	0.073	5.06	4.5
A56523.02	Adams	2	19.62	0.041	8.92	8.5
A56523.03	Adams	3	27	0.03	12.16	11
A56523.04	Adams	4	41.54	0.018	20.39	20
A56523.05	Adams	5	57.99	0.015	24.69	25
A56523.07	Adams	a	2	0.213	1.72	2.75
A56523.08	Adams	b	2.8	0.172	2.13	4
A600168.01	Adams	1	2.47	0.212	1.73	2
A600168.02	Adams	2	7.34	0.089	4.13	4
A600168.03	Adams	3	12.12	0.078	4.7	5.5

Continued on next page

invent.no.	made by	type	f	NA	d(μm)	MRP
A600168.04	Adams	4	16.44	0.048	7.58	6.75
A600168.05	Adams	6	33.14	0.036	10.17	9
A645025.01	Adams	1	3.55	0.266	1.38	3.5
A645025.02	Adams	4	10	0.082	4.5	4.75
A645025.03	Adams	5	15.11	0.061	5.97	5.5
A645025.04	Adams	6	16.57	0.061	6.02	5.5
UM967.01	Adams	1	3.71	0.16	2.29	2.5
UM967.02	Adams	2	6.87	0.09	4.07	6.5
UM967.03	Adams	3	11.23	0.08	4.58	6.5
UM967.04	Adams	4	16.55	0.07	5.23	6.5
UM967.05	Adams	5	24.1	0.05	7.33	8
UM967.06	Adams	6	32.2	0.04	9.16	10
UM967.07	Adams	7	55.5	0.024	15.27	14
UM967.08	Adams	8	73	0.025	14.66	19
A56301.01	Adams, D.	1	6.29	0.096	3.83	4.5
A56301.02	Adams, D.	2	7.62	0.062	5.93	6.25
A56301.03	Adams, D.	3	11.08	0.061	6	8
A56301.04	Adams, D.	4	15.92	0.039	9.48	9.5
A56301.05	Adams, D.	5	22.16	0.035	10.4	11
A56301.06	Adams, D.	6	26.92	0.031	11.76	11
A56305.01	Adams, D.	1	3.99	0.123	2.99	3.25
A56305.02	Adams, D.	2	7.62	0.077	4.78	4.5
A56305.03	Adams, D.	3	13.15	0.05	7.4	7.75
A56305.04	Adams, D.	4	16.57	0.044	8.24	7.75
A56305.05	Adams, D.	5	22.59	0.046	7.98	10
A56305.06	Adams, D.	6	28.17	0.028	12.9	11.5
UM576.01	Canzius	1	3.64	0.11	3.33	4
UM576.02	Canzius	2	5.7	0.077	4.76	6.5
UM576.03	Canzius	4	17.9	0.04	9.16	10
UM576.04	Canzius	5	30.7	0.025	14.66	19
UM576.05	Canzius	3	12.5	0.049	7.48	8
UM73.01	Cary	I	38.7	0.011	33.33	26
UM73.02	Cary	II	29.7	0.016	22.91	21
UM73.03	Cary	III	18.6	0.031	11.82	12
UM73.04	Cary	L	9.6	0.072	5.09	6.5
A62993.03	Cuff	3	8.81	0.089	4.14	4.5
A62993.04	Cuff	4	13.5	0.084	4.39	5
A62993.06	Cuff	5	17.4	0.066	5.56	7
A62993.07	Cuff	6	29.82	0.039	9.33	8
UM578.01	Cuff	1	3.23	0.13	2.82	2.5
UM578.02	Cuff	2	5	0.12	3.05	3.2
UM578.03	Cuff	3	8	0.1	3.66	4
UM578.04	Cuff	4	12.9	0.063	5.82	6.5
UM578.05	Cuff	5	18.5	0.049	7.48	8
UM578.06	Cuff	6	31	0.034	10.78	10
UM10.01	Culpeper	1	3.27	0.14	2.61	3.2
UM10.02	Culpeper	2	8.07	0.069	5.31	6.5

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invent.no.	made by	type	f	NA	d(μm)	MRP
UM10.03	Culpeper	3	10.3	0.11	3.33	4
UM10.04	Culpeper	4	14.5	0.08	4.58	6.5
UM10.05	Culpeper	5	25.6	0.062	5.91	8
UM1846.01	Culpeper	1	4.07	0.16	2.29	2.5
UM1846.02	Culpeper	2	5.84	0.093	3.94	6.5
UM1846.03	Culpeper	3	7.3	0.096	3.81	6.5
A60955.01	Dellebarre	4	32.89	0.027	13.48	12.5
Chrs.02	Dellebarre	2	5.33	0.082	4.46	4.25
Chrs.03	Dellebarre	4	15.39	0.056	6.59	6.5
UM23.01	Dellebarre (?)	1	13.63	0.079	4.64	6.5
UM23.02	Dellebarre (?)	2	3.55	0.086	4.26	3
A135495.01	Dellebarre, (?)	1	3	0.138	2.65	3
A135495.02	Dellebarre, (?)	2	7.55	0.086	4.27	4
A135495.03	Dellebarre, (?)	3	8.52	0.077	4.74	4.5
A159502.01	Dollond	1	6.11	0.086	4.25	4.25
A159502.02	Dollond	2	9.69	0.063	5.81	6
A159502.03	Dollond	6	26.51	0.04	9.19	8.5
A50965.02	Dollond	3	22.78	0.021	17.16	15
A50965.04	Dollond	5	28.4	0.042	8.67	8
A50965.05	Dollond	5	18.23	0.051	7.22	6.75
A56304.01	Dollond	a	21.54	0.07	5.23	4.75
A600179.01	Dollond	a	19.88	0.129	2.85	
A600179.02	Dollond	b	33.14	0.13	2.81	4
A645008.02	Dollond	2	7.48	0.058	6.37	4
A645008.03	Dollond	3	13.85	0.055	6.65	6.25
A645008.04	Dollond	4	20.71	0.046	7.98	7.5
A645008.05	Dollond	5	30.38	0.036	10.3	9.25
A645008.06	Dollond	6	41.42	0.034	10.69	10.5
UM1018.01	Dutch (?)	'2'	8.49	0.068	5.39	8
UM1018.02	Dutch (?)	'1'	3.73	0.19	1.93	3.2
UM1018.03	Dutch (?)	'3'	30.2	0.018	20.37	19
UM146.01	Dutch (?)	2	6.54	0.083	4.41	6.5
UM146.02	Dutch (?)	3	6.68	0.091	4.02	6.5
UM146.03	Dutch (?)	4	12.8	0.062	5.91	10
UM22.01	Dutch (?)	1	5.48	0.11	3.33	3.2
UM22.02	Dutch (?)	3	16.06	0.051	7.19	8
UM22.03	Dutch (?)	4	21.35	0.045	8.14	10
UM22.04	Dutch (?)	5	27.01	0.053	6.91	8
UM235.01	Dutch (?)	I	10.1	0.15	2.44	4
UM235.02	Dutch (?)	II	16.8	0.083	4.41	5
UM235.03	Dutch (?)	III	25.2	0.053	6.91	0
UM378.01	Dutch (?)	'1'	6.11	0.093	3.94	4
UM378.02	Dutch (?)	'2'	7.31	0.073	5.02	6.5
UM378.03	Dutch (?)	'3'	12.63	0.043	8.52	10
UM378.04	Dutch (?)	'4'	17.16	0.029	12.64	12
UM378.05	Dutch (?)	'5'	39.8	0.025	14.66	14
UM568.01	Dutch (?)	'1'	3.74	0.15	2.44	2.5

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invent.no.	made by	type	f	NA	d(μm)	MRP
UM568.02	Dutch (?)	'2'	4.75	0.11	3.33	2.5
UM568.03	Dutch (?)	'3'	5.23	0.13	2.82	3.2
UM568.04	Dutch (?)	'4'	5.96	0.083	4.42	6.5
UM568.05	Dutch (?)	'5'	9.63	0.074	4.96	6.5
UM568.06	Dutch (?)	'2'	7.38	0.13	2.82	4
UM568.07	Dutch (?)	'3'	14.63	0.079	4.64	8
UM568.08	Dutch (?)	'4'	3.65	0.16	2.29	2.5
UM568.09	Dutch (?)	'4'	19.35	0.054	6.79	10
UM568.10	Dutch (?)	'5'	25.06	0.095	3.86	8
UM568.11	Dutch (?)	'6'	32.61	0.079	4.64	10
UM229.01	Eastland	'1'	4.4	0.11	3.33	3.2
UM229.02	Eastland	'2'	3.05	0.2	1.83	2.5
UM229.03	Eastland	'3'	2.95	0.11	3.33	2.5
UM229.04	Eastland	'4'	4.3	0.1	3.66	3.2
SM1.01	English (?)	-	9.54	0.079	4.64	6.5
UM11.01	English (?)	1	3.7	0.13	2.82	3.2
UM11.02	English (?)	2	6	0.11	3.33	3.2
UM11.03	English (?)	3	13.5	0.057	6.43	6.5
UM11.04	English (?)	4	21.4	0.042	8.73	8
UM11.05	English (?)	5	31.4	0.029	12.64	10
UM14.01	English (?)	1	3.3	0.13	2.82	2.5
UM14.02	English (?)	2	7.9	0.08	4.58	5
UM14.03	English (?)	3	13.3	0.06	6.11	8
UM14.04	English (?)	4	17.8	0.05	7.33	8
UM17.01	English (?)	1	3.31	0.04	9.16	10
UM17.02	English (?)	2	6	0.05	7.33	8
UM17.03	English (?)	3	8.4	0.067	5.47	8
UM17.04	English (?)	4	16.8	0.08	4.58	6
UM17.05	English (?)	5	20.8	0.1	3.66	3.2
UM17.06	English (?)	6	28.6	0.16	2.29	2.5
UM292.01	English (?)	-	2.52	0.18	2.03	2.5
UM43.01	English (?)	I	40.7	0.012	30.55	28
UM43.02	English (?)	II	28.35	0.022	16.66	15
UM43.03	English (?)	III	23.36	0.029	12.64	12
UM77.01	English (?)	4	24.7	0.041	8.94	10
1925?143.01	Fokkenberg	a	5.29	0.14	2.63	3
UM312.01	French (?)	-	9.7	0.11	3.33	0
UM42.01	German		6.39	0.076	4.82	6.5
UM577.01	German	-	10.95	0.058	6.32	8
A212741.07	Jones, W & S	a	45	0.043	8.62	9
A56801.01	Jones, W & S	1	7.1	0.069	5.32	4.75
A56801.02	Jones, W & S	2	11.37	0.049	7.52	6.75
A56801.03	Jones, W & S	4	24.23	0.035	10.36	9.5
A600166.07	Jones, W & S	a	2.62	0.145	2.53	2
A600166.08	Jones, W & S	b	4.42	0.113	3.24	3.5
UM514.01	Kleman	1	4.11	0.1	3.66	0
UM514.02	Kleman	2	7.67	0.06	6.11	6.5

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invent.no.	made by	type	f	NA	d(μm)	MRP
UM514.03	Kleman	3	11.77	0.047	7.8	8
UM514.04	Kleman	4	16.06	0.034	10.78	10
UM986.01	Kleman	1	4.14	0.19	1.93	2.5
UM986.02	Kleman	2	7.24	0.19	1.93	2
UM986.03	Kleman	3	7.15	0.21	1.74	2.5
UM986.04	Kleman	4	12.05	0.083	4.41	4
UM986.05	Kleman	5	16.3	0.088	4.16	6.5
UM986.06	Kleman	6	25.9	0.044	8.33	10
UM18.01	Lincoln	1	5.85	0.14	2.61	3.2
UM18.02	Lincoln	2	9.27	0.11	3.33	3.2
UM18.03	Lincoln	3	18.5	0.057	6.43	8
UM18.04	Lincoln	4	19	0.082	4.47	4
UM18.05	Lincoln	5	25.3	0.063	5.82	6.5
UM18.06	Lincoln	6	31.6	0.073	5.02	6.5
A101926.04	Martin	4	18	0.059	6.25	6
A101926.05	Martin	5	23.37	0.055	6.67	6
A101926.06	Martin	6	32.02	0.069	5.31	8.5
Li117.01	Martin	2	7.35	0.06	6.11	6.5
1882–1.02	Martin	2	3.78	0.097	3.79	3.5
1882–1.03	Martin	3	9.44	0.051	7.18	6.75
1882–1.05	Martin	4	13.39	0.045	8.21	7.75
1882–1.06	Martin	5	19.39	0.052	7.11	7
UM330.01	Martin	(B)	17.8	0.2	1.83	5
UM330.02	Martin	(C)	13.9	0.07	5.23	6.5
UM330.03	Martin	(D)	5.6	0.12	3.05	5
A76350.04	Martin (?)	4	13.85	0.062	5.94	5.5
A76350.05	Martin (?)	5	20.39	0.048	7.63	8.25
A76350.06	Martin (?)	6	27.62	0.035	10.42	9.5
UM399.01	Martin (?)	3	8.94	0.071	5.16	6.5
UM399.02	Martin (?)	4	13.87	0.061	6.01	8
UM399.03	Martin (?)	5	18.62	0.048	7.63	8
UM399.04	Martin (?)	6	33.46	0.028	13.09	14
UM399.05	Martin (?)	L	9	0.088	4.16	8
UM19.01	'Martin et Fils'	1	10	0.055	6.66	8
UM19.02	'Martin et Fils'	2	19.3	0.035	10.47	10
UM19.03	'Martin et Fils'	3	22.9	0.029	12.64	14
UM19.04	'Martin et Fils'	4	23.8	0.032	11.45	14
UM19.05	'Martin et Fils'	5	25.2	0.027	13.58	14
1913–293.01	Ross, A.	a	7.13	0.067	5.44	5
1913–293.02	Ross, A.	b	9.92	0.073	5.06	5.25
1913–293.03	Ross, A.	c	16.15	0.055	6.66	6.25
1913–293.05	Ross, A.	d	19.78	0.046	7.91	7
UM13.01	Scarlet	1	3.56	0.16	2.29	2.5
UM13.02	Scarlet	2	8	0.07	5.23	6.5
UM13.03	Scarlet	3	11.32	0.085	4.31	4
UM13.04	Scarlet	4	24.82	0.036	10.18	10
UM13.05	Scarlet	5	34.3	0.03	12.22	14

Continued on next page

invent.no.	made by	type	f	NA	d(μm)	MRP
UM16.01	Sterrop	1	3.81	0.11	3.33	4
UM16.02	Sterrop	2	4.83	0.1	3.66	4
UM16.03	Sterrop	3	10.9	0.05	7.33	8
UM16.04	Sterrop	4	13.4	0.054	6.79	8
UM16.05	Sterrop	5	17.5	0.049	7.48	8
UM16.06	Sterrop	6	22.3	0.049	7.48	8
UM646.01	Sterrop	1	3.75	0.14	2.61	2.5
UM646.02	Sterrop	2	10.65	0.064	5.72	8
UM646.03	Sterrop	3	15.4	0.05	7.33	8
UM646.04	Sterrop	4	23.3	0.035	10.47	10
UM646.05	Sterrop	5	32.2	0.04	9.16	0
A600182.01	unknown	1	6.49	0.09	4.06	3.75
A600182.02	unknown	2	12.46	0.053	6.89	6.25
A600182.04	unknown	3	16.57	0.046	8.04	7.25
UM2510.01	unknown	4	17.2	0.042	8.73	10
UM291.01	unknown	1	3.55	0.13	2.82	5
UM291.02	unknown	2	7.73	0.061	6.01	8
UM291.03	unknown	3	11.8	0.052	7.05	8
UM291.04	unknown	4	15.6	0.052	7.05	8
UM291.05	unknown	5	21	0.047	7.8	8
UM291.06	unknown	6	28	0.039	9.4	10
UM354.01	Urings	1	4.1	0.13	2.82	2.5
UM354.02	Urings	2	9.4	0.066	5.55	6.5
UM354.03	Urings	3	14.4	0.052	7.05	8
UM354.04	Urings	4	22.3	0.038	9.65	10
UM72.01	Urings	1	3.73	0.14	2.61	3.2
UM72.02	Urings	2	5	0.17	2.15	2.5
UM72.03	Urings	4	21.9	0.042	8.73	10
UM72.04	Urings	5	28.2	0.042	8.73	10

10

APPENDIX 3: LISTER LENSES

In the collection of the Royal Microscopical Society, inventory number 209 is described as: 'Experimental lenses by J.J. Lister'. The lenses are kept in a presentation cabinet in the Museum of the History of Science in Oxford.[1] A description of these lenses is found in Spitta and Bracegirdle.[2]

As no information regarding the optical parameters of these lenses existed it was decided to make a detailed survey of the ca. 63 items that constitute this group. Their optical construction was analysed as this was not done very carefully in the past. The curvatures of their surfaces were measured together with the thickness and the focal length. The results are assembled in this appendix. The numbers correspond to those given by Bracegirdle in his 1987 article.

10.1 PLANO-CONVEX LENSES

No.	Description
15	Forced in a threaded brass mount, ø20.3/40tpi. The overall diameter of the mount is 21mm.
17	Forced in a threaded brass mount, ø18.8/40tpi. The overall diameter of the mount is 19.5mm.
24	An unmounted lens, the rim is irregular.
59	An unmounted lens, the rim is irregular. The paper in which it is wrapped says 'lens to apply to plane side of the flint plano concave of no. 3 Utzschneider'.[3]
60.2	Unmounted lens, wrapped in a piece of paper together with 60.1 (biconvex). The surface has been ground but not polished, the rim is only partly worked, the diameter varies from 4.5 to 4.8mm.
61	Unmounted lens, the rim is irregular.
62	Two unmounted lenses in a packet, marked 'plano conv[ex] 0.28 for an 0.4 concave' and on the inside of the paper 'plano convex for concave of dense flint 0.4 rad thin 0.28'.

No	radius mm	radius inch	thns mm	diam. mm	focus mm	focus inch	N
15	13.78	0.542	3.36	15.6	27.22	1.07	1.506
17	18.96	0.746	1.72	11.6	33.73	1.33	1.562
24	13.76	0.542	2.93	15.1	27	1.06	1.51
59	7.83	0.308	2.33	10.3	15.39	0.61	1.509
60.2			1.75				
61	13.24	0.521	2.53	16	25.77	1.01	1.514
62.1	7.73	0.304	2.48	10.6	15.39	0.61	1.502
62.2	9.05	0.356	3.93	10.8	18	0.71	1.503

10.2 PLANO-CONCAVE LENSES

No. Description

1 Turner [107]), 309–310, catalogue number 382. Collection inventory number 52745.
2 Spitta [98], 145–149; Bracegirdle [16], 273–297.
3 Lister Archive, L104a.

6,7,8 These unmounted lenses were wrapped in a paper stating 'Lenses of light flint, by Tulley'.[4] The lenses have a facetted rim marked with a hook, they are not centred, the diameter of lens no. 8 for instance varies between 13.55 and 13.82mm. The radius is given as 0.6".[5]

12 The paper of lens no. 12 is marked 'Faraday's dense flint'.[6] The flat face was badly weathered, I doubt whether the concave face was ever polished, the surface is very rough.[7]

63 This unmounted lens is wrapped in a slip of paper marked 'concave of 3/10 radius light flint'.[8]

No	radius mm	radius inch	thns mm	rim mm	diam. mm	focus mm	focus inch	N
		mm	inch	mm	mm	mm	inch	
6	15.06	0.593	1.24	2.7	13.7	−25.66	−1.01	1.587
7	15	0.591	1.9	3.3	13.8	?25.18	−0.992	1.596
8	14.95	0.589	1.83	3.28	13.7	?25.60	−1.008	1.584
12			1.28	1.95	8.2			
63	7.91	0.311	0.52		7.9	−16.13	−0.635	1.603

10.3 BICONVEX LENSES

No. Description

10,11 Two unmounted lenses in a paper marked as follows: 'Orig[inal] convexes by Tulley .04.'.

16 Cemented in a brass mount. The overall diameter is 21mm, the thread is ø19.6/2tpmm.

22 Simple eighteenth-century objective lens, size 5. Thread ø15.25/30tpi.

25 An unmounted lens with a faceted rim.[9]

31 A lens in a brass mount, thread ø15.1/32tpi. The lens is mounted on the top end of a narrow tube (ø6.2mm), the length of the tube is 11.5mm.

45 An unmounted lens, wrapped in paper marked as follows: 'convex .4 .43 french pl[ate]'.

46 An unmounted lens, wrapped in paper marked as follows: 'conv[ex] Engl[ish] pl[ate] .4 .43'.

47 An unmounted lens, wrapped in paper marked as follows: 'convex 0.4 .43 veiny'.

49 An unmounted lens, wrapped in paper marked as follows: 'Eng[lish] pl[ate] convex .4 .38'.

50 An unmounted lens, wrapped in paper marked as follows: 'convex .3 .3'.

51 An unmounted lens, wrapped in paper marked as follows: 'convex .4 .4'.

53 An unmounted lens, wrapped in paper marked as follows: '06 07 for back rather thin'.[10]

58 An unmounted lens, wrapped in paper marked as follows: 'convex radii 0.7 & 0.6 light plate glass veiny'. The rim is rather crudely worked.

4 Spitta [98], 146.
5 It is more probable these are the first lenses Lister made by himself in 1831, see Lister Archive, L28.
6 Spitta [98], 146
7 Lister received this piece of Faraday's dense flint probably in 1831 from Barlow, see L50 (Lister Archive).
8 Lister Archive, L28 and L29. This lens was probably made by Tulley.
9 Together with the numbers 53 and 58 these are probably the lenses mentioned in L28 (Lister Archive).
10 see the note to number 25.

60.1 An unmounted lens, wrapped in a piece of paper together with 60.2 (plano-convex). No. 60.1 was very dirty but in good condition, only the rim was partly worked.[11]

No	rds.1 mm	rds.1 inch	rds.2 mm	rds.2 inch	thns mm	diam. mm	focus mm	focus inch	N
10	9.96	0.392	10.08	0.397	3.47	10.6	10.36	0.408	1.514
11	10.06	0.396	10.08	0.397	3.76	10.9	10.65	0.419	1.504
16	12.29	0.484	11.38	0.448	3.08	11	12.36	0.486	1.5
22	17.46	0.687	17.49	0.689	0.94	6	17.31	0.681	1.51
25	17.46	0.688	15.42	0.607	3.32	13.3	16.81	0.662	1.504
31	0.977	0.038	1.15	0.045	1.48		1.277	0.0503	1.55
45	10.09	0.397	10.67	0.42	3.02	10.4	10.7	0.421	1.51
46	10.06	0.396	10.58	0.417	2.78	10	10.79	0.425	1.50
47	10.64	0.419	9.99	0.393	2.82	10.1	10.65	0.419	1.507
49	9.38	0.369	9.80	0.386	2.77	9.65	9.89	0.389	1.51
50	7.62	0.3	7.45	0.293	2.11	7.3	7.85	0.309	1.504
51	9.96	0.392	10.09	0.397	2.95	9.65	10.49	0.413	1.502
53	17.57	0.692	15.19	0.598	2.85	13	16.73	0.659	1.502
58	15.5	0.61	17.61	0.693	3.39	13.6	17.2		1.5
60.1	4.56	0.179	6.03	0.238	1.85	5.7	5.31	0.209	1.52

10.4 doublet lenses

10.4.1 *Wollaston doublet*

30 Mounted in brass, thread ø15.2/32tpi. The construction is as usual: a small plano-convex front lens, a stop, and immediately behind this a larger plano-convex lens. The convex side of the front lens is damaged and the flat side of the back lens has a bad polish.

10.4.2 *Achromatic doublets*

The construction of all these doublet lenses is the same, a plano-concave front lens and a cemented biconvex back lens. In the following tables plain text indicates the measured data and the data written on slips of paper which accompany the doublets (radius of curvature in inches, the first column). The italic numbers indicate the values which have been calculated using the curvature of the cemented surface measured through-the-lens.

1 An achromatic doublet in a brass mount, the diameter of the mount is 18.8mm. Numbered on the back of the mount 'XIII' and '•' on the front. Measured focal length: 32.16mm (1.266").

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.51	0.515	13.073	3.18	1.52	10.3	stop
2	−0.6	−0.581	−14.76	1.67	1.66	13.85	lenses
3	∞	∞	∞	4.87	1	9.6	stop

11 see the note to number 25.

2 An achromatic doublet in a brass mount, the overall diameter is 17.9mm, with a threaded front (ø13.5/48tpi) and back (ø17/40tpi). The doublet has been cemented in its mount with balsam. There is no stop on the front. Numbered 'X' on the back and '●●' on the front. Measured focal length: 35.34mm (1.392").

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.58	0.577	14.65	2.69	1.512	9.2	stop
2	−0.5	−0.494	−12.54	1.71	1.6	11.5	lenses
3	∞	∞	∞	4.40	1		

3 An achromatic doublet in a brass mount, the overall diameter is 18.9mm, the back is threaded (ø18.2/48tpi). The back is marked '● ● ●', and with pencil '55' and '58'. These values are mentioned on the accompanying slip of paper as well. Measured focal length: 35.50mm (1.398").

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.55	0.555	14.11	2.93	1.516	9.7	stop
2	−0.58	−0.58	−14.72	2.06	1.65	11.8	lenses
3	∞	∞	∞	4.99	1		

4 An achromatic doublet in a brass mount, the overall diameter is 17.9mm, the back is threaded (ø17.1/48tpi). The back of the mount is marked 'XI' and with '● ● ●●' on the front. According to the accompanying slip of paper the glass is English plate.[12]

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.48	0.479	12.15	2.66	1.522	7.3	stop
2	−0.4	−0.4	10.16	1.38	1.62		
3	∞	∞	∞	4.04	1	8.3	stop

5 An achromatic doublet in a brass mount, the overall diameter is 19.5mm, the back is threaded (ø17.6/48tpi). Measured focal length: 32.81mm (1.292").

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	-.-	0.545	13.87	2.74	1.513	7.8	stop
2	-.-	−0.498	−12.50	1.76	1.6	11.5	lenses
3	-.-	∞	∞	4.5	1	6.1	stop

9 An achromatic doublet in a brass mount, set in a wooden rim (ø17.5mm and thick 4mm). The doublet and the paper in which it is wrapped are marked 'X'. The paper mentions that this is a 'Chevalier 1 1/2 in doublet'. See section 5.5.2 of this thesis. Measured focal length: 38.11mm (1.5").

12 This is probably the doublet mentioned in F40 (Lister Archive).

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	-.-	0.614	15.61	1.81	1.501	7.5	stop
2	-.-	−0.614	−15.61	1.24	1.614	9.3	lenses
3	-.-	∞	∞	3.08	1		

13 An achromatic doublet in a brass mount, the overall diameter is 16.2mm. The mount and the accompanying paper are marked with four dots in a T shaped pattern. The biconvex lens is made of English plate, the plano-concave lens is made of Swiss flint.[13] Measured focal length: 17.95mm (0.707”).

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.28	0.286	7.26	2.02	1.504	6.5	mount
2	0.3	0.304	7.71	1.02	1.62	8	lenses
3	∞	∞	∞	3.04	1		

14 An achromatic doublet in a brass mount, the overall diameter is 24.1mm, on the rear the mount is threaded (ø22.5/40tpi). Measured focal length: 62.13mm (2.446")

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	-.-	1.078	27.39	4.78	1.519	16.5	mount
2	-.-	0.914	23.22	1.00	1.59	19.5	lenses
3	-.-	∞	∞	5.78	1	16	stop

26 An achromatic doublet in a brass mount. The doublet is mounted on a barrel which can slide over a back component, the internal diameter of the barrel is 14.2mm. The doublet is cemented in its mount. Over the doublet screws a little cap serving as a stop. The back side of the mount is marked ‘Δ’. There is an accompanying slip of paper which mentions that this is the ‘Front Glass makes with the back glass of Joseph’s 4/10 a 2/3 inch (that used in expts on defining powers 1842 etc.)’. The optical construction of this doublet is different, the front lens is a plano-convex crown and the back lens a concave-convex flint. Measured focal length: 28.40mm (1.118").

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	-.-	0.434	11.04	1.27	1.62		
2	-.-	0.215	5.47	2.77	1.5	9	lenses
3	-.-	∞	∞			5.6	stop

33 An achromatic doublet in a brass mount. The doublet is mounted on a barrel, a diaphragm which screws on top of the barrel fixes the doublet. The barrel has three slits, its internal diameter is 19mm, it slides over no. 34. Measured focal length: 10.38mm (0.409").

13 Lister (1830), 187–200, (199). Lister mentions that Tulley made three plano-convex glasses for him, the focal length of the shortest one being 0.7in.

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	-.-	0.187	4.74	2.24	1.521	5.5	mount
2	-.-	?0.167	?4.23	0.23	1.59		
3	-.-	∞	∞	2.47	1		

34 An achromatic doublet in a brass mount of the same construction as no. 33. The cemented surface looks like it is cracked. Measured focal length: 24.73mm (0.973″).

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	-.-	0.398	10.116	1.349	1.523	6	mount
2	-.-	0.395	10.023	1.551	1.62		
3	-.-	∞	∞	2.9	1		

48 An achromatic doublet in a brass mount, the overall diameter is 9.9mm. According to the accompanying note the glass is English flint. Measured focal length: 26.31mm (1.036″).

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.46	0.442	11.219	2.414	1.52		
2	0.4	0.396	10.052	1.666	1.61	9.9	lenses
3	∞	∞	∞	4.08	1		

52 An achromatic doublet in a brass mount with a threaded front (ø13.5/48tpi) and back (ø18.5/48tpi). The doublet is cemented in its mount. It is marked 'XIII' and '51 thin'. The accompanying paper is difficult to decipher, the curvatures are probably 0.5″. The cemented surface has a round faulty spot in the middle. Measured focal length: 32.89mm (1.295″).

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.5	0.492	12.499	2.62	1.512		
2	0.5	0.479	12.174	1.61	1.65	11.8	lenses
3	∞	∞	∞	4.23	1		

54 An achromatic doublet in a brass mount with a threaded back (ø18.2/48tpi). The mount is marked 'VI'. The accompanying slip of paper shows a drawing of the doublet. It says: 'a small glass'. Measured focal length: 42.93mm (1.69″).

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	-.-	0.683	17.35	3.22	1.52	10	mount
2	-.-	0.549	13.936	1.285	1.62		
3	-.-	∞	∞	4.505	1	9.6	mount

55 An achromatic doublet in a brass mount with a threaded back (ø18.4/48tpi). The mount is marked 'VIII'. Measured focal length: 37.39 (1.472").[14]

srf.	radius inch	radius inch	radius mm	thns mm	N	diam. mm	remarks
1	0.6	0.593	15.06	3.13	1.504	11.1	
2	0.65	0.652	−16.55	1.75	1.62	13.4	
3	∞	∞	∞	4.88	1		

10.5 TRIPLET LENSES

The surfaces and the lenses are numbered from back to front, measures are in mm, unless indicated otherwise. All these four non cemented triplets are mounted in the same type of cell.

21 A non cemented triplet lens in a brass mount, the overall diameter of the mount is 19.3mm. The thread is ø9.7/2tpmm. The diameter of the lenses is ca. 7mm. The front aperture is 5.5mm, the back aperture is 5.1mm. Measured focal length: 13.85mm (0.545 inch).[15]

lens	rds.1	rds.2	thns	dst	f	N
1	6.14	20.22	1.68	0.075	9.23	1.522
2	16.66	3.90	0.50	0.15	−5.32	1.589
3	4.23	25.42	2.11		7.12	1.522

23 A non cemented triplet lens in a brass mount, the overall diameter of the mount is 11.5mm. The thread is ø9.7/2tpmm. The diameter of the lenses is ca. 7mm. The front aperture is 5.3mm. Measured focal length: 12.46mm (0.491 inch).[16]

lens	rds.1	rds.2	thns	dst	f	N
1	5.51	18.81	1.84	0.15	8.90	1.491
2	17.53	3.94	0.64	0.25	−5.57	1.572
3	4.21	25.41	2.09		7.13	1.52

28 A non cemented triplet in a brass mount, the construction of the cell is similar to that of the other triplets. The cell is threaded (ø10.4/40tpi). The mount in which the cell screws is threaded too (ø15/32tpi). There are two aperture stops, one in the tube ø4.6mm and a separate diaphragm of ø3.8mm. Measured focal length: 10.03mm (0.395 inch). [17]

lens	rds.1	rds.2	thns	dst	f	N
1	5.45	6.80	2.82	0.2	6.23	1.528
2	4.67	4.63	0.46	0.2	−3.57	1.628
3	4.71	6.11	2.95		5.54	1.530

14 This might be the doublet mentioned in F40 (Lister Archive), only the radii have been interchanged.
15 This might be the doublet mentioned in F40 (Lister Archive), only the radii have been interchanged.
16 This is a typical Tulley lens, it could be the front triplet for a compound objective.
17 This is a typical Tulley lens, it could be a the back system of a compound objective.

29 A non cemented triplet in a brass mount, the construction of the cell is similar to that of the other triplets. The cell has a diameter of 8.1mm. The mount in which the cell screws is threaded too (ø19.5/40tpi). The mount is marked in pencil 'J J L'. Measured focal length: 9.231mm (0.363 inch)[18]

lens	rds.1	rds.2	thns	dst	f	N
1	5.73	5.07	2	0.15	5.54	1.519
2	4.58	4.55	0.33	0.1	−3.85	1.586
3	4.76	7.81	1.76		5.86	1.531

10.6 COMPOUND SYSTEMS

40 The purpose of this system is not clear, it might be a condensor. The system consists of two plano-convex lenses, the front component in a barrel to slide on the rear component. The rear is threaded (ø19.9/32tpi). The plane surfaces are both to the front. The combination is marked 'I', the body component '4'. Measured focal length: 11.54mm (0.454 inch).

	radius mm	radius inch	thns mm	f mm	f inch	N
front	10.07	0.397	2.57	19.88	0.783	1.507
back	11.67	0.459	2.25	22.94	0.903	1.509

Used as an objective (with eyepiece 5x and 160mm body) the following data were obtained: total magnification: 72.2x (the objective alone 14.5x), numerical aperture 0.34. Measured resolving power 2.75μm (while 0.94 might be expected). Very strong spherical under-correction and also a lot of chromatic aberration. This combination is described by Spitta as:[19]

> This is probably one of the earliest of Lister's combinations. Of about 1 1/2in. focal length, it shows but a poor image. Although much time and trouble were spent in trying all kinds of adjustment, the red and blue images seem quite distinct, so much so that no adjustment will make any sensible change ...

41 This is an objective in three parts, a front and a middle triplet and a doublet back. The thread is ø19.8, 32tpi. It is marked 'II'.[20]

focal length:	mm	inch
total	10.07	0.396
front	27	1.063
middle	25.39	0.999
back	30.66	1.207

Used as an objective (with eyepiece 10x and 160mm body) the following data were obtained:

18 This is a typical Tulley lens, it could be a the back system of a compound objective.
19 Spitta [98], (147).
20 The middle and the back lenses are probably the lenses mentioned in L32 (Lister Archive).

total magnification 164 diameters (the objective alone 16.7 diameters), numerical aperture 0.44 (d = 0.73μm). Measured resolving power 1.25μm (Navicula lyra was resolved in dots). There is spherical under-correction and a lot of coma. This combination is described by Spitta as:[21]

> Is a 2/3in. and shows a great advance. Although the components are only mounted in cardboard, still, with care and time, a position was found when this combination furnished quite a good image, more especially in the preferred colour, which seems to be the apple-green as selected for the most part by modern artists in the present day ...

42 With this objective are two notes, the first one saying 'Tulley's orig[ina]l 9/10 & Chevalier's glasses applied before it'. The second note states 'First 9/10 triple obj. glass made by Tulley & Chevaliers 5th added'. Contrary to these notes both components are doublet lenses, constructed in the same way. They are set in a cell which is screwed on a barrel, the front one sliding over the back one. The thread is ø19.9, 32tpi. The objective is marked 'III'.

focal length:	mm	inch
total	14.19	0.559
front	23.08	0.909
back	26.92	1.06

Used as an objective (with eyepiece 10x and 160mm body) the following data were obtained:

total magnification 111.5 diameters (the objective alone 11.4 diameters), numerical aperture 0.3 (d = 1.1μm). Measured resolving power 2μm. There was some spherical over-correction. This combination is described by Spitta as:[22]

> This is an objective of renown, being – according to the memorandum accompanying it – "Tulley?s original 9/10, with glasses by Chevalier." Its performance is really very wonderful, especially when allowed for the small range of glasses of the period...

43 This objective has three doublet lenses, the back one is mounted on a barrel, the middle and front ones are mounted on a second barrel with three slits which slides over the inner one. The inner barrel is marked in ink '2'. The thread is ø20, 32tpi. The objective is marked 'IV'. Measured focal length: 6.92mm (0.273in.).

srf	radius (mm)	N	dst (mm)	f (mm)	f (inch)
1	7.866	1.52	2.60	20.171	0.794
2	−8.03	1.67	1.03		
3	∞	1	1		
4	7.543	1.52	2.61	19.054	0.750
5	−7.95	1.67	0.64		
6	∞	1	1		
7	4.254	1.52	2.47	10.962	0.432
8	−3.92	1.67	0.78		
9	∞	1			

21 Spitta [98], (147).
22 Spitta [98], (147).

Used as an objective (with eyepiece 5x and 160mm body) the following data were obtained:

total magnification 123 diameters (the objective alone 24.7 diameters), numerical aperture 0.49 (d = 0.66μm). Measured resolving power 1.25μm. Cymbella gastroides was resolved into dots. This combination is described by Spitta as:[23]

> This is an objective of about 1/3in. focal length. With careful adjustment throughout, a positively fine image is presented when a medium aperture only is used. It is a monument to the ability of Lister.

44 This objective has two non cemented triplet lenses. The thread is ø19.9, 32tpi. The objective is marked 'V'. The triplets are built in the same way as the numbers 21, 23, 28 and 29, which were made by Tulley.[24]

focal length	mm	inch
front triplet	13.08	0.515
back triplet	24.55	0.966
total	10.77	0.424

Used as an objective (with eyepiece 5x and 160mm body) the following data were obtained:

total magnification 76.5 diameters (the objective alone 15.4 diameters), numerical aperture 0.34 (d = 0.96μm). Measured resolving power 1.5μm. Navicula lyra was resolved into dots. The contrast was bad and there was a lot of coma. This combination is described by Spitta as:[25]

> Of about 1 1/2in. focal length. This objective is spoilt by the degeneration (it is presumed) of one of its components. It is, however, another remarkable objective. If cut down severely so as to stop out entirely the outer and the greater portion of the intermediate zone, its performance is really good, but if the objective be used at its full aperture, the effects of "outward coma" become very pronounced, and the image of any object is almost entirely spoiled and blurred. It has seemed as if this was another experiment: To perfect the inner and intermediate zones at the expense of the outer.

10.7 UNIDENTIFIED COMBINATIONS

18 A cemented combination on a brass mount, the overall diameter is 17mm. Over the concave front lens screws a little hood with an aperture of 3mm.The diameter of the lenses is about 8mm. The aperture at the backside is 6.2mm. The outer radius of the front lens is −7.82mm (0.308"). The radius of the back surface is 15.19mm (0.598"). The focal length is 43.08mm (1.696"). Though the curvatures of the through-the-lens surfaces were measured they gave no consistent results. It might be a triplet.

19 A cemented combination in a brass mount, the overall diameter is 17mm. The mount is blackened and it has three slits in its upright rim. The front is flat, the back surface has a radius of 8.993mm (0.354"). The focal length is 20.08mm (0.79"). The diameter of the lenses is 8mm, their total thickness is 3.64mm.

23 Spitta [98], (147).

24 These triplets could be the ones mentioned in: Lister [75], 187. See also L62 and L64 (Lister Archive).

25 Spitta [98], (147).

Though it was possible to measure the through-the-lens curvatures the results were not consistent, it might be a triplet.

20 A cemented triplet in a brass mount, the overall diameter of the mount is 18.5mm. The front is flat, the back has a radius of 4.85mm (0.191"). The focal lenght is 9.59mm (0.377"). It was not possible to determine the internal structure of the triplet, though reflections from the cemented surfaces could be observed.

10.8 various objects

27 Brass cone apparently intended to slide over an objective to act as a stop. Overall length 26.6mm. Overall diameter 19.1mm.[26] It could be an illumination cone as was used in the eighteenth and early nineteenth century.

32 Dark ground illuminator. Simple lens with patch stop on flattened under surface and ground flat on upper surface. Overall diameter of lens 14.3mm. With a long barreled brass mount.[27] The mount has a thread ø20.1/32tpi. The overall length is 48.4mm.

35 Lieberkühn on sliding brass mount. Overall diameter 20mm.[28] The diameter of the mirror is 19mm, the aperture is ø5.5mm. There is also a cardboard rim to fit the Lieberkühn on a lower diameter objective. The internal diameter of the barrel is 18.8mm, the cardboard allows its use on an 17.5mm objective. The overall length is 21.2mm.

36 Lieberkühn on sliding brass mount. Overall diameter 19.3mm.[29] The diameter of the mirror is 19mm, the aperture is ø3.7mm. The internal diameter of the barrel is 15mm. The overall length is 18.7mm.

37 Brass cap. Overall diameter 18.1mm.[30] The internal diameter is 15.1mm, the height is 4.7mm (external). The rim has one slit.

38 Brass cap. Overall diameter 12.5mm.[31] The internal diameter is 11.4mm, the height is 5.3mm (external). The rim has three slits.

39 Lieberkühn. Overall diameter 17.4mm.[32] The diameter of the mirror is 13mm, the aperture is ø3mm. The internal diameter is 15.7mm, the overall length is 9.1mm. There are no slits. There is red paint on the rim of the aperture.

56 With accompanying slip of paper marked 'Adapter for Chevalier's Object Glasses 1843'. Overall diameter 24.9mm, length 8.3mm. The thread on the outer surface is ø20/32tpi with a very sharp profile. The internal thread is ø14.7mm.

57 A cardboard pillbox marked 'Various Lenses Experimental', in it are the lenses 58–63. In addition the box contains a piece of pitch and a crudely cut blackened cardboard stop with a diameter of ø17.2mm and an aperture of ø4.5mm. There is also an empty mount for a lens, its overall diameter is 4.1mm.

64 Optical lathe chuck.[33] Overall diameter 18.3mm. The threaded side is ø10.9/16tpi (3/8") and marked '.46'. The radius of curvature could not be measured because of the small depth in the centre. There were still traces of pitch in the curved side.

65 Optical lathe chuck.[34] Overall diameter 18.5mm. The threaded side is ø10.9/16tpi (3/8") and marked '.66'. The radius of curvature could not be measured because of the small depth in the centre.

26 Bracegirdle [16], 297.
27 Bracegirdle [16], 297.
28 Bracegirdle [16], 297.
29 Bracegirdle [16], 297.
30 Bracegirdle [16], 297.
31 Bracegirdle [16], 297.
32 Bracegirdle [16], 297.
33 Bracegirdle [16], 297.
34 Bracegirdle [16], 297.

66 Polishing stick.[35]

67 Part of an envelope addressed to J.J. Lister Esq., Upton, Essex and postmarked 1841.[36]

35 Bracegirdle [16], 297.

36 Bracegirdle [16], 297.

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APPENDIX 4: THE LISTER ARCHIVE

An inventory has been made of part of the Lister papers in the archives of the Royal Microscopical Society (Bracegirdle, 1987). Bracegirdle describes eight groups of documents:

A: Five printed pamphlets: A1–A5.
B: A drawing of the microscope of 1826: B1.
C: Drawings: C1–C6.
D: Miscellaneous notes and diagrams: D1–D36.
E: Experiments on the eye: E1–E5.
F: Various optical papers and notes: F1–F87.
G: Manuscript of 'On the Limit to Defining Power...': G1–G21.
H: Various optical Memoranda: H1–H17.

Apart from these the following portfolios were found:

J: '1825–1828 Tulley, Cuthbert, Amici, Chevalier'.
K: 'Memoir on Object Glasses made for experiment 12 mo. 1829 to 5 mo. 1830'.
L: Notes, '1829–1831'.
M: '[unreadable] + correspond[ence] with P. Barlow 1828–1831'.
N: '1837 Mem[oir] for & of A. Ross'.

J: Portfolio '1825–1828 Tulley, Cuthbert, Amici, Chevalier':
L60a Numbered '1'.
L60b Numbered '2', dated '11 mo. 1825' [November 1825].
L61a Numbered '3', 'Amici's Catoptrical Microscope', experiment dated '2mo.16 1826' [16 February 1826].
L61b Numbered '4', continuation of L61a.
L62 Numbered '5', drawings of Lister's first triplet lenses. One of these is dated '1826 3mo.2' [2 March 1826].
L63 Numbered '6', drawing C, 'W. Tulley's first trial for the 3/10th'. One drawing is dated '1mo.26.1827' [26 January 1827], 'W. Tulley's trial 3/10 which gives fine performance but has not its aberrations perfectly corrected'. The other drawing is dated '2/14 1827' [14 February 1827], 'W. Tulley's 3rd trial 3/10th'.
L64 Dated 'mo12.6.1827' [6 December 1827], drawing and description of an object glass of two triplet lenses.
L65 'Measurement of W. Tulley's front triple (1828)'.
L57 'On the compound Achromatic Microscope of Mr. W. Tulley with some account of the present state of the Microscope and suggestions for its improvement on a new principle. By Joseph Jackson Lister. Communicated by D. Royal Soc. R.S. Read Jan. 21 1830'.
L58 Continuation of L57.
L59 Continuation of L58.
L107 Single sheet, dated '10mo.11, 1827' [11 October 1827], 'Experiments with Tulley's double and triple object glasses'.
L108 Single sheet, dated '10/12' [12 October 1827], 'Experiments with Herschels, Tulleys and Chevalier object glasses'.
L19 Quire of two double sheets, numbered '1', 'Chevalier's microscope p[ai]d for 12mo 16 1826' [16 December 1826].
L20 Continuation of L19. Numbered '2'.
L21 Continuation of L20. Numbered '3'.

L22 Continuation of L21. Numbered '4'.
L23 Continuation of L22. Numbered '5'.
L24 Continuation of L23. Numbered '6'.
L25 Continuation of L24. Numbered '7'.

K: Portfolio 'Memoir on Object Glasses made for experiment 12 mo. 1829 to 5 mo. 1830':
L1 Double sheet, together with L18, watermark '1827' and a coat of arms. Contents on the cover, written in pencil, pages numbered from '3' to '14' [L1-L18].
L2 Double sheet, together with L17, L5, L16, watermark '1827' and a coat of arms. A drawing of a telescope, a Huygenian eyepiece, and an objective consisting of two doublets.
L3 Single sheet together with L4, watermark '1827' and a coat of arms. Numbered '1A'. Drawings of lenses and some text.
L4 Numbered '1B'. A drawing of a triplet lens.
L5 Some remarks about a convex lens.
L6 Single sheet, watermark '1827'. Numbered '2'. Two drawings of biconvex lenses and some experiments related to them.
L7 Double sheet, together with L8, L9, watermark '1827' and a coat of arms. Numbered '5'. Dated '1.9.1830' [1 January 1830].
L8 Continuation of the experiments on L7.
L9 Numbered '6'. Dated '1/1? 1830' [12 or 14 January 1830]. Continuation of the experiments on L8.
L10 Single sheet, watermark a coat of arms. Numbered '7'. A drawing of two biconvex lenses.
L11 Double sheet, together with L12, watermark '1827' and a coat of arms. Numbered '8'. Dated '1/20' [20 January 1830].
L12 Numbered '9'. Dated '1/20' and '1/27' [20 and 27 January 1830].
L13 Numbered '10'. Double sheet, together with L14, L15, watermark '1827' and a coat of arms.
L14 -
L15 Numbered '11'.
L16 Numbered '12'. Dated '3mo.2.1830' [2 March 1830]
L17 Numbered '13'. Telescope, 'Experiment to apply the principle of aplanatic foci to the telescope'.
L18 Numbered '14'.

L: Portfolio '1829–1831':
L28 Double sheet, together with L29, watermark '1827' and a coat of arms. Dated '1830, 11 mo.11' [11 November 1830].
L29 Continuation of the experiments of L28.
L30 Double sheet, together with L31, L32, watermark '1827' and a coat of arms. Dated '1831 2mo.' [February 1831].
L31 Continuation of the experiments of L30.
L32 Continuation of the experiments of L31. A drawing of an objective glass.

M: Portfolio '[unreadable] + correspond[ence] with P. Barlow 1828–1831':
L33 Double sheet, together with L33a, L34, watermark 'Munn & Stephens'. Duplicate of a letter from Lister to Prof. Barlow. Dated '5mo17.1828' [17 May 1828].
L33a Continuation of L33.
L34 Continuation of L33a.
L35 Double sheet, together with L36, L37, watermark 'RM & C' and a coat of arms. Dated 'May 20th 1828'. A letter from P. Barlow to J.J. Lister.
L36 Continuation of L35.
L37 Continuation of L36.

L38 Double sheet, together with L39, L40, watermark 'I & I DEWDNEY 1827'. Duplicate of a letter from Lister to Barlow. Dated '6mo4. 1828' [6 June 1828].
L39 Continuation of L38.
L40 Continuation of L39.
L41 Double sheet, together with L42, watermark 'IM & M 1827' and a coat of arms. Dated 'June 18th 1828'. A letter from P. Barlow to J.J. Lister.
L42 Continuation of L41.
L43 Single sheet, together with L44, watermark 'C WILMOT 1830'. Dated '24th of 2 Mo 1831' [24 February 1830]. Duplicate of a letter from J.J. Lister to J.F.W. Herschel. See also L70, which is a later copy.
L44 Continuation of L43.
L45 Double sheet, together with L46, L47, watermark 'C WILMOT 1830'. Duplicate of a letter from J.J. Lister to P. Barlow. Dated '25 of 5mo 1831' [25 May 1831].
L46 Continuation of L45.
L47 Continuation of L46.
L48 Single sheet, together with L49. Continuation of L47.
L49 Continuation of L48.
L50 Single sheet, watermark a coat of arms. Dated 'April 20th 1831'. A letter from P. Barlow to J.J. Lister.
L51 Double sheet, together with L52, L53, watermark a coat of arms. Dated 'May 28th 1831'. A letter from P. Barlow to J.J. Lister.
L52 Continuation of L51.
L53 Continuation of L52.
L54 Double sheet, together with L55 watermark 'P. EVERITT 1830' and a coat of arms. Dated '6.16.1831' [16 June 1831].
L55 Continuation of L54.
L56 Double sheet, folded, with postmarks '4.EVEN.4. JU.5 1830', '12.NOON.12 JU.5 1830' and 'WOOLWICH'. Letter from P. Barlow to J.J. Lister.
L66 Double sheet, together with L67, L68, L69, L70, watermark '1841' and a coat of arms. 'Barlow on the refr. [unreadable] Journ[al] of Royal Inst[itutio]n No. 4 p.3'.
L67 Continuation of L66.
L68 Continuation of L67.
L69 Continuation of L68.
L70 Single sheet, watermark 'A. Pirie & Sons 1866'. Copy of a letter from J.J. Lister to J.F.W. Herschel. See also L43, L44.
L71 Double sheet, together with L72, watermark '1827' and a coat of arms. Some drawings and calculations.
L72 Continuation of L71, calculations.
L73 Single sheet, watermark '1827'. Some drawings and data of lenses.

N: Portfolio '1837 Mem[oir] for & of A. Ross':
L74 Folded sheet, together with L75, watermark 'R TURNER Chafford Mills 1836'. Dated '1/6.1838' [6 January 1838]. 'Trials for producing 3 powers with but 3 glasses'.
L75 Continuation of L74.
L76 Folded sheet. The history of Lister's discoveries.
L77 Continuation of L76.
L78 Single sheet. Dated '28 Dec[embe]r 1841'. A letter from Andrew Ross to J.J. Lister.
L79 Single sheet. 'AR for 1/6th. 1843'.
L80 Single sheet. Curvatures and dimensions of an object glass.

L81 Double folded sheet, together with L82, embossed stamp 'Bath'. Dated 'April 9th 1838'. A letter from Andrew Ross to J.J. Lister.

L82 Continuation of L81.

L83 Single sheet, embossed stamp 'Superfine'. Design of an objective glass, '1st success'.

L84 Single sheet. Dated '10/5 1837' [5 October 1837]. Design of a double combination.

L85 Single sheet. Dated '10/18. 37' [18 October 1837]. About the double combination of L84.

L86 Single sheet, wax seal on the back 'ARB'. Dated '4/19.' [19 April 1838]. 'Trial made at Mr. Bowerbank's request between Ross; & Powell's glasses'.

L87a Double sheet, together with L87b. Dated '4/19. 1838' [19 April 1838]. 'Comparison of Powell & Ross Mr. B[owerbank]'s'.

L87b Continuation of L87a.

L88a Folded sheet, together with L88b, watermark 'C. ANSELL 1837'. Dated 'April 18. 1838'. A letter from J.S. Bowerbank to J.J. Lister.

L88b Continuation of L88a.

L89 Single sheet, watermark a coat of arms. Dated '8/14. 39' [14 August 1839].

L90 Single sheet, watermark '1842'. Dated '3.21.1843' [21 March 1843]. Table of focal lenght and aperture of object glasses belonging to 'A. Ross's microscope for Microsc. Soc[iet]y'.

L91 Single sheet. An experiment with an objective.

L92 Single sheet. Dated '10.1.1845' [1 October 1845]. 'A Ross 1/8" '.

L93 Single sheet. 'A R[oss]'s own triple and alone'.

L94 Single sheet. Dated '1mo.1842' [January 1842]. A 1/4 inch object glass.

L95 Single sheet. 'Remarks on A. Ross's suggestion for 3 glasses to admit a larger pencil'.

L96 Single sheet. 'Trial triple for front before [a drawing of two combinations] in our attempts to make 3 gl[asse]s serve for 3 powers'.

L97 Single sheet. Dated '8/14 1839' [14 August 1839]. 'A. R[oss]'s var[iatio]n from J.J. L[ister]'s [unreadable] his glasses made on this plan give much outward coma the concave [unreadable] of the back glass & the low power of the front glass (see observ[ation] 8/14. 1839)'.

L98 Single sheet. Dated '12mo. 4. 1841' [4 December 1841]. A table of focal length, aperture, and price, of some object glasses by A. Ross.

L99 Single sheet. Remarks about an object glass.

L100a Single sheet. Remarks about Ross's object glasses.

L100b Dated '7/4. 1837' [4 July 1837]. Continuation of L100a.

L101a Single sheet. About glass.

L101b Continuation of L101a.

L102 Numbered '1'. Dated '11/10.1829' [11 November 1829]. 'Fraunhofer Obj[ective glass] [unreadable] lent by Mr. Brown–Tube drawn out 3 in[ch] (i.e. fr[om] glass to end of tube 12 in[ch]) Eyepiece №1'.

L103a Numbered '5'. Double sheet, together with L103b, watermark '1827' and a coat of arms. Drawing of doublet lens, Fraunhofer size 3.

L103b Continuation of L103a. Drawings of Fraunhofer size 1 and size 3.

L104a Single sheet, together with L104b, watermark a coat of arms. A drawing of a doublet lens. The principle of the aplanatic foci.

L104b Continuation of L104a.

L105 Numbered '7'. Single sheet, watermark 'R. MUNN & Co. 1829'. Dated '5mo. 1830' [May 1830]. 'Memoir delivered to Mr. B[rown]'.

L106a Single sheet, together with L106b, watermark a coat of arms. Numbered '8'. 'G.S. Plössl – Vienna – List of articles sold'.

L106b Continuation of L106a.

– Double sheet, blue paper, watermark 'E TOWGOOD 1866' and a coat of arms. Extracts from R. Becks diary.

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APPENDIX 5: MICROSCOPES WHICH HAVE BEEN INVESTIGATED

12.1 LONDON, SCIENCE MUSEUM AND WELLCOME COLLECTION

Inventory number and signature of the microscopes from the Science Museum, London, which have been investigated:

1925-136	Invented and made by Geo. Adams in Fleet Street / Instrument Maker to His Royal Highness the Prince of Wales.
A56523	Adams / London.
A159192	Adams / London.
A159473	Adams / London.
A159980	Adams / London.
A196842	G. Adams / No. 60 Fleet Street / London.
A600168	G. Adams / No. 60 Fleet Street / London.
A645025	Adams / London.
A56301	D. Adams / London.
A56305	D. Adams / London.
1921-189	unsigned, optics by Amici.
1921-192	unsigned, optics by Amici.
1921-754	Amici / Modena.
1928-799	unsigned, Amici (P. Harting?s 1848 microscope).
1928-847	unsigned, Amici (E. Haeckel?s microscope).
1938-688	unsigned, optics by Amici.
1954-287	unsigned, optics by Amici.
1954-288	Petrus Belkmeer/ Me Fecit Enchusae / Anno MD CC XXX II.
1921-252	C. Kellner in Wetzlar / Belthle & Rexroth No. 320.
1921-746	Selon Euler/ Perfectionné/ Par Vinc.t Chevalier ainé et fils,/ Ing.rs Opt.ns Brevetes, quai de l'Horloge n. 69 à Paris.
A54219	Selon Euler/ Perfectionné/ Par Vinc.t Chevalier ainé et fils,/ Ing.rs Opt.ns Brevetes, quai de l'Horloge n. 69 à Paris.
1921-185	Microscope Achromatique / Perfectionné / Vincent Chevalier/ Ing.r Opt.en Brev.té / Quai de l'horloge, 69, / Paris.
A601001	Charles Chevalier / Palais Royal 165 / Paris.
1906-63	Microscope Achromatique / Inventé par / Charles Chevalier / Ingénieur Opticien Breveté / Palais Royal no.163 à Paris.
1921-188	Charles Chevalier / Ingénieur Opticien / Palais Royal 163 / Paris.
1921-249	Charles Chevalier / Ingénieur Opticien / Breveté / Palais Royal 163 / Paris.
1921-184	Charles Chevalier / Palais National 158 / à Paris.
A203049	Microscope Achromatique Universel / Inventé par / CHARLES-CHEVALIER / Ingénieur / Arthur Chevalier Fils et Suc.r / Palais Royal 158, / Paris.
A62993	J. Cuff Londini Inv = & = Fecit.
A650687	J * Cuff London.
A60955	Dellebarre / 1784.
1928-817	Dellebarre / 1793.
A135495	unsigned, Dellebarre microscope.
RMS018	unsigned, Dellebarre microscope.
1928-784	Dellebarre / 1806 / Onderdewijngaart Canzius / Confecit / Delft.
A600249	Dellebarre / Onderdewijngaart Canzius; / Confecit / Delft.

1921-236	Deutgens / Micrometer / microscope / Jermsy [?] / 1886 - 14673 [?], scratched on cover of mirror.
1921-208	Dollond.
1921-209	Dollond / London.
1928-860	Dollond / London.
1928-867	Dollond / London.
A18469	Dollond / London.
A50965	Dollond / London.
A56304	Dollond / London.
A159502	Dollond / London.
A600179	Dollond / London.
A600242	Dollond / London.
A645008	Dollond / London.
1925-143	J.D.V. Fokkenberg / Fecit Utrecht 1777.
1921-741	Utzschneider, Reichenbach & Fraunhofer in Benedictbeurn.
1928-850	Utzschneider und Fraunhofer in München.
1936-648	E. Hartnack & A. Prazmowski / Rue Bonaparte 1 / Paris // no.13521 [on box].
1938-690	unsigned.
A71683	Jones & Son / Fecerunt / Holborn, London.
A56801	W & S Jones / Opticians / No.30 Opposite Furnivals Inn / Holborn London.
A56300	W & S Jones / 30, Holborn London.
A195731	W & S Jones / 30, Holborn London.
A212741	W & S Jones / 30, Holborn London.
A600166	W & S Jones / 30, Holborn London.
A56418	Kellner / Wetzlar.
1882-1	B. Martin / London.
A101926	B. Martin / Inv.t & Fecit / No. 4.
A76350	unsigned, Martin type.
A645049	unsigned, Martin type.
1921-251	G. Merz und Söhne / in München.
1928-769	Musschenbroek, oriental lamp with crossed keys.
1921-750	F.A. Nobert / Barth in Pommern.
1917-102	Trécourt / & / Georges Oberhaeuser / Place Dauphine No.19 / Paris.
1918-58	Brevet d? Invention,/ Trécourt & Georges Oberhaeuser,/ Place Dauphine no.19 à Paris. On body tube: Georges Oberhaeuser.
1921-253	Georges / Oberhaeuser / Ingénieur Opticien / breveté / Place Dauphine 19 / à Paris / no. 778.
1912-212	G. Oberhaeuser / Place Dauphine / Paris. The number ?2537? is painted on the leather under the base.
1925-149	Ploessl in Wien.
1928-801	Plössl in Wien.
1921-206	unsigned, made by Powell.
1918-17	Hugh Powell / 1840.
1921-181	Powell & Lealand / London.
1966-417	Powell & Lealand / Makers / London / 1843.
A71911	Powell & Lealand / Makers / London / 1845.
1913-291	Powell & Lealand / Makers / London / 1846.
A140784	Powell & Lealand / 4, Seymour Place / Euston Square London / 1849.
A601303	Powell & Lealand / 4 Seymour Place / Euston Square / London / 1856.
1907-83	Powell & Lealand, / -170- / Euston Road, / London / 1860.
1967-41	Powell & Lealand, 1874.
A600239	Powell and Lealand / London.

A41397	Pritchard / Picket St. Strand.
A71679	Andrew Pritchard. / 263, Strand, London [on foot] Pritchards / Fine adjusting body / 162 Fleet Strt. London [on body-tube].
1876-617	Andrew Pritchard / 162, Fleet Street / London.
1928-774	I. Reghter / A Delft.
1928-849	S.J. Rienks / Leijden 1826.
1921-216	Andw. Ross / Optician / London / No.50.
1891-17	A. Ross, / London, / No.216.
1913-293	Andw. Ross & Co. / 33 Regent St. / Piccadilly.
1919-469	Andw. Ross & Co. / Opticians / 33 Regent St. / Piccadilly.
1921-213	Andw. Ross & Co. / Opticians / 33 Regent St. / Piccadilly.
A601295	A. Ross / London / 1721.
A4888	Ross London 1962.
A601097	Ross / London / 3360 / St. George?s School.
A601094	Ross / London / 4966.
1972-49	Ross London 1/10 inch no. 21544 Immersion [objective].
1921-250	Schiek in Berlin / No.32.
A54204	unsigned, James Smith, Lister?s 1826 microscope.
A46257	Ja.s Smith. / London.
1891-19	James Smith / London / 76.
A604181	unsigned, James Smith, Lister?s 1840 microscope.
A54205	Smith & Beck / 6 Coleman St. / London / 353.
A50476	Smith & Beck / 6 Coleman St. / London / 807.
A56382	Smith & Beck / London / 1151.
A601103	Smith & Beck / 6 Coleman St. / London / 1543.
A54072	Smith Beck & Beck / London / 3013.
A159563	Smith Beck & Beck / London / Universal Microscope / no. 3308.
A601306	Smith Beck & Beck / London / Universal Microscope / no. 3814.
A40983	Trécourt / & / Georges Oberhaeuser / Place Dauphine no.19 / à Paris.
1938-686	Tulley & Sons Islington London.
1918-84	unsigned.
A18817	unsigned.
A56519	unsigned.
A600182	unsigned.
A601290	unsigned.
A169733	Varley / London

12.2 OXFORD, ROYAL MICROSCOPICAL SOCIETY

TU: number from the 1989 catalogue by G. L'E. Turner.[1] Inv.: inventory number of the Royal Microscopical Society

1 Turner [107]

Turner	RMS	signature
238	187	Adams.
20	217	Cuff.
21	127	Cuff.
82	133	English, unsigned.
382	209	Lister Lenses.
28	5	Martin.
217	28	Oberhaeuser.
113	359	Powell.
114	234	Powell.
115	128	Powell.
117	199	Powell.
118	2	Powell.
119	122	Powell & Lealand.
120	256	Powell & Lealand.
121	370	Powell & Lealand.
122	426	Powell & Lealand.
126	169	Powell & Lealand.
127	282	Powell & Lealand.
128	327	Powell & Lealand.
129	376	Powell & Lealand.
130	278	Powell & Lealand.
131	297	Powell & Lealand.
138	316	Powell & Lealand.
139	102	Powell & Lealand.
140	103	Powell & Lealand.
144	332	Powell & Lealand.
136	129	Powell & Lealand (unsigned).
179	444	R & J Beck.
148	47	Ross.
152	8	Ross.
158	112	Ross.
159	177	Ross.
161	348	Ross.
162	399	Ross.
163	123	Ross.
164	104	Ross.
149	248	Ross, no.158.
150	358	Ross, no.520.
171	1	Smith.
172	3	Smith.
389	106	Smith.
173	412	Smith & Beck.
174	15	Smith & Beck.
175	269	Smith & Beck.

12.3 UTRECHT, UNIVERSITY MUSEUM

inv. no.	maker	signature and description
UM435	Adams	Invt. & made by G. Adams at Tycho Brahe's Head in Fleet Street London: side-pillar microscope, on tripod.
UM967	Adams, G.	G. Adams / No.60 Fleet Street / London: side-pillar microscope, on tripod.
UM461	American made ?	UNIVERSA: universal scissors with stanhope lens.
Li118	Amici	Amici Firenze: compound achromatic side-pillar microscope, on tripod.
UM351	Amici	box with object glasses, the microscope is in the Science Museum, London.
UM352	Amici	eyepiece.
UM1177	Arnold & Sons	Arnold & Sons/ London: microscope, raised claw foot.
Sm9	Bausch & Lomb	Bausch & Lomb Optical Co. / Rochester / N.Y.: horseshoe stand.
UM2605	Beck	Beck / Kassel: binocular stand.
UM1295	Beck, R & J	R & J Beck/ London & Philadelphia: triangular base, binocular.
UM298	Beeldsnijder ?	triplet lens.
UM367	Belthle & Rexroth	C. Kellner in Wetzlar / Belthle & Rexroth: side-pillar microscope, on base-plate.
UM1914	Bleeker	Dr. C.E. Bleeker N.V.: stand M, inverted metal microscope.
UM2532	Bleeker	Nedoptifa / Zeist / Nederland; stand S, with mechanical stage.
UM2601	Bleeker	Nedoptifa / Zeist / Nederland: stand S.
UM140	Brinckman, J.G.	J.G. Brinckman / Fec Bremen: Hartsoeker-Wilson type, on box with drawer.
UM73	Cary	Cary / London: Gould type microscope on base-plate.
UM37	Chevalier, A.	Arthur Chevalier / Palais Royal 158 / Paris: horseshoe, platine à tourbillon.
Li116	Chevalier, Ch.	Charles Chevalier / Ingenieur Opticien / Palais Royal 163/ Paris: Simple doublet microscope, on box with drawer.
UM230	Chevalier, Ch.	Microscope achromatique de Charles Chevalier / Palais Royal 163 à Paris: Chevalier-type on box.
UM40	Cramer, G.	G. Cramer / Groningen / Fecit: Hartsoeker-Wilson type.
UM469	Cramer, G.	G. Cramer / Groningae Fecit: Hartsoeker-Wilson type, on pillar and base.
Sm5	Crouch, H.	Henry Crouch / London: English stand.
Sm7	Crouch, H.	Henry Crouch / London: English stand.
UM578	Cuff	J. Cuff / Londini / Invt. & Fecit: Cuff type microscope.

inv. no.	maker	signature and description
UM10	Culpeper	Culpeper trade chart in box: Culpeper type, circular base.
UM250	Culpeper	Culpeper Fecit: Hartsoeker-Wilson type, simple microscope.
UM1846	Culpeper	Culpeper Londini (foot) / Culpeper Fecit (microsc.): Hartsoeker-Wilson, on pillar and tripod.
Li122	Cuthbertson	J. Cuthbertson te Amsterdam: solar microscope.
UM25	Deijl, H. van	Harm.s van Deijl / Inv= et Fecit / Amsterdam: side-pillar microscope, on tripod.
UM26	Deijl, H. van	Harm.s van Deijl / Inv et fecit / Amsterdam: side-pillar microscope, on tripod.
UM23	Dellebarre ?	C.F. Dellebarre: side-pillar microscope, on tripod.
Li114	Dollond	Dollond / London: Simple Wollaston-doublet microscope.
Li115	Dollond	Dollond London: Simple pocket microscope after Robert Brown.
Li123	Dollond	Dollond London: Simple chromatic solar microscope for opaque and transparent objects.
Li124	Dubosq-Soleil	J. Dubosq-Soleil à Paris: projection microscope.
UM22	Dutch made ?	side-pillar microscope, on box with drawer, rack and pinion focussing.
UM24	Dutch made ?	side-pillar microscope, on tripod.
UM38	Dutch made ?	Cuff-Baker type, projection.
UM146	Dutch made ?	side-pillar microscope, on box with drawer, rack and pinion focussing.
UM233	Dutch made ?	side-pillar microscope, on base-plate.
UM235	Dutch made ?	side-pillar microscope, on base-plate.
UM236	Dutch made ?	Hartsoeker-Wilson type, projection.
UM378	Dutch made ?	side-pillar microscope, on box with drawer.
UM568	Dutch made ?	side-pillar microscope, on tripod.
UM1018	Dutch made ?	Chest microscope.
UM229	Eastland	Eastland & Comp / London: side-pillar microscope, on tripod.
UM295	Engell	Schaeffer & Budenberg: Engells Patent Schul- und Salonmikroskop.
UM448	Engell ?	Engell's Patent Schul- und Salonmikroskop.
UM2812	Engell ?	Engell's Patent Schul- und Salonmikroskop.
Sm1	English	Marshall microscope.
Sm4	English	Society of Arts microscope.
UM11	English made ?	Culpeper type, on box with drawer.
UM14	English made ?	Culpeper type, on box with drawer.
UM17	English made ?	Cuff type, on box with drawer.
UM43	English made ?	Gould type microscope on box.
UM77	English made ?	Culpeper type, circular base-plate.
UM252	English made ?	side-pillar microscope, on tripod.
UM255	English made ?	English stand.
UM293	English made ?	side-pillar microscope, on tripod.

inv. no.	maker	signature and description
Sm3	English made ?	Society of Arts microscope.
Li259	French made ?	drum microscope.
UM141	French made ?	Leeuwenhoek type, modified.
UM144	French made ?	compound microscope.
UM253	French made ?	drum microscope on box.
UM312	French made ?	drum microscope (small).
UM344	French made ?	P.J. Kipp en Zoon te Delft: drum microscope.
UM369	French made ?	side-pillar microscope, on circular base.
UM456	French made ?	drum microscope (small).
UM1819	French made ?	drum microscope.
UM1852	French made ?	drum microscope.
UM2155	French made ?	two pillars, on box.
UM42	German made ?	I.M. : Culpeper type, circular base.
UM577	German made ?	I.M. : drum microscope.
UM2814	German made ?	horseshoe stand.
UM297	Gundlach, E.	E. Gundlach/ Berlin: horseshoe stand.
UM6	Harting ?	unsigned: Simple microscope, Wollaston-type, as modified by Harting.
UM28	Hartnack	E. Hartnack et Cie / Place Dauphine 21/ Paris: horseshoe stand.
UM452	Hartnack ?	horseshoe, long pillar.
UM542	Hartnack	E. Hartnack et Cie / Place Dauphine 21 / Paris: horseshoe stand.
UM543	Hartnack	E. Hartnack & Cie. / Place Dauphine 21 / Paris: horseshoe stand.
UM1086	Hartnack	E. Hartnack / Potsdam: horseshoe stand.
UM2606	Hensoldt	Hensoldt Wetzlar/ Made in Germany: Binocular dissecting microscope.
UM374	Huysen ?	side-pillar microscope, on box with drawer.
Li113	Huysen, J.	unsigned: Simple microscope, side-pillar on box with drawer.
UM9	Huysen, J.	unsigned: side-pillar microscope, on box with drawer.
UM248	Italian ?	side-pillar microscope, on box with drawer.
Li121	Junker ?	unsigned: simple chromatic solar microscope, wood.
UM396	Junker ?	simple chromatic solar microscope, wood.
UM455	Kellner	C. Kellner in Wetzlar / Belthle & Rexroth / No.60: circular pillar on octagonal base.
UM514	Kleman	J.M. Kleman: side-pillar microscope, on tripod, rack and pinion focussing.
UM986	Kleman, J.M.	J.M. Kleman & Zoon / Amsterdam: side-pillar microscope, on box with two drawers, rack and pinion focussing.
UM1	Leeuwenhoek	Leeuwenhoek microscope.
Li344	Leitz	E. Leitz / Wetzlar
Sm11	Leitz	Ernst Leitz / Wetzlar: Binocular, on triangular base plate.

inv. no.	maker	signature and description
Sm12	Leitz	Ernst Leitz / Wetzlar: Ortolux type.
Sm14	Leitz	E. Leitz / Wetzlar: stand I.
Sm17	Leitz	Leitz / Wetzlar / Germany: Orthoplan, with Ploemopak.
UM331	Leitz	E. Leitz Wetzlar: horseshoe stand.
UM450	Leitz	E. Leitz / Wetzlar: stand II, English stand.
UM475	Leitz	E. Leitz / Wetzlar: horseshoe, parallel movement.
UM544	Leitz	E. Leitz/ Wetzlar: horseshoe stand.
UM696	Leitz	E. Leitz/ Wetzlar.
UM913	Leitz	E. Leitz / Wetzlar.
UM984	Leitz	E. Leitz /Wetzlar.
UM1421	Leitz	E. Leitz/ Wetzlar: mineralogical microscope.
UM1505	Leitz	E. Leitz / Wetzlar: mineralogical microscope.
UM1506	Leitz	E. Leitz / Wetzlar: stand III M.
UM1809	Leitz	E. Leitz / Wetzlar: stand K 16 ?.
UM1810	Leitz	E. Leitz / Wetzlar: mineralogical microscope.
UM1812	Leitz	E. Leitz / Wetzlar / Filiale New York.
UM1813	Leitz	E. Leitz / Wetzlar: stand CB ?.
UM1815	Leitz	E. Leitz / Wetzlar: mineralogical microscope.
UM1868	Leitz	E. Leitz Wetzlar: ultra-microscope, incomplete.
UM1869	Leitz	E. Leitz Wetzlar: stand J II.
UM2394	Leitz	E. Leitz/ Wetzlar: stand Ia.
UM2813	Leitz	E. Leitz / Wetzlar: stand III ?.
UM2815	Leitz	E. Leitz Wetzlar: stand AST.
UM2961	Leitz	AE. Leitz/ Wetzlar: projection microscope.
UM3125	Leitz	Leitz Wetzlar: horseshoe, parallel movement.
UM228	Lerebours ?	Lerebours type.
UM76	Lerebours	Lerebours et Secretan à Paris: Chevalier type on box.
UM249	Lerebours	Lerebours et Secretan à Paris: drum microscope.
UM18	Lincoln	Lincoln / London: Cuff type, on box with drawer.
Li112	Lommers, Jac.	Jacobus Lommers Fecit / Utrecht 1760: Simple Hartsoeker-Wilson microscope, on box with drawer.
Li117	Martin	B. Martin / Invt et Fecit / Londini / No.1: Compound side-pillar microscope, on tripod.
UM330	Martin	B. Martin / London / No.10: side-pillar microscope, on tripod, rack and pinion focussing.
UM386	Martin	B. Martin, London: Cuff-Baker type, projection microscope.
UM399	Martin ?	side-pillar microscope, on tripod.
UM19	Martin, B. et fils	B. Martin et fils fecit [sic]: Cuff type, on box with drawer.
Sm10	MBS	MBS-1 / Made in USSR: Russian stereo microscope.
UM385	Merz	G & S Merz in Munchen: horseshoe stand.
UM813	Merz	G & S Merz / in Munchen: horseshoe stand.

inv. no.	maker	signature and description
UM3	Musschenbroek, J.	Oriental lamp and crossed keys: Simple microscope with object holder.
UM387	Musschenbroek, J.	Oriental lamp and crossed keys: Simple microscope with object holder.
UM531	Musschenbroek, J.	Oriental lamp and crossed keys: Musschenbroek type, second form.
Li119	Nachet	Nachet Opticien / Rue des Grands Augustins 4 / Paris: Compound achromatic drum microscope.
Li120	Nachet	Nachet et Fils / Rue St. Severin 17 / Paris: Compound achromatic side-pillar microscope.
Li268	Nachet	Nachet et Fils / Paris / Rue St. Severin 47
Li269	Nachet	Nachet / Opticien à Paris / Rue Serpente 16: horseshoe and pillar.
Li341	Nachet	Nachet à Paris.
UM29	Nachet	Nachet Opticien / Rue des Grands Augustins 1 / Paris: drum microscope.
UM35	Nachet ?	drum microscope.
UM36	Nachet	Nachet no.7 objective, correction collar.
UM355	Nachet	Nachet et fils / 17, rue St. Severin / Paris: side-pillar microscope, on base-plate.
UM388	Nachet	Nachet et Fils / à Paris / Rue Serpente 16
UM458	Nachet ?	drum microscope.
UM591	Nachet	Nachet et Fils/ 17 Rue St. Severin/ Paris: base-plate, pillar, platine a tourbillon.
UM1022	Nachet	Nachet à Paris: mineralogical microscope, grand stand.
UM1107	Nachet	Nachet à Paris/ 17 Rue St. Severin: horseshoe, aquatic motion.
UM1818	Nachet	Nachet Opticien / Rue Serpente 16 / Paris: drum microscope.
Li125	Newman	J. Newman / Regent Street / London: oxy-hydrogen projection microscope.
UM27	Oberhäuser	George Oberhäuser / Place Dauphiné 19 / Paris: horseshoe, platine a tourbillon.
Li126	Onderdewijngaart	lucernal microscope.
UM576	Onderdewijngaart	Dellebarre/1797/Onderdewijngaart Canzius Confecit: Dellebarre type.
Li296	Oude Delft	De Oude Delft: reflection microscope.
UM15	Paauw ?	side-pillar microscope on elliptical wooden block.
UM296	Plössl	Plössl in Wien: side-pillar microscope, on tripod.
UM551	Powell & Lealand	Powell & Lealand / 170 / Euston Road / London /1892: kettle-drum stand.
Li342	Prazmowski	E. Hartnack & A. Prazmowski / A. Prazm. sucr / Paris
Sm8	Prior, W.R.	W.R. Prior & Co. / London: horseshoe stand.
UM2607	PZO	PZO / Made in Poland: Binocular microscope.
Li237	Rebaillo	Rebaillo & Zoon / Rotterdam: horseshoe stand.
UM1072	Reichert	Reichert / Austria: horseshoe, with heating table.
UM1105	Reichert	C. Reichert/ Wien: horseshoe, aquatic motion.

inv. no.	maker	signature and description
UM1106	Reichert	C. Reichert / Wien: horseshoe, aquatic motion.
UM1422	Reichert	C. Reichert/ Wien: horseshoe stand.
UM1491	Reichert	C. Reichert Wien.
UM2600	Reichert	Reichert/ Austria: horseshoe, with built-in illumination, and mechanical stage.
UM2602	Reichert	Reichert / Wien; binocular dissecting microscope.
UM2603	Reichert	Reichert / Wien: binocular dissecting microscope.
UM2604	Reichert	Reichert / Wien: binocular dissecting microscope.
UM3129	Reichert	C. Reichert Wien: horseshoe, drawtube, Schlittenschraube.
Sm6	Robbins, A.L.	Alfred Robbins Co. / Chicago: horseshoe stand.
UM13	Scarlet	J.Scarlet / London: Culpeper type, on box with drawer.
UM31	Schiek	Schiek in Berlin: drum microscope.
UM142	Schokking, J.A.J.	J.A.J. Schokking / Spui 18 / Amsterdam: side-pillar microscope, on base-plate.
UM1034	Seibert	W & H Seibert / Wetzlar: horseshoe stand.
UM1499	Seibert	Seibert: horseshoe stand.
UM1811	Seibert	W & H Seibert / Wetzlar: horseshoe stand.
UM1814	Seibert	W & H Seibert / Wetzlar: horseshoe stand.
UM688	Smith, B. & B.	Smith Beck & Beck / 31 Cornhill / London: reversed claw foot.
UM39	Spiering	Jan Hendrik Spiering / Amsterdam: solar microscope.
Sm2	Sterrop	Sterrop Fecit: Hartsoeker-Wilson type.
UM16	Sterrop	Geo Sterrop, Maker: Cuff type, on box with drawer.
UM646	Sterrop	Sterrop London Fecit: Culpeper type, tripod on box with drawer.
Li343	unknown	unsigned: compass microscope.
UM7	unknown	unsigned: simple doublet dissecting microscope.
UM8	unknown	unsigned: simple microscope, pillar and spring stage on box.
UM12	unknown	Culpeper type, circular base.
UM41	unknown	drum microscope.
UM71	unknown	Cuff-Baker type, projection.
UM143	unknown	Hartsoeker-Wilson type, modified.
UM227	unknown	side-pillar microscope, on tripod.
UM291	unknown	side-pillar microscope, on tripod.
UM292	unknown	side-pillar microscope, on tripod or box with drawer.
UM294	unknown	drum microscope.
UM329	unknown	side-pillar microscope, on box with drawer.
UM368	unknown	side-pillar microscope, on box with drawer, rack and pinion focussing.
UM384	unknown	projection microscope.

inv. no.	maker	signature and description
UM395	unknown	compass microscope in case.
UM480	unknown	magnifier on tripod.
UM488	unknown	circular wooden base with lens on pillar and object pin.
UM525	unknown	small ivory telescope with built-in magnifier.
UM530	unknown	compass microscope.
UM755	unknown	Stanhope lens.
UM979	unknown	side-pillar microscope, not complete.
UM1068	unknown	Hartsoeker-Wilson type, ivory.
UM2510	unknown	Cuff type, not complete.
UM4	unknown	simple microscope with object holder.
UM72	Urings	Urings fecit. Label in box: A. Ciouino, A'dam: Culpeper type, tripod on box with drawer.
UM354	Urings	Urings Fecit: Culpeper type, tripod on box with drawer.
UM375	Waechter, P.	Paul Wächter/ Optische Werkstätte / Berlin: stand Vb.
Sm13	Watson, W.	W. Watson & Sons Ltd. / London: horseshoe stand.
UM234	Wijk, C. van	C. van Wijk Fecit Utrecht 1783: Hartsoeker-Wilson type, on box with drawer.
Li238	Winkel	R. Winkel/ Gottingen: horseshoe stand.
Li346	Winkel	R. Winkel/ Gottingen.
UM545	Winkel	R. Winkel/ Gottingen: horseshoe stand.
UM1423	Winkel	R. Winkel/ Göttingen.
UM2084	Winkel	R. Winkel / Gottingen: travel microscope.
UM2558	Winkel	R. Winkel/ Gottingen.
UM3130	Winkel	R. Winkel Gottingen: horseshoe stand.
UM3132	Winkel	R. Winkel Göttingen: horseshoe stand.
UM1855	Winkel Zeiss	Winkel Zeiss / Gottingen.
UM2559	Winkel Zeiss	Winkel Zeiss / Gottingen: stand GBC.
UM2560	Winkel Zeiss	Winkel Zeiss/ Göttingen: stand GBC.
UM2962	Winkel Zeiss	Zeiss Winkel.
UM254	Zaalberg van Zelst	side-pillar on base.
Li239	Zeiss	Carl Zeiss/ Jena: stand Ia ?.
Li345	Zeiss	Carl Zeiss / Jena.
Li347	Zeiss	Carl Zeiss / Jena.
Li348	Zeiss	Carl Zeiss / Jena: horseshoe stand.
Sm15	Zeiss	binocular microscope.
UM30	Zeiss	Carl Zeiss / Jena: side-pillar microscope, on base-plate.
UM451	Zeiss	Carl Zeiss Jena: stand Ia ?.
UM465	Zeiss	Carl Zeiss / Jena: horseshoe stand.
UM550	Zeiss	Carl Zeiss / Jena.
UM1079	Zeiss	Carl Zeiss / Jena.
UM1365	Zeiss	Carl Zeiss / Jena: Compound achromatic projection microscope.
UM1437	Zeiss	Carl Zeiss / Jena.

inv. no.	maker	signature and description
UM1504	Zeiss	Carl Zeiss / Jena.
UM1820	Zeiss	Carl Zeiss / Jena: stand VI.
UM1912	Zeiss	Carl Zeiss / Jena: stand Ia.
UM1913	Zeiss	Carl Zeiss / Jena: stand B.
UM2557	Zeiss	Carl Zeiss / Jena.
UM2866	Zeiss	Carl Zeiss Jena: stand I.
UM3036	Zeiss	Carl Zeiss Jena: stand ESG / EOG.
UM3126	Zeiss	Carl Zeiss / Jena: stand Va / VI.
UM3128	Zeiss	Carl Zeiss Jena: stand VII.
UM3131	Zeiss	Carl Zeiss Jena: stand Ia.
UM3135	Zeiss	Carl Zeiss Jena: stand Xb.
UM3902	Zeiss	C. Zeiss / Jena: stand BCD.
UM4010	Zeiss	C. Zeiss / Jena: hand held.
UM4212	Zeiss	Carl Zeiss / Jena: horseshoe stand.
UM2276	Zeiss Winkel	Zeiss Winkel: metal microscope.

13

APPENDIX 6: EYEPIECES, SCIENCE MUSEUM

Eyepieces and lenses measured in the Science Museum and the Wellcome Collection in the Science Museum, London.

Inventory numbers of Science museum instruments are composed of the year of acquisition, a dash and a series number.

Instruments from the Wellcome collection are preceded by an 'A'. The decimal part of the inventory number indicates the specific eyepiece or part of it. The magnification M is defined as 250/f. Thickness of the lens: dst.1; distance between the lenses: dst.2. The radius closest to the eye is rds 1, the other one is rds 2.

Table 93: eyepieces

Maker	inv.no.	diam.	type	f(mm)	mgn	ref.
Adams	A56523	-	4 lens	49.71	5.03	3.7.4
Adams	A159192	-	3 lens	55.23	4.53	3.6.5
Adams	A159473	-	4 lens	46.39	5.39	3.7.3
Adams	A159980	-	2 lens	63.91	3.91	3.5.8
Adams	A196842	40	3 lens	127.03	1.97	13.0.0.1
Adams	A600168	40	3 lens	47.22	5.29	3.6.2
Adams	A645025	29	3 lens	39.77	6.29	3.6.4
Adams	1918-84	-	3 lens	59.65	4.19	3.6.3
Adams	1925-136	-	2 lens	53.02	4.72	3.5.7
Adams, D.	A56301	-	3 lens	36.45	6.86	3.6.6
Adams, D.	A56305	44.5	3 lens	44.18	5.66	3.6.7
Amici	1921-189	m14.8;48	Hu	12.46	20.06	3.5.12
Amici	1921-192	m19.8;22	Hu	24.55	10.18	
Amici	1921-754.3	m19.8;20	bicx a	3.87	64.55	
Amici	1921-754.4	m19.8;20	Hu b	8.74	28.60	
Amici	1921-754.5	m19.8;20	Hu c	13.64	18.33	
Amici	1921-754.6	m19.8;20	Hu d	16.99	14.71	
Amici	1921-754.7	m26.6;19	Hu e	38.66	6.47	
Amici	1928-847.3	-	Hu I	28.39	8.81	
Amici	1928-847.4	-	Hu II	20.08	12.45	
Amici	1938-688.3	26	Hu	24.93	10.03	
Amici	1938-688.31	-	eyel	13.16	19.00	
Amici	1938-688.32	-	fieldl	43.49	5.75	
Amici	1938-688.4	26	Hu 1	23.85	10.48	
Amici	1938-688.5	26	Hu 2	44.31	5.64	
Amici	1954-287.3	m19.8/22	Hu s	14.54	17.19	
Amici	1954-287.4	m19.8/22	Hu l	21.12	11.84	
Canzius	A600249	m40;24	Dell	43.08	-	13.0.0.7
Chev., C.	1906-63.3	bajonet	Hu l,a	43.08	5.80	
Chev., C.	1906-63.4	bajonet	Hu l,b	34.98	7.15	
Chev., C.	1906-63.5	bajonet	Hu s,a	23.37	10.70	
Chev., C.	1906-63.6	bajonet	Hu s,b	17.31	14.44	
Chev., C.	1921-184.3	11.2	d,d,d	9.89	25.28	

Continued on next page

Maker	inv.no.	diam.	type	f(mm)	mgn	ref.
Chev., C.	1921-184.31	-	a	25.39		
Chev., C.	1921-184.32	-	b	25.72		
Chev., C.	1921-184.33	-	c	25.96		
Chev., C.	1921-184.4	-	d,d	13.50	-	
Chev., C.	1921-188.3	m33.4;30	Hu l	53.02	4.72	
Chev., C.	1921-188.4	m33.4;30	Hu s	45.57	5.49	
Chev., C.	1921-249.3	25	Hu l	38.08	6.57	
Chev., C.	1921-249.4	25	Hu s	31.16	8.02	
Chev., C-A.	A203049.3	27.9	Hu, a	19.78	12.64	
Chev., C-A.	A203049.31	-	eyel	12.98	-	
Chev., C-A.	A203049.32	-	fieldl	39.81	-	
Chev., C-A.	A203049.4	27.9	Hu, b	31.48	7.94	
Chev., C-A.	A203049.41	-	eyel	25.49	-	
Chev., C-A.	A203049.42	-	fieldl	43.08	-	
Chev., V.	A54219.3	30.4	2 lens	36.45	6.86	3.5.11
Chev., V.	1921-185.3	29.2	Hu 1	34.62	7.22	
Chev., V.	1921-746.3	30.5	Hu	30.93	8.08	13.0.0.2
Cuff	A62993	-	2 lens	45.19	5.53	3.5.3
Cuff	A650687	-	2 lens	-	-	13.0.0.3
Delleb.	A60955	m40;24	Del.	-	-	13.0.0.4
Delleb.	1928-784	m39.6;32	4 lens	-	-	13.0.0.5
Delleb.	1928-817	m40.3;24	5 lens	-	-	13.0.0.6
Delleb. ?	RMS 18	m40.8;23	4 lens	16.84	14.85	3.8.1
Delleb. ?	A135495	m40;24	5 lens	19.88	12.57	3.8.2
Deutgens	1921-236	-	-	20.28	12.33	-
Dollond	A18469	44.6	3 lens	55.23	4.53	3.6.11
Dollond	A50965	-	3 lens	46.39	5.39	3.6.9
Dollond	A56304	-	3 lens	47.64	5.25	3.6.10
Dollond	A159502	-	3 lens	39.51	6.33	3.6.1
Dollond	A600179	26.4	3 lens	27.22	9.18	13.0.0.8
Dollond	A600242.3	38.8	3 lens	53.39	4.68	13.0.0.9
Dollond	A600242.4	38.8	3 lens	38.11	6.56	13.0.0.10
Dollond	A600242.5	38.8	3 lens	18.46	13.54	
Dollond	A600242.51	-	eyel	12.86	-	
Dollond	A600242.52	-	fieldl	27.38	-	-
Dollond	A600242.6	38.8	3 lens	6.92	36.11	-
Dollond	A600242.61	-	eyel	4.74	-	
Dollond	A600242.62	-	fieldl	10.70	-	
Dollond	A645008.3	30	3 lens	45.57	5.49	13.0.0.11
Dollond	1928-860	26.5	Hu	34.98	7.15	13.0.0.12
Dollond	1928-867.3	-	3 lens	-	-	13.0.0.13
Dollond	1928-867.4	26.5	Hu	30.93	8.08	13.0.0.13
Dollond	1928-867.5	26.5	Hu	17.31	14.44	-
Dollond	1928-867.51	-	eyel	12.98	-	-
Dollond	1928-867.52	-	fieldl	26.51	-	-
Dollond	1928-867.6	26.5	Hu	10.70	23.36	
Dollond	1928-867.61	-	eyeL	7.85	-	

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Maker	inv.no.	diam.	type	f(mm)	mgn	ref.
Dollond	1928-867.62	-	fieldl	18.00	-	
Dollond	1928-867.7	26.5	Hu	7.55	33.10	
Dollond	1928-867.71	-	eyeL	11.54	-	
Dollond	1928-867.72	-	fieldl	10.39	-	
Dollond	1928-867.8	26.5	Rams	20.77	12.04	13.0.0.15
Fokkenberg	1925-243.3	-	2 lens	31.48	7.94	13.0.0.16
Frau-Utz	1928-850.3	m26.5;40	Hu	20.31	12.31	3.5.10
Frau-Utz	1928-850.4	m26.5;40	3 lens	14.91	16.76	-
Frau-Utz	1928-850.41	-	eyel 1	11.54	-	-
Frau-Utz	1928-850.42	-	eyel 2	23.54	-	-
Frau-Utz	1928-850.5	m26.5;40	Hu	6.29	39.72	-
Frau-Utz	1928-850.51	-	eyel	4.37	-	-
Frau-Utz	1928-850.52	-	fieldl	13.52	-	-
Frau-Utz-R	1921-741.3	m26.7;40	Hu	23.08	10.83	13.0.0.17
Hartnack	1936-648.3	23.45	Hu 2	43.27	5.78	
Hartnack	1936-648.4	23.45	Hu 3	34.62	7.22	
Hartnack	1936-648.5	23.45	Hu 4	25.39	9.85	
Jones	A 71683	41.4	5 lens	55.23	4.53	13.0.0.18
Jones ?	A 601290	41.4	4 lens	30.13	8.30	13.0.0.19
Jones, W/S	A 56300	41.4	4 lens	30.13	na	3.7.5
Jones, W/S	A 56801	-	3 lens	45.57	5.49	3.6.8
Jones, W/S	A 212741.3	27.8	2 lens	29.08	8.60	3.5.9
Jones, W/S	A 212741.4	27.8	2 lens	29.77	8.40	3.5.9
Jones, W/S	A 212741.5	31.1	2 lens	33.80	7.40	13.0.0.20
Jones, W/S	A 600166	41.8	5 lens	55.23	4.53	3.7.6
Kellner	A 56418	25.3	Hu	53.85	4.64	13.0.0.21
Kellner	1921-252.3	25.7	Hu I	30.93	8.08	-
Martin	A 101926	-	4 lens	103.56	2.41	3.7.2
Martin	1882-1	-	3 lens	38.66	6.47	13.0.0.22
Martin ?	A76350	35.7	4 lens	112.67	2.22	13.0.0.23
Martin ?	A645049	32.4	4 lens	93.89	2.66	13.0.0.24
Merz, G.	1921-251.3	28.8	Hu	30.59	8.17	-
Nobert	1921-750.4	32.4	Hu	26.04	9.60	-
Nobert	1921-750.5	32.4	Hu	30	8.33	-
Oberh.	1912-212.3	23.35	Hu 1	52.47	4.76	-
Oberh.	1912-212.4	23.35	Hu 4	25.49	9.81	13.0.0.25
Oberh-Tr.	A40983.3	23.2	Hu	44.18	5.66	-
Oberh-Tr.	1917-102.3	23.3	Hu 3	33.14	7.54	13.0.0.26
Oberh-Tr.	1918-58.3	17.9	Hu	33.14	7.54	13.0.0.27
Plössl	1925-149.3	23.6	Hu	25.39	9.85	13.0.0.28
Plössl	1925-149.4	23.6	3 lens	11.33	22.07	13.0.0.29
Plössl	1928-801.3	m39.6;40	2 lens	48.20	5.19	13.0.0.30
Powell	1918-17.3	38.6	Hu, a	54.44	4.59	13.0.0.31
Powell	1918-17.4	38.6	Hu, b	37.28	6.71	13.0.0.32
Powell	1918-17.5	38.6	Hu, c	27.11	9.22	13.0.0.33
Pow-Leal	A71911.3	29.7	Hu	27.69	9.03	13.0.0.34
Pow-Leal	A71911.4	29.7	Hu	49.71	5.03	-

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Maker	inv.no.	diam.	type	f(mm)	mgn	ref.
Pow-Leal	A140784.3	29.7	Hu, a	34.57	7.23	13.0.0.35
Pow-Leal	A140784.4	29.7	Hu, b	36.15	6.92	13.0.0.36
Pow-Leal	A600239.3	29.7	Hu	34.01	7.35	13.0.0.37
Pow-Leal	A601303.3	29.7	Hu sh	29.82	8.38	-
Pow-Leal	A601303.4	29.7	Hu lo	51.36	4.87	-
Pow-Leal	1907-83.3	36.45	Hu sh	11.37	21.98	-
Pow-Leal	1907-83.4	36.45	Hu me	25.62	9.76	-
Pow-Leal	1907-83.5	36.45	Hu lo	36.96	6.76	-
Pow-Leal	1907-83.6	36.45	Hu lo	36.45	6.86	-
Pow-Leal	1913-291.3	29.7	Hu, a	50.98	4.90	13.0.0.38
Pow-Leal	1913.291.4	29.7	Hu, b	24.85	10.06	13.0.0.39
Pow-Leal	1921-181.3	35.9	Hu	43.08	5.80	13.0.0.40
Pow-Leal	1966-417.3	29.7	Hu, a	24.10	10.37	13.0.0.41
Pow-Leal	1966-417.4	29.7	Hu, b	51.78	4.83	13.0.0.42
Pow-Leal	1966-417.5	29.7	Hu, c	48.52	5.15	13.0.0.43
Pritchard	A41397.3	-	4 lens	61.31	4.08	13.0.0.44
Pritchard	A41397.4	31.3	Hu, l	44.18	5.66	13.0.0.45
Pritchard	A41397.5	31.3	Hu, s	24.85	10.06	13.0.0.46
Pritchard	A71679.3	36.1	Hu lo	47.16	5.30	-
Pritchard	A71679.4	36.1	Hu me	36.45	6.86	-
Pritchard	A71679.5	36.1	Hu sho	25.49	9.81	-
Pritchard	1876-617.3	36.1	2 lens	50.17	4.98	13.0.0.47
Rienks	1928-849.3	-	eyel	36.16	-	13.0.0.48
Ross	A4888.3	29	Hu	57.07	4.38	-
Ross	A601094.3	-	Hu B	36.82	6.79	-
Ross	A601097.3	33.2	Hu B	36.45	6.86	-
Ross	A601295.3	33.2	Hu D	14.54	17.19	-
Ross	A601295.4	33.2	Kell D	11.00	22.74	-
Ross	1891-17.3	33.45	Hu lo	61.31	4.08	-
Ross	1891-17.4	34.7	Hu	33.14	7.54	-
Ross	1891-17.5	34.7	Hu sh	20.12	12.43	-
Ross	1891-17.6	34.7	Ram	36.15	6.92	-
Ross	1900-172.1	33.2	Hu 6	14.19	17.61	-
Ross	1900-172.3	33.2	Hu A	59.18	4.22	-
Ross	1900-172.4	33.2	Hu B	36.45	6.86	-
Ross	1900-172.5	33.2	Hu C	23.54	10.62	-
Ross	1900-172.6	33.2	Kell C	21.76	11.49	-
Ross	1900-172.7	33.2	Kell D	10.39	24.07	-
Ross	1900-172.8	33.2	Hu E	12.12	20.63	-
Ross	1900-172.9	33.2	Hu F	8.31	30.09	-
Ross	1913-293.3	37.4	2 lens	44.74	5.59	13.0.0.49
Ross	1919-469.3	30.7	Hu	40.50	6.17	13.0.0.50
Ross	1921-213.3	29.3	Hu	31.63	7.90	13.0.0.51
Ross	1921-216.3	33.25	Hu	57.99	4.31	13.0.0.52
Ross	1921-216.4	33.25	Hu B	36.15	6.92	-
Schiek	1921-250.3	39.3	-	72.90	3.43	-
Smith, J.	A46257.3	37.3	Hu 1	47.50	5.26	-

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Maker	inv.no.	diam.	type	f(mm)	mgn	ref.
Smith, J.	A46257.4	37.3	Hu 3	18.78	13.31	-
Smith, J.	A54204.3	m41.8;16	2 lens	43.08	5.80	13.0.0.53
Smith, J.	A604181.3	m40.4;24	2 lens, a	49.71	5.03	13.0.0.54
Smith, J.	A604181.4	m40.4;24	2 lens, b	25.49	9.81	13.0.0.55
Smith, J.	A604181.5	m40.4;24	2 lens, c	15.39	16.25	13.0.0.56
Smith, J.	1891-19.30	33.4	Hu sh	30.59	8.17	-
Smith, J.	1891-19.40	33.4	Hu me	29.82	8.38	-
Smith, J.	1891-19.50	33.4	Huy lo	45.57	5.49	-
Smith-B	A50467.3	35.75	Hu	53.85	4.64	-
Smith-B	A50467.4	35.75	Hu med	16.57	15.09	-
Smith-B	A50467.5	35.75	Hu, a	19.19	13.03	-
Smith-B	A50467.6	35.75	Hu, b	18.41	13.58	-
Smith-B	A54072.3	20.2	Kell 1	33.14	7.54	-
Smith-B	A54205.3	33.6	Hu 1	39.77	6.29	-
Smith-B	A54205.4	33.6	Hu 2	32.03	7.80	-
Smith-B	A54205.5	33.6	Hu 3	18.78	13.31	-
Smith-B	A56382.3	32.3	Hu lo	52.47	4.76	-
Smith-B	A56382.4	32.3	Hu sh	34.24	7.30	-
Smith-B	A159563.4	20.2	Kell 1	34.24	7.30	-
Smith-B	A601103.3	33.6	Hu a	30.38	8.23	-
Tulley	1938-686.3	m41.5;18	Hu	55.23	4.53	13.0.0.57
Tulley	1938-686.4	m41.5;18	Hu me	26.31	9.50	-
Tulley	1938-686.5	m41.5;18	Hu sh	18.25	13.70	-
unsigned	A 18817.3	41.2	5 lens	63.52	3.94	13.0.0.58
unsigned	A 56303.3	35	Hu	44.97	5.56	-
unsigned	A 56519.3	-	2 lens	67.93	3.68	13.0.0.59
unsigned	A 600182.3	-	3 lens	27.62	9.05	13.0.0.60
Varley	A 169733.3	28.6	Hu, a	26.93	9.29	13.0.0.61
Varley	A 169733.4	28.6	Hu, b	14.07	17.77	13.0.0.62

13.0.0.1 *Adams, A196842*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total (3L)	127.03					
eyelens 1	46.39	55.21	43.16	3.44	59.78	1.528
fieldlens	69.04	72.78	72.78	6.08	70.8-105.8	1.535
between lens	143.60	169.47	144.93	2.32	36.50	1.545
1+2	53.02					

13.0.0.2 *Chevalier, V., 1921-746.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	30.93					
eyelens	23.82	flat	12.84	4.19	31.20	1.539
fieldlens	43.49	flat	22.85	4.89		1.525

13.0.0.3 *Cuff, A650687*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	-					
eyelens	31.48	33.84	33.84	4.14	48.80	1.549
fieldlens	68.12	72.33	72.33	4.56	108.00	1.537

13.0.0.4 *Dellebarre, A60955*

lens	f	rad 1	rad 2	dist 1	dist 2	N
lens "1"	47.34	46.88	46.88	7.28	-	1.508

13.0.0.5 *Dellebarre, 1928-784*

lens	f	rad 1	rad 2	dist 1	dist 2	N
lens 1	43.49	45.48	45.48	5.59	0.32	1.534
lens 2	63.52	63.68	63.68	5.79	6.51	1.509
lens 3	63.52	72.63	63.74	5.40	150–250	1.542
between lens	60.06	63.62	63.62	3.68	c. 260	1.535

13.0.0.6 *Dellebarre, 1928-817*

lens	f	rad 1	rad 2	dist 1	dist 2	N
lens 1	53.02	52.59	52.59	7.22	1.36	1.508
lens 2	57.99	57.55	57.41	5.99	3.14	1.504
lens 3	61.54	63.92	63.92	5.78	-	1.528
lens 5	71.80	77.30	77.38	5.57	-	1.546

13.0.0.7 *Dellebarre type by Canzius, A600249*

lens	f	rad 1	rad 2	dist 1	dist 2	N
lens "1"	43.08	45.31	45.31	-	-	1.526
between lens	60.75	63.62	63.62	-	-	1.524

13.0.0.8 *Dollond, A600179*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	27.22					
eyelens	29.00	29.05	29.05	-	-	1.501
fieldlens	51.36	52.93	50.75	-	-	1.504

13.0.0.9 *Dollond, A600242.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	53.39					
eyelens	32.03	flat	16.52	2.94	52.19	1.516
fieldlens	62.13	flat	31.90	7.07	120	1.513

13.0.0.10 *Dollond, A600242.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	38.11					
eyelens	24.55	flat	12.52	2.15	34.66	1.510
fieldlens	41.42	flat	21.57	7.53	140	1.521

13.0.0.11 *Dollond, A645008*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	45.57					
eyelens 1	26.51	133.45	15.58	3.38	9.42	1.530
eyelens 2	35.51	35.40	35.40	3.54	52	1.507
fieldlens	75.74	79.41	79.41	4.06	110	1.529

13.0.0.12 *Dollond, 1928-860*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	34.98					
eyelens	24.03	flat	12.46	1.96	31.58	1.519
fieldlens	42.61	flat	21.58	4.26	-	1.506

13.0.0.13 *Dollond, 1928-867.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total						
eyelens 1	37.59	38.92	39.10	3.42	13.75	1.527
eyelens 2	43.08	45.07	45.07	3.61	-	1.530
fieldlens	-	-	-	-	-	-

13.0.0.14 *Dollond, 1928-867.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	30.93					
eyelens	23.93	flat	12.48	1.86	-	1.521
fieldlens	41.42	flat	21.67	4.11	-	1.523

13.0.0.15 *Dollond, 1928-867.8*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	20.77					
eyelens	27.69	flat	13.87	2.88	16.92	1.501
fieldlens	31.85	flat	16.47	4.98	-	1.517

13.0.0.16 *Fokkenberg, 1925-243*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	31.48					
eyelens	37.28	37.32	37.30	6.25	34.95	1.515
fieldlens	76.15	79.68	79.77	4.87	148.55	1.529

13.0.0.17 *Fraunhofer, Utschneider und Reichenbach, 1921-741*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	23.08					
eyelens	14.19	flat	7.41	1.28	24.50	1.522
fieldlens	39.81	flat	20.78	2.50	-	1.522

13.0.0.18 *Jones, A71683*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	55.23					
eyelens 1	42.61	flat	22.88	4.34	1.29	1.537
eyelens 2	82.85	87.15	87.15	5.02	1.67	1.531
eyelens 3	82.85	87.15	87.15	4.13	28.89	1.530
field lens	82.85	87.15	87.15	5.56	52.6-82.6	1.532
between lens	135.87	-	-	-	41.00	

13.0.0.19 *Jones (?), A601290*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	30.13					
eyelens 1	49.71	162.4	32.15	3.75	3.96	1.544
eyelens 2	72.90	75.87	75.87	5.23	2.06	1.527
eyelens 3	72.90	75.87	75.87	5.41	27.34	1.527
field lens	68.64	71.73	71.73	5.55	100	1.530

13.0.0.20 *Jones, W and S, A212741.5*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	33.80					
eyelens	24.85	flat	12.97	3.27	36.69	1.522
fieldlens	57.99	flat	29.70	4.99	96.00	1.512

13.0.0.21 *Kellner, A56418*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	53.85					
eyelens	20.71	flat	10.97	2.00	45.65	1.530
fieldlens	44.18	flat	22.94	3.18	-	1.519

13.0.0.22 *Martin, 1882-1*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	38.66					
eyelens 1	27.34	29.05	29.05	3.36	-	1.542
eyelens 2	62.13	-	-	-	-	-
fieldlens	94.68	flat	51.36	3.68	-	1.532

13.0.0.23 *Martin (?), A76350*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	112.67					
eyelens 1	52.07	flat	28.61	3.48	7.22	1.549
eyelens 2	68.64	flat	38.20	2.95	34.52	1.557
fieldlens	80.48	flat	43.21	3.76	44–70	1.536
between lens	80.48	49.58	436.1	2.45	45	1.554

13.0.0.24 *Martin (?), A645049*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	93.89					
eyelens 1	50.37	flat	27.25	3.30	7.52	1.541
eyelens 2	71.80	flat	38.04	3.80	33.5–53.5	1.529
fieldlens	80.48	flat	43.18	3.76	45.60	1.537
between lens	93.89	flat	50.02	2.00	36.00	1.533

13.0.0.25 *Oberhaeuser, 1912-212.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep. no. '4'	25.49					
eyelens	13.50	flat	6.90	2.65	26.49	1.511
fieldlens	33.46	flat	16.63	4.04	1.497	

13.0.0.26 *Oberhaeuser and Trécourt, 1917-102.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep. no. '3'	33.14					
eyelens	27.22	flat	14.30	2.08	32.46	1.525
fieldlens	38.66	flat	20.15	3.27	120	1.521

13.0.0.27 *Oberhaeuser and Trécourt, 1918-58.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	33.14					
eyelens	23.67	flat	12.69	1.73	31.60	1.536
fieldlens	32.03	flat	17.32	2.50	1.541	

13.0.0.28 *Plössl, 1925-149.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep no. '1'	25.39					
eyelens	17.31	flat	8.82	1.51	28.02	1.509
fieldlens	41.54	flat	21.93	3.76	-	1.528

13.0.0.29 *Plössl, 1925-149.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep no. '2'	11.33					
eyelens 1	16.62	flat	8.86	1.88	2.43	1.533
eyelens 2	30.00	flat	15.14	2.09	17.56	1.505
fieldlens	-	-	-	-	-	-

13.0.0.30 *Plössl, 1928-801.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	48.20					
eyelens	92.79	541.80	46.11	8.98	4.77	1.460
fieldlens	96.10	46.11	541.8	9.30	-	1.444

13.0.0.31 *Powell, 1918-17.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'a'	54.44					
eyelens	41.42	flat	21.18	3.82	57.95	1.511
fieldlens	76.22	flat	38.53	3.98	-	1.505

13.0.0.32 *Powell, 1918-17.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'b'	37.28					
eyelens	30.13	flat	15.35	4.11	35.12	1.510
fieldlens	48.05	flat	24.39	6.15	-	1.508

13.0.0.33 *Powell, 1918-17.5*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'c'	27.11					
eyelens	23.20	flat	11.88	2.93	29.78	1.512
fieldlens	42.06	flat	21.30	7.01	-	1.506

13.0.0.34 *Powell & Lealand, A71911.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	27.69					
eyelens	21.92	flat	10.98	2.47	27.18	1.501
fieldlens	40.24	flat	20.47	4.29	-	1.509

13.0.0.35 *Powell & Lealand, A140784.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'a'	34.57					
eyelens	40.24	flat	20.65	3.18	30.87	1.513
fieldlens	41.42	flat	21.14	3.45	-	1.510

13.0.0.36 *Powell & Lealand, A140784.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'b'	36.15					
eyelens	19.05	flat	9.70	2.64	54.06	1.509
fieldlens	76.22	flat	38.72	3.30	-	1.508

13.0.0.37 *Powell & Lealand, A600239.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	34.01					
eyelens	25.08	flat	12.57	2.96	10.84	1.501
fieldlens	52.12	flat	26.21	4.06	-	1.503

13.0.0.38 *Powell & Lealand, 1913-291.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'a'	50.98					
eyelens	39.16	flat	20.57	2.45	53.94	1.525
fieldlens	71.25	flat	36.17	3.26	-	1.508

13.0.0.39 *Powell & Lealand, 1913-291.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'b'	24.85					
eyelens	17.40	flat	8.86	3.11	28.18	1.509
fieldlens	40.50	flat	20.58	3.65	-	1.508

13.0.0.40 *Powell & Lealand, 1921-181.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	43.08					
eyelens	38.66	flat	19.98	2.08	39.68	1.517
fieldlens	47.34	flat	24.00	5.79	-	1.507

13.0.0.41 *Powell & Lealand, 1966-417.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'a'	24.10					
eyelens	17.95	flat	9.18	2.72	31.63	1.511
fieldlens	41.42	flat	21.18	3.45	-	1.511

13.0.0.42 *Powell & Lealand, 1966-417.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'b'	51.78					
eyelens	40.04	flat	20.37	2.41	54.25	1.509
fieldlens	71.01	flat	35.98	3.25	-	1.507

13.0.0.43 *Powell & Lealand, 1966-417.5*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'c'	48.52					
eyelens	40.24	flat	20.52	2.56	52.95	1.510
fieldlens	82.54	flat	40.96	2.99	-	1.496

13.0.0.44 *Pritchard, A41397.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	61.31					
eyelens 1	51.36	flat	25.05	3.10	4.91	1.488
eyelens 2	74.56	75.62	75.62	3.71	47.30	1.511
fieldlens 1	103.05	flat	52.16	4.64	1.68	1.504
fieldlens 2	102.80	flat	52.20	4.19	c.90	1.506

13.0.0.45 *Pritchard, A41397.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep. 'long'	44.18					
eyelens	34.24	127.04	20.50	3.81	c.44	1.520
fieldlens	48.05	50.68	50.68	3.78	-	1.534

13.0.0.46 *Pritchard, A41397.5*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep. 'short'	24.85					
eyelens	19.51	flat	9.90	1.48	12.72	1.507
fieldlens	36.45	349	20.30	2.94	-	1.528

13.0.0.47 *Pritchard, 1876-617.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	50.17					
eyelens	41.42	flat	21.09	3.22	-	1.509
fieldlens	62.59	flat	31.86	5.10	-	1.508

13.0.0.48 *Rienks, 1928-849.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
eyelens	36.16	105.50	23.16	2.41	-	1.529

13.0.0.49 *Ross, 1913-293.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	44.74					
eyelens	34.80	131.41	20.60	3.09	45.18	1.515
fieldlens	60.06	364.6	33.09	4.71	-	1.507

13.0.0.50 *Ross, 1919-469.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	40.50					
eyelens	30.59	flat	16.10	2.71	41.93	1.526
fieldlens	57.99	flat	29.56	4.99	-	1.510

13.0.0.51 *Ross, 1921-213.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	31.63					
eyelens	24.10	-	-	2.11	31.72	-
fieldlens	43.08	flat	21.84	4.36	-	1.507

13.0.0.52 *Ross, 1921-216.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	57.99					
eyelens	41.54	flat	22.19	3.07	61.47	1.534
fieldlens	74.56	flat	39.51	3.86	-	1.530

13.0.0.53 *Smith, J., A54204.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	43.08					
eyelens	32.50	160.8	18.68	3.73	46.88	1.519
fieldlens	66.28	213.5	40.31	4.60	-	1.515

13.0.0.54 *Smith, J., A604181.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep ‘a’	49.71					
eyelens	38.11	162	22.02	2.58	51.08	1.511
fieldlens	97.76	652	34.82	4.45	-	1.339

13.0.0.55 *Smith, J., A604181.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep ‘b’	25.49					
eyelens	17.67	flat	9.38	2.50	26.30	1.531
fieldlens	38.11	flat	19.36	5.03	-	1.507

13.0.0.56 *Smith, J., A604181.5*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep ‘c’	15.39					
eyelens	11.54	flat	6.00	2.13	15.60	1.520
fieldlens	25.72	970	13.37	3.30	-	1.513

13.0.0.57 *Tulley, 1938-686.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	55.23					
eyelens	42.34	flat	23.92	2.79	54.17	1.565
fieldlens	62.13	flat	34.39	4.54	-	1.554

13.0.0.58 *unsigned, A18817.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	63.52					
eyelens 1	51.55	72.38	42.89	3.59	3.89	1.528
eyelens 2	69.04	72.48	72.48	4.94	1.35	1.531
eyelens 3	68.35	72.48	72.48	4.64	30.69	1.536
fieldlens	69.04	72.48	72.48	5.40	51.4–81.4	1.532
between lens	143.60	172	145.5	2.17	41.00	1.550

13.0.0.59 *unsigned, A56519.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	67.93					
eyelens	37.28	39.15	39.29	5.55	72.70	1.539
fieldlens	62.13	50.61	88.22	7.29	34	1.527

13.0.0.60 *unsigned, A600182.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
total	27.62					
eyelens 1	38.99	40.29	40.29	2.80	1.85	1.523
eyelens 2	38.11	40.15	40.15	5.05	31.10	1.539
fieldlens	55.23	58.57	58.57	4.55	81.50	1.538

13.0.0.61 *Varley, A169733.3*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'a'	26.93					
eyelens	22.37	flat	11.50	2.39	26.48	1.514
fieldlens	44.97	flat	23.32	4.56	-	1.518

13.0.0.62 *Varley, A169733.4*

lens	f	rad 1	rad 2	dist 1	dist 2	N
Ep 'b'	14.07					
eyelens	10.12	flat	5.34	2.21	15.70	1.527
fieldlens	28.17	flat	14.48	3.40	-	1.514

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APPENDIX 7: OBJECTIVES, SCIENCE MUSEUM

Legends:

- inventory numbers: see appendix 6.
- type: the way the objective is marked, if not marked a dash or a range a, b, c.
- optical construction, the following codes are used:
  bicx: biconvex lens plcx: plano-convex lens
  cc: correction collar t: triplet
  d: doublet f: single front lens
  WI: water-immersion HI homogenous immersion
- thread: f, female; m, male; diameter in mm; number of threads per inch (tpi).
- f: focal length in mm.
- b tube: length of the body measured from the shoulder of the objective to the upper rim of the body.
- mgn. obj.: the magnification of the objective without the eyepiece.
- NA: the numerical aperture.
- d(μm): the least resolvable distance, calculated from the NA.
- MRP: the measured resolving power (μm), measured with the line test-plate.
- Diatoms: type and whether lines or dots are resolved.
  When two types are mentioned the first is resolved into lines and the second into dots.

invent. no.	maker	type	opt.	thread
1921-192.010	Amici	1.2.3	d,d,d	f;14.3;48tpi
1921-192.020	Amici	4.5.6	d,d,d	f;14.3;48tpi
1921-192.01	Amici	./../.../....	f,d,d,d	f;14.3;48tpi
1921-754.01	Amici	.../../.	d,d,f	f;14.3;48tpi
1928-847.01	Amici	././.	d,d,f	-
1928-847.02	Amici	../../..	d,d,f	-
1928-847.03	Amici	.../.../...	d,d,f	-
1928-847.04	Amici	A/B/C	d,-,d	-
1938-688.01	Amici	10	WI	f;14.3;48tpi
1938-688.02	Amici	3	d, d, d	f;14.3;48tpi
1938-688.03	Amici	6?	d	f;14.3;48tpi
1954-287.01	Amici	./../.../....	cxcf,d,d,f	f;14.3;48tpi
1921-252.01	Belthle & Rexroth	1	d	m;17.5;40tpi
1921-252.02	Belthle & Rexroth	1/3"	d,d,d	m;17.5;40tpi
1921-252.03	Belthle & Rexroth	1/6"	d,d,d	m;17.5;40tpi
1921-184.01	Chevalier		d,d,d	-
A 203049.01	Chevalier, A.	1	d	bajonet
A 203049.02	Chevalier, A.	3	d,d,d	bajonet
A 203049.03	Chevalier, A.	4	d,d,d	bajonet
A 203049.04	Chevalier, A.	5	d,d,f	bajonet
A 203049.05	Chevalier, A.	6	d,d,f	bajonet
1906-63.02	Chevalier, Ch.	a	d,d	bajonet

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invent. no.	maker	type	opt.	thread
1906-63.03	Chevalier, Ch.	b	d	bajonet
1921-188.01	Chevalier, Ch.	1+2+3	d, d, d	m;14.8;48tpi
1921-188.02	Chevalier, Ch.	2+3+?	d, d, d	m;14.8;48tpi
1921-249.01	Chevalier, Ch.	1	d,d	m;14.6;48tpi
1921-249.02	Chevalier, Ch.	I/II/III	d,d,d	m;14.6;48tpi
A 54219.01	Chevalier, V.	2	d	-
1921-185.01	Chevalier, V.	1+3+4	d, d, d	m;18.9;48tpi
A 600179.03	Dollond	a+b	bicx,bicx	m;13.6;36tpi
A 600242.01	Dollond	b	d	-
A 600242.02	Dollond	a+b	f, d [?]	-
1921-209.01	Dollond	40	d	-
1928-860.01	Dollond		d	soc. screw
1928-850.01	Fraunhofer & U.	a	d	f;14;40(?)tpi
1928-850.02	Fraunhofer & U.	b	d	f;14;40(?)tpi
1928-850.04	Fraunhofer & U.	b+c	d,d	f;14;40(?)tpi
1936-648.01	Hartnack & Pr.	4	d,d,d	f;12.5;40tpi
1936-648.02	Hartnack & Pr.	7	d,d,f	f;12.5;40tpi
1936-648.03	Hartnack & Pr.	8	d,d,f	f;12.5;40tpi
A 212741.08	Jones, W & S	b	plcx,plcx,plcx	m;14.8;40tpi
A 56418.01	Kellner	-	d,d,d	m;17.6;48tpi
1921-750.01	Nobert	4 (long)	d?,d?,d?, cc	f;13;44tpi
1921-750.02	Nobert	4 (short)	d?,d?,d?, cc	f;13;44tpi
1921-750.03	Nobert	5	d?,d?,d?, cc	f;13;44tpi
1921-750.04	Nobert	1+2+3	d,d,d	f;13;44tpi
1921-750.05	Nobert	1	d	f;13;44tpi
1921-750.06	Nobert	1+2	d, d	f;13;44tpi
1921-750.07	Nobert	2+3	d, d	f;13;44tpi
1921-750.08	Nobert	a	d, d	f;13;44tpi
1912-212.01	Oberhaeuser, G.	3	d,d	m;23.3;40tpi
1912-212.02	Oberhaeuser, G.	8	d,d,d	m;23.3;40tpi
A 71911.06	Pillisher, M.	2″		m;17.4;36tpi
1925-149.01	Plössl	1	d	f;15;48tpi
1925-149.02	Plössl	1+2	d,d	f;15;48tpi
1925-149.03	Plössl	1+3+4	d,d,d	f;15;48tpi
1925-149.04	Plössl	4+5+6	d,d,d	f;15;48tpi
1928-801.01	Plössl	1	d	f;10.4;48tpi
1928-801.02	Plössl	1+2	d, d	f;10.4;48tpi
1928-801.03	Plössl	1+3+4	d,d,d	f;10.4;48tpi
1928-801.04	Plössl	4+5+6	d,d,d	f;10.4;48tpi
1928-801.05	Plössl	5+6+7	d,d,d	f;10.4;48tpi
1928-801.06	Plössl	3+6+7	d,d,d	f;10.4;48tpi
1918-17.01	Powell	1/16″	d,d,d, cc	m;17.4;36tpi
1918-17.02	Powell	1/8″	cc	m;17.4;36tpi
1918-17.03	Powell	1/4″	cc	m;17.4;36tpi
1918-17.04	Powell	1/4″	cc	m;17.4;36tpi
1918-17.05	Powell	1/2″		m;17.4;36tpi
1918-17.06	Powell	1″		soc. screw+adapter

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invent. no.	maker	type	opt.	thread
1918-17.07	Powell	2"		soc. screw+adapter
1907-83.05	Powell & Lealand	1/8"	?,?,d	soc. screw
A 71911.01	Powell & Lealand	1/4"	d,d,t, cc	m;17.4;36tpi
A 71911.02	Powell & Lealand	1/8", dry	t,d,plcx, cc	m;17.4;36tpi
A 71911.03	Powell & Lealand	1/8",Immersion	t,d,plcx, cc	m;17.4;36tpi
A 71911.04	Powell & Lealand	1/12" Apo HI	d,d,plcx,plcx	m;17.4;36tpi
A 71911.05	Powell & Lealand	1"		m;17.4;36tpi
A 140784.01	Powell & Lealand	1 inch	3 elements	m;17.3/36tpi
A 140784.02	Powell & Lealand	1/4"	3 elements, cc	m;17.3/36tpi
A 140784.03	Powell & Lealand		3 elements	m;17.3/36tpi
A 600239.01	Powell & Lealand	a		m;17.2;36tpi
A 600239.02	Powell & Lealand	b		m;17.2;36tpi
A 601303.03	Powell & Lealand	1/4"	f?,t?,t?	soc. screw
1907-83.01	Powell & Lealand	2"	d,d	soc. screw
1907-83.02	Powell & Lealand	1"	d,d,d	soc. screw
1907-83.03	Powell & Lealand	1/2"	t,t,d(?)	soc. screw
1907-83.04	Powell & Lealand	1/4"	t,d,t	soc. screw
1907-83.05	Powell & Lealand	1/8?	?,?,d	soc. screw
1907-83.06	Powell & Lealand	1/12"	?,?,d	soc. screw
1921-181.01	Powell & Lealand	weak, 2 elts	x,x	m;12;36tpi
1921-181.02	Powell & Lealand	weak, 3 elts	x,x,x	m;12;36tpi
1921-181.03	Powell & Lealand	strong, total		m;12;36tpi
1921-181.04	Powell & Lealand	strong, back		m;12;36tpi
1921-181.05	Powell & Lealand	very weak		m;12;36tpi
1967-41.01	Powell & Lealand	1/4" Apo	three pts	soc. screw
1967-41.02	Powell & Lealand	1/4"		soc. screw
1967-41.03	Powell & Lealand	1/8" dry		soc. screw
1967-41.04	Powell & Lealand	1/8" imm.		soc. screw
1967-41.06	Powell & Lealand	1/16"imm.		soc. screw
A 41397.01	Pritchard	a	plcx, plcx	m;13.4;36tpi
A 41397.02	Pritchard	b	plcx, plcx	m;13.4;36tpi
A 41397.03	Pritchard	c	plcx, plcx	m;13.4;36tpi
A 41397.04	Pritchard	No.16	d,d,d	m;13.4;36tpi
A 41397.05	Pritchard	12/144	bicx, bicx	m;13.4;36tpi
A 41397.06	Pritchard	20/400	plcx, plcx	m;13.4;36tpi
A 41397.07	Pritchard	35/1225	plcx, bicx	m;13.4;36tpi
A 41397.08	Pritchard	60/3600	plcx, bicx	m;13.4;36tpi
1876-617.01	Pritchard, A.	-	t	m;14.5;40tpi
A 4888.01	Ross	a	d,d,d ?	soc. screw
A 4888.02	Ross	b	d,d,d ?	soc. screw
A 601094.01	Ross	-	d?,d?	soc. screw
A 601295.02	Ross	3"	t,t	soc. screw
A 601295.03	Ross	1/2"	t,d,d, cc	soc. screw
A 601295.04	Ross	1/5"	t,d,f, cc	soc. screw
1891-17.01	Ross	1/12 In.	d,d,d, cc	m;16.55;48/tpi
1891-17.02	Ross	1/8 In.	d,d,d, cc	m;16.55;48/tpi
1891-17.03	Ross	1/4 In.	d,d,d, cc	m;16.55;48/tpi

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invent. no.	maker	type	opt.	thread
1891-17.04	Ross	1/2 In.	d,d,d, cc	m;16.55;48/tpi
1891-17.05	Ross	1 In.	d,d,d	m;16.55;48/tpi
1891-17.06	Ross	2 In.	d,d	m;16.55;48/tpi
1900-172.01	Ross	1/7"	d,d,f(?),cc	soc. screw
1900-172.02	Ross	1/7",WI	d,d,f?,cc	soc. screw
1900-172.03	Ross	1/2"	plcx,t,f?,cc	soc. screw
1900-172.04	Ross	1"	d,d	soc. screw
1900-172.05	Ross	2"	d,d	soc. screw
1967-41.11	Ross	2/3"	d,d	soc. screw
1967-41.12	Ross	1 1/2"	d,d	soc. screw
1972-49.01	Ross	1/10" no.21544	t,d,f, cc	soc. screw
1919-469.02	Ross, A.	1"	?	f;12.9;48/tpi
1919-469.01	Ross, A.	1/4"	d,d,d	f;12.9;48/tpi
1921-216.01	Ross, A.	1/4"	d,d,d	f;12.9;48/tpi
1921-213.01	Ross, A.	-		-
A 601295.05	Sands & Hunter	1/4"	?	soc. screw
1921-250.01	Schiek	4	d,d,d	f;13.2;48tpi
1921-250.02	Schiek	5	d,d,d	f;13.2;48tpi
1921-250.03	Schiek	1	d	f;13.2;48tpi
1921-250.09	Schiek	1+2	d, d	f;13.2;48tpi
1921-250.10	Schiek	4+5+6	d, d, d	f;13.2;48tpi
A 50476.01	Smith & Beck	4/10"	d?, d,d, cc	m;17.7;48tpi
A 50476.02	Smith & Beck	1/5"	d?, d,d, cc	m;17.7;48tpi
A 50476.03	Smith & Beck	2/3"	d,d	m;17.7;48tpi
A 54205.01	Smith & Beck	a	d, d	o,20.3;36tpi
A 54205.02	Smith & Beck	1 1/2"	d,d	o,20.3;36tpi
A 54205.03	Smith & Beck	2/3"	d,d, cc	o,20.3;36tpi
A 54205.04	Smith & Beck	4/10"	d?, d?, d, cc	o,20.3;36tpi
A 54205.05	Smith & Beck	1/8"	?, cc	o,20.3;36tpi
A 56382.01	Smith & Beck	a	d	m;17.6;48tpi
A 56382.02	Smith & Beck	b	d,d	m;17.6;48tpi
A 56382.03	Smith & Beck	c	d,d,d	m;17.6;48tpi
A 159563	Smith Beck & B	b	d,d	m;15.15;32tpi
A 601306	Smith Beck & B	a	d,d,d	m;15.15;32tpi
A 54204.01	Smith, J.	Lister, 1826	t	m;21.5;32tpi
A 54204.02	Smith, J.	Lister, 1826	t	m;21.5;32tpi
A 604181.01	Smith, J.	back	d	soc. screw
A 604181.02	Smith, J.	back	d	soc. screw
A 604181.03	Smith, J.	back+frt a	d,d	soc. screw
A 604181.04	Smith, J.	bk/mid/frt b	d,d,t, cc	soc. screw
1891-19.01	Smith, J.	4/10"	d?,d?,d?, cc	soc. screw
1891-19.03	Smith, J.	1 1/4"	d	soc. screw
1891-19.04	Smith, J.	2/3"	d,d	soc. screw
1938-686.01	Tulley		t	m;16.2;32tpi
1938-686.02	Tulley		t,d(?)	m;16.2;32tpi
A 56519.01	unsigned	1,3		m;15.2;48tpi
A 56519.02	unsigned	1,4,5		m;15.2;48tpi

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invent. no.	maker	type	opt.	thread
A 56519.03	unsigned	1,3,4,5		m;15.2;48tpi
A 56519.031	unsigned	1	d, pl/cx	m;14;48tpi
A 56519.04	unsigned	2,3		m;15.2;48tpi
A 56519.05	unsigned	2,4,5		m;15.2;48tpi
A 56519.06	unsigned	2,3,4,5		m;15.2;48tpi
A 56519.061	unsigned	2	d, pl/cx	m;14;48tpi
A 169733.01	Varley	1/2"	d,d,d	m;17.4;36tpi
A 601103.01	Zeiss	D, no.3110	d,d,f	soc. screw
A 601303.01	Zeiss	E, no.951	f,plcx,t, cc	soc. screw
1967-41.10	Zeiss, no.1640	8mm Apo	-	soc. screw
1967-41.09	Zeiss, no.2139	4mm Apo	cc	soc. screw
1967-41.08	Zeiss, no.296	2.5mm WI	cc	soc. screw
1967-41.07	Zeiss, no.399	3mm Apo HI		soc. screw

invent. no.	f(mm)	btube	magn.	NA	rp	MRP	diat	li/dt
1921-192.010	7.05	192.5	26.35	0.44	0.84	1.25	Stau	dt
1921-192.020	25.39	192.5	9.72	0.27	1.35	2	-	-
1921-192.01	3.43	175	52.22	0.67	0.55	<1	Stau.	dt
1921-754.01	6.78	175	24.70	0.45	0.82	1	Cym	dt
1928-847.01	2.01	154	76.57	0.90	0.41	<1	Stau.	dt
1928-847.02	3.41	154	44.91	0.77	0.48	1	Nav	li
1928-847.03	3.82	154	39.52	0.64	0.58	1.25	Nav	dt
1928-847.04	15.53	154	8.78	0.19	1.90	2	Nav	li
1938-688.01	1.73	192.5	114.60	1.04	0.35	<1	Pleua	li
1938-688.02	10.39	194.5	17.78	0.37	1.00	1.75	Nav	dt
1938-688.03	22.16	192.5	7.62	0.13	2.81	3.5	-	-
1954-287.01	4.32	192.5	46.58	0.57	0.64	<1	Pleub	li
1921-252.01	30.38	160	4.15	0.05	7.22	7	-	-
1921-252.02	8.18	160	20.10	0.54	0.68	1	Stau	dt
1921-252.03	3.78	160	44.91	0.57	0.64	1	Stau	dt
1921-184.01	4.76	-	-	0.30	1.22	2.75	Nav	li
A 203049.01	32.64	200	5.27	0.06	5.99	5.5	-	
A 203049.02	8.77	200	22.72	0.17	2.20	2.25	Ara	dt
A 203049.03	4.70	200	42.81	0.30	1.21	1.25	Nav	dt
A 203049.04	2.89	200	71.13	0.51	0.71	1	Stau	dt
A 203049.05	2.32	200	87.27	0.51	0.72	<1	Cym	dt
1906-63.02	7.97	175	21.74	0.19	1.97	2.25	-	-
1906-63.03	10.58	175	15.81	0.14	2.71	2.75	-	-
1921-188.01	4.20	200	47.99	0.36	1.02	1.25	Nav	dt
1921-188.02	4.28	200	46.10	0.35	1.05	1.5	Nav	dt
1921-249.01	5.77	144	30.74	0.26	1.43	1.5	Nav	li
1921-249.02	9.92	144	17.43	0.15	2.42	2.5	-	-
A 54219.01	11.08	185	15.15	0.22	1.71	2.75	-	-
1921-185.01	4.48	200	44.46	0.29	1.25	1.25	Nav	dt
A 600179.03	13.85	170	14.62	0.30	1.21	3.5	-	-
A 600242.01	4.58	188	40.84	0.34	1.10	1.5	Nav	pe
A 600242.02	3.23	188	58.04	0.48	0.76	<1	Pleub	li
1921-209.01	0.82	-	-	0.52	0.71	<1	-	-
1928-860.01	26.77	175	5.03	0.19	1.93	2.25	-	-
1928-850.01	37.70	-	3.36	0.06	5.87	5.75	-	-
1928-850.02	25.39	-	5.53	0.10	3.76	3.5	-	-
1928-850.04	12.12	160	11.53	0.23	1.63	2.25	-	-
1936-648.01	11.77	174	14.57	0.42	0.86	1.25	Nav	dt
1936-648.02	4.44	174	40.93	0.84	0.44	<1	Navrh	dt
1936-648.03	2.94	174	62.10	0.83	0.44	-	-	-
A 212741.08	4.48	185	39.52	0.45	0.82	2	-	-
A 56418.01	14.48	160	10.34	0.34	1.07	1.25	Nav	dt
1921-750.01	6.00	180	31.61	0.49	0.75	1.5	Stau	dt
1921-750.02	5.16	180	36.88	0.45	0.81	1	Cym	dt
1921-750.03	2.31	180	84.68	0.68	0.54	<1	Pleub	dt
1921-750.04	15.74	180	11.66	0.19	1.96	2	Nav	li
1921-750.05	45.00	180	2.96	0.05	7.72	7.75	-	-

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invent. no.	f(mm)	btube	magn.	NA	rp	MRP	diat	li/dt
1921-750.06	23.97	180	6.67	0.11	3.43	3.5	-	-
1921-750.07	13.16	180	13.44	0.17	2.15	2	Ara	dt
1921-750.08	3.96	180	47.42	0.70	0.53	1.75	-	-
1912-212.01	23.54	175	9.68	0.11	3.44	3	-	-
1912-212.02	4.13	175	43.22	0.37	0.99	1.25	Nav -	dt
A 71911.06	33.14	250	6.82	0.11	3.28	3	-	-
1925-149.01	47.34	144	1.91	0.06	6.54	7	-	-
1925-149.02	24.23	144	4.93	0.14	2.58	5	-	-
1925-149.03	12.36	144	10.86	0.28	1.30	2	Nav	li
1925-149.04	6.87	156	22.13	0.49	0.74	1	Cym	dt
1928-801.01	38.08	218	4.67	0.09	4.09	4	-	-
1928-801.02	20.46	218	9.63	0.18	1.99	2	Nav	li
1928-801.03	11.39	218	18.35	0.35	1.05	1.25	Nav	dt
1928-801.04	7.69	218	28.23	0.48	0.77	1.5	Nav	dt
1928-801.05	4.39	218	49.40	0.59	0.62	<1	Cym	dt
1928-801.06	4.20	218	51.37	0.60	0.61	<1	Stau	dt
1918-17.01	1.40	200	158.07	0.64	0.58	<1	Stau	dt
1918-17.02	2.92	200	72.45	0.60	0.61	<1	Stau	dt
1918-17.03	5.81	200	37.32	0.49	0.74	1	Cym	dt
1918-17.04	5.81	-	-	0.51	0.73	1	-	-
1918-17.05	13.35	200	14.33	0.25	1.46	1.75	Nav	li
1918-17.06	24.23	200	7.60	0.16	2.25	2.75	-	-
1918-17.07	43.08	200	4.10	0.14	2.67	3	-	-
1907-83.05	2.86	250	94.84	0.88	0.42	<1	Pleua	dt
A 71911.01	5.40	200	38.11	0.49	0.74	<1	Cym	dt
A 71911.02	2.84	250	106.21	0.99	0.37	<1	Navrh	dt
A 71911.03	2.65	250	102.75	1.01	0.37	<1	Pleua	li
A 71911.04	2.16	250	122.51	1.35	0.27	<1	Pleua	dt
A 71911.05	24.23	250	9.88	0.22	1.69	2	-	-
A 140784.01	25.72	200	6.78	0.20	1.84	2	Ara	li
A 140784.02	5.46	200	38.53	0.50	0.73	<1	Cym	dt
A 140784.03	5.72	200	35.93	0.48	0.77	<1	Cym	dt
A 600239.01	8.19	200	25.25	0.27	1.36	1.25	Nav	dt
A 600239.02	11.08	200	17.96	0.19	1.92	2	Ara	dt
A 601303.03	5.87	200	37.54	0.74	0.50	<0.8	Pleua	dt
1907-83.01	41.42	250	5.53	0.14	2.55	2.75	-	-
1907-83.02	21.67	250	11.07	0.27	1.35	1.75	Nav	dt
1907-83.03	9.00	250	28.74	0.58	0.64	<1	Stau	dt
1907-83.04	5.60	250	47.75	0.73	0.51	<1	Nei	dt
1907-83.05	2.86	250	94.84	0.88	0.42	<1	Pleua	dt
1907-83.06	1.99	250	138.31	0.98	0.37	<1	Pleua	li
1913-291.01	6.40	193	27.66	0.39	0.95	1	Cym	dt
1921-181.01	19.58	178	7.90	0.11	3.21	3	-	-
1921-181.02	11.87	178	14.82	0.22	1.70	2	Nav	li
1921-181.03	2.73	193	69.16	0.59	0.62	1	Cym	dt
1921-181.04	4.84	193	39.52	0.34	1.08	1.5	Nav	li
1921-181.05	29.67	193	4.55	0.08	4.89	5.25	-	

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invent. no.	f(mm)	btube	magn.	NA	rp	MRP	diat	li/dt
1967-41.01	6.99	250	39.52	0.92	0.40	<1	-	-
1967-41.02	5.81	250	46.43	0.73	0.50	-	-	-
1967-41.03	2.57	250	110.09	0.97	0.38	-	-	-
1967-41.04	2.82	250	110.09	1.08	0.34	-	-	-
1967-41.06	1.45	250	230.52	1.10	0.33	-	-	-
A 41397.01	7.69	160	18.77	0.12	3.19	3	Ara	li
A 41397.02	20.77	160	6.52	0.06	6.05	5.5	-	
A 41397.03	31.16	160	4.15	0.05	7.77	7	-	-
A 41397.04	4.11	160	39.52	0.46	0.79	1	Nav	dt
A 41397.05	26.40	165	5.14	0.12	2.98	4.25	Ara	li
A 41397.06	13.05	165	15.41	0.14	2.56	3.5	Ara	li/dt
A 41397.07	7.96	165	19.27	0.15	2.51	2.5	Ara	li/dt
A 41397.08	4.48	165	35.28	0.21	1.77	2	Nav	li
1876-617.01	52.72	205	2.96	0.06	6.48	8	-	-
A 4888.01	6.49	200	22.72	0.27	1.35	2	Nav	-
A 4888.02	4.20	200	51.37	0.58	0.63	1.25	Nav	-
A 601094.01	15.98	200	12.65	0.27	1.36	1.5	Nav	dt
A 601295.02	52.47	250	4.02	0.12	3.11	3	-	-
A 601295.03	10.39	250	25.51	0.69	0.53	<1	Stau	dt
A 601295.04	4.94	250	57.08	0.98	0.38	<1	Nei	dt
1891-17.01	2.21	250	121.85	0.69	0.54	<1	-	
1891-17.02	2.45	250	105.38	0.65	0.57	<1	Pleub	dt
1891-17.03	4.87	250	54.34	0.52	0.71	<1	Nei	dt
1891-17.04	8.65	250	29.64	0.37	0.98	1.25	Cym	dt
1891-17.05	19.33	250	12.42	0.20	1.89	2	-	-
1891-17.06	40.04	250	5.47	0.09	4.31	4	-	-
1900-172.01	4.27	250	71.13	0.94	0.39	<1	Nei	dt
1900-172.02	3.97	250	69.16	0.91	0.40	<1	Nei	dt
1900-172.03	10.68	250	25.29	0.59	0.62	<1	Pleub	dt
1900-172.04	22.09	250	10.87	0.24	1.56	1.75	Nav	dt
1900-172.05	40.50	250	5.31	0.16	2.35	2.25	Ara	dt
1967-41.11	18.46	250	13.34	0.26	1.42	1.5	Ara	dt
1967-41.12	33.23	250	6.61	0.19	1.89	2.25	Ara	li
1972-49.01	3.26	175	64.92	1.11	0.33	<1	Pleub	li
1919-469.02	25.96	190	6.72	0.16	2.32	2.25	-	-
1919-469.01	5.60	190	33.59	0.37	0.99	1.25	Nav	li
1921-216.01	6.39	220	35.93	0.35	1.06	1.25	-	-
1921-213.01	3.08	220	77.52	0.48	0.76	1	Nav	dt
A 601295.05	4.98	250	53.35	0.69	0.53	<1	Nei	dt
1921-250.01	6.23	200	31.61	0.53	0.69	<1	Stau	dt
1921-250.02	7.55	200	42.34	0.56	0.66	<1	Stau	dt
1921-250.03	43.27	200	3.56	0.06	5.81	5.5	-	-
1921-250.09	20.19	200	8.78	0.16	2.35	2.75	Ara	dt
1921-250.10	5.60	200	35.36	0.36	1.01	1	Nav	dt
A 50476.01	7.92	250	31.61	0.53	0.70	<1	Pleub	li
A 50476.02	4.50	250	57.30	0.83	0.44	<1	Navrh	dt
A 50476.03	10.39	250	14.11	0.25	1.50	1.5	Nav	dt

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invent. no.	f(mm)	btube	magn.	NA	rp	MRP	diat	li/dt
A 54205.01	29.00	250	8.24	0.21	1.78	2	Ara	dt
A 54205.02	31.48	250	7.44	0.20	1.85	2	Ara	dt
A 54205.03	16.57	250	14.56	0.24	1.50	1.75	Nav	li
A 54205.04	7.69	250	32.93	0.52	0.70	<1	Pleub	li
A 54205.05	2.72	250	98.80	0.88	0.42	<1	Pleub	dt
A 56382.01	37.87	200	4.35	0.08	4.42	4.5	-	-
A 56382.02	16.62	200	14.16	0.24	1.56	2	Nav	li
A 56382.03	5.46	200	40.18	0.58	0.63	<1	Stau.	dt
A 159563	-	164	8.54	0.23	1.59	1.75	Ara	dt
A 601306	6.29	164	25.03	0.33	1.11	1.25	Nav	dt
A 54204.01	22.78	200	7.71	0.17	2.16	4.75	-	-
A 54204.02	22.78	200	7.82	0.23	1.57	4.75	-	-
A 604181.01	41.54	200	3.95	0.07	5.66	5.25	-	-
A 604181.02	41.54	200	3.95	0.10	3.87	4	-	-
A 604181.03	19.58	200	9.39	0.20	1.80	1.75	Ara	dt
A 604181.04	12.59	200	15.81	0.39	0.95	1	Nav	dt
1891-19.01	9.23	175	19.10	0.44	0.84	1.25	Nav	dt
1891-19.03	32.64	250	6.92	0.11	3.28	3.25	-	-
1891-19.04	16.62	250	14.82	0.24	1.53	1.75	Ara	dt
1938-686.01	23.66	250	9.68	0.15	2.42	2.75	-	-
1938-686.02	10.07	250	24.15	0.19	1.97	2.75	-	-
A 56519.01	17.38	160	8.40	0.17	2.16	2.25	Ara	dt
A 56519.02	6.46	160	24.70	0.45	0.82	1.75	Cym	dt
A 56519.03	6.53	160	24.70	0.50	0.74	1.25	Stau	dt
A 56519.031	43.27	160	2.01	0.05	8.07	6.25	-	-
A 56519.04	15.94	160	9.22	0.21	1.77	1.75	Nav	pe
A 56519.05	6.71	160	23.71	0.47	0.78	1.75	Nav	pe
A 56519.06	7.13	160	22.92	0.52	0.70	< 1	Pleub	li
A 56519.061	31.85	160	4.05	0.09	3.94	6	-	-
A 169733.01	11.18	175	15.81	0.38	0.96	1.25	Cym	dt
A 601103.01	4.20	160	42.34	0.65	0.57	<1	Nei	dt
A 601303.01	2.82	161	67.18	0.86	0.43	<0.8	Pleua	dt
1967-41.10	4.55	250	34.87	0.68	0.54	-	-	-
1967-41.09	4.50	250	60.59	0.99	0.37	-	-	-
1967-41.08	-	250	110.65	1.25	0.29	-	-	-
1967-41.07	2.94	250	90.33	1.44	0.26	-	-	-

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APPENDIX 8: OBJECTIVES BY ROSS AND POWELL AND LEALAND

15.1 LEGENDS

The objectives made by Ross and Powell & Lealand in the collections of the Science Museum, the Wellcome Collection in the Science Museum, the Museum of the History of Science and the collection of the Royal Microscopical Society were investigated in greater detail than most other objectives. Their data are assembled in this appendix. Column 1, inventory number, the letter codes refer to the different collections: RMS Collection of the Royal Microscopical Society, in the Museum of the History of Science, Oxford. Turner catalogue numbers. MHS Museum of the History of Science, Oxford S Science Museum, London SW Wellcome Collection, Science Museum, London Column 2, year, refers to the year of manufacture. If ?mic.? is added this means the year of manufacture of the microscope. Powell & Lealand microscopes usually have such a year of production. Column 3, thread refers to the thread of the objective, ? s-scr, the thread standardized by the Royal Microscopical Society since 1857/1858.1 There are 36 threads in an inch and the outer diameter of the male thread is 0.7982in. ? other, i stands for internal (female) thread, o stands for outer (male) thread; the following number indicates the diameter in mm, the last number indicates the number of threads per inch (). Column 4, dwg, refers to the drawing at the end of the appendix. The front lens is always to the left in these drawings. The component upon which the correction collar acts is indicated by a double arrow. The fixed components are linked by a line. Column 5, f, the focal length. Column 6, M, the magnification of the objective only. Column 7, NA, the numerical aperture. Column 8, MRP, the resolving power in microns, measured with the line test-plate.

15.2 OBJECTIVES BY ROSS

15.2.1 *3 inch objectives*

RMS15.5	3in Ross LONDON
RMS8.1	3in Ross LONDON; 27 [on can]
SW-A601295.2	no note made

inv.nu.	date	thread	dwg	f	M	NA	mRP
RMS15.5	1859–1873	s-scr	42b	50.54	4.22	0.102	3.25
RMS8.1	1863	s-scr	42b	51.36	4.22	0.107	3.25
A601295.2	-	s-scr	42h	52.47	4.02	0.118	3

15.2.2 *2 inch objectives*

MHSBL253.1	2 In Andw. Ross & Co. Opticians 33 Regent St. Piccadilly [on can]
SM1891-17.6	no note made
RMS104.1	A. Ross, London; 2 In And.w Ross, Optician, London [on can]
RMS123.1	2 In A. Ross, London [on can]
RMS8.2	2 In Ross London; 28 [on can]
SM1900-172.5	no note made

inv.nu.	date	thread	dwg	f	M	NA	mRP
MHSBL253.1	1838	f12.7;40	-	49.71	4.1	0.062	5.25
SM1891-17.6	-	m16.5;48	42a	40.04	5.47	0.085	4
RMS104.1	-	s-scr	42a	36.96	5.9	0.098	3.25
RMS123.1	ca.1854	f12.6;40	42g	32.65	6.9	0.107	3.25
RMS8.2	ca. 1863	s-scr	42b	40.04	5.3	0.141	2.5
SM1900-172.5	ca.1862	s-scr	1-2	40.50	5.3	0.156	2.25

15.2.3 *1.5 inch objectives*

RMS8.3 1 1/2In Ross London; 29 [on can]
SM1967-41.12 no note made

inv.nu.	date	thread	dwg	f	M	NA	mRP
RMS8.3	1863	s-scr	42g	31.86	6.8	0.173	2
SM1967-41.12	-	s-scr	-	33.23	6.6	0.194	2.25

15.2.4 *1 inch objectives*

MHSBL253.2 1 In Andw. Ross & Co. Opticians 33 Regent St. Piccadilly [on can]
MHS32-42.1 1.In. A. Ross, London [on can]
SM1919-469.2 no note made
MHS32-A2 Andw. Ross Optician, London [on can]
SM1891-17.5 no note made
RMS104.2 A. Ross, London; 1 In And.w Ross, Optician, London [on can]
SM1900-172.4 no note made
RMS8.4 1 In Ross London; 30 [on can]

inv.nu.	date	thread	dwg	f	M	NA	mRP
MHSBL253.2	1838 (micr.)	f12.7;40	-	25.61	8.9	0.121	3
MHS32-42.1		f12.7;40	-	21.54	10.7	0.127	2.75
SM1919-469.2	-	f2.9;40	-	25.96	8.8	0.158	2.25
MHS32-A2	-	f12.7;40	43b	19.33	12.3	0.189	2
SM1891-17.5	-	m16.5;48	42c	19.33	12.42	0.195	2-
RMS104.2	1864	s-scr	43b	19.12	12.4	0.201	1.75
SM1900-172.4	-	s-scr	-	22.09	10.9	0.235	1.75
RMS8.4	1863	s-scr	43a	20.12	11.6	0.253	1.5

15.2.5 *1/2 inch objectives*

MHS32-42.11 1/2 A. Ross Optician 15 St. John Sque. Clerkenwell LONDON [can]
MHSBL253.3 1/2 In Andw. Ross & Co. Opticians 33 Regent St. Piccadilly [can]
RMS104.3 A. Ross, London; 1/2 In And.w Ross, Optician, London [on can]
SM1891-17.4 no note made
RMS345 A. Ross, 1852 ; 1/2In A. Ross, London [on can]
MHS32-42.12 A. Ross. 1856; A. Ross, London [on can]
SM1900-172.3 no note made
MHS32-42.3 1/2 in Ross London; 1/2.In. Ross, London [on can]
SM-A601295.3 no note made

RMS8.6 1/2 In Ross London; 32 [on can]

inv.nu.	date	thread	dwg	f	M	NA	mRP
MHS32-42.11	<1837	f13;56	-	11.08	21.48	0.168	2.5
MHSBL253.3	1838, mic.	f12.7;40	-	10.77	23.25	0.284	1.25
RMS104.3	1864	s-scr	43c	10.15	23.99	0.341	1.25
SM1891-17.4	-	m16.5;56	43c	8.65	29.64	0.374	1.25
RMS345	1852	f12.6;40	42i	7.99	33.59	0.464	1
MHS32-42.12	1856	s-scr	43f	10.18	26.00	0.490	1
SM1900-172.3	-	s-scr	-	10.68	25.29	0.588	<1
MHS32-42.3	-	s-scr	43f	9.81	25.42	0.660	1
SM-A601295.3	-	s-scr	42e	10.39	25.51	0.687	<1
RMS8.6	1863	s-scr	43e	9.59	27.64	0.718	<1

15.2.6 *1/4 inch objectives*

SM1921-216.1 no note made
MHSBL253.4 1/4 In A. Ross & Co. Opticians 33 Regent St. Piccadilly [on can]
MHS32-42.16 Andw. Ross Optician London [on can].[1]
SM1919-469.1 no note made
RMS348 A. Ross, 1852 ; 1/4 [on can]
RMS104.4 A. Ross, London; 1/4 In And.w Ross, Optician, London [on can]
SM1891-17 no note made
MHS32-42.15 A. Ross 1854; 1/4. In A. Ross, London [on can]
MHS32-42.4 A. Ross 1851 W.P. King; 1/4 In. A. Ross, London [on can]
MHS32-B2 A. Ross 1856 T.D. King 100°; 1/4 In. A. Ross , London [on can]
RMS8.7 1/4 In Ross London; 33 [on can]
MHS32-42.14 1/4. In. [on can]; Ross, London [on objective and can].[2]

inv.nu.	date	thread	dwg	f	M	NA	mRP
SM1921-216.1	-	f12.9;56	42c?	6.39	35.93	0.347	1.25
MHSBL253.4	-	f12.7;40	-	5.42	47.42	0.354	1
MHS32-42.16	1837, ca.	f12.7;40	42c	6.46	41.16	0.370	1
SM1919-469.1	-	f12.9;56	42c?	5.59	33.59	0.370	1.25
RMS348	1852	s-scr	-	6.26	44.46	0.457	<1
RMS104.4	1864	s-scr	43d	5.88	45.16	0.508	1
SM1891-17	-	0;16.5;56	43c	4.87	54.34	0.519	<1
MHS32-42.15	1854	f12.7;40	-	4.76	59.28	0.624	<1
MHS32-42.4	1851	s-scr	43c	5.04	55.98	0.712	-
MHS32-B2	1856	f12.7;40	43d	5.19	52.69	0.806	1
RMS8.7	1863	s-scr	43e	5.45	49.40	0.882	1
MHS32-42.14	-	s-scr	-	5.33	51.37	0.949	<1

15.2.7 *1/8 inch objectives*

MHSBL253.5 A. Ross London; 1/8 In And.w. Ross & Co. Opticians 33 Regent St. Piccadilly [on can]

1 This objective has no correction collar, like the first ones Ross made for by Lister.
2 A note by E.M. Nelson states that this was one of Andrew Ross's last lenses.

RMS177 A. Ross, London; 1/8 In And.w. Ross & Co. Opticians 33 Regent St. Piccadilly [on can]
SM1891-17.2 no note made
RMS8.a (water immersion) 1/8 In Ross London, immersion; 34 [on can]
RMS8.b the same same objective as the previous one, but with a ?dry? front
RMS370.4 Ross, London Standard T.R.[3]

inv.nu.	date	thread	dwg	f	M	NA	mRP
MHSBL253.5	-	f12.7;40	-	2.96	93.15	0.490	<1
RMS177	ca.1840	f12.6;40	43d	2.69	98.80	0.604	0.75
SM1891-17.2	-	0;16.5;56	43c	2.45	105.38	0.645	<1
RMS8.a	1863	s-scr	43h	2.40	98.80	0.846	1
RMS8.b	1863	s-scr	43e	2.94	104.72	0.897	1
RMS370.4	-	s-scr	43e	2.70	103.73	0.914	<1

15.2.8 *1/5 - 1/12 inch objectives*

MHS32.42.17 Ross, London 20373 Patent; 1/5 In. Ross, London [on can].[4]
SMWA601295.4 no note made
MHS32.42.18 A. Roßs 1854; A. Ross, London [on can].[5]
RMS123.2 A. Ross 1854; 1/6 In A. Ross, London [on can]
SM1900-172.1 no note made
SM1900-172.2 no note made
MHS32.42.13 4/10 In. Ross London [on objective and can]
RMS15.6 4/10 In. Ross London
SM1972-49.1 no note made
SM1891-17.1 no note made
RMS8.091 1/12 In Ross London; 35 [on can
RMS104.5 A. Ross, London; 1/12 In And.w Ross Optician London [on can]
MHS32.42.2 A. Roßs, London; Andw. Roßs, Optician, London [on can].[6]
RMS8.092 1/12 Immersion. See also RMS8.091, the ?dry? objective.

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3 A note by Elliott Merlin, dated 14 August 1928 states that this was probably Thomas Ross's standard 1/8 comparison objective. Merlin found that it resolved Grayson's 100000 lines/inch band, he measured a NA of 0.87. With axial illumination I resolved the 1/1600mm band (0.625μm) of the Grayson Ruling in the RMS collection. Navicula rhomboides was resolved by me into dots.

4 A note by E.M. Nelson states: 'Focus 0.185 [4.7mm], Initial power 54. NA 0.87 0.1.16.1 Ross patent water immersion 1/5. Date 1872, designed by Wenham. Resolves when used wet the old amphipleura surdheineri [?] 76500 striae per inch. Not well corrected. Edward M. Nelson. C.collar halfway. When used 'wet' the magnification is 62.3, the N.A. is 0.808. The difference is not worthwile'.

5 A note by E.M. Nelson states: 'Focus (collar line 18) 0.155 [3.937mm] Initial power 64.5 N.A. .906 0.1.14.0 a quadruple combination dated 1854. A very rare example and a remarkable lens for its date. Correction very good for so large an aperture.'

6 A note by E.M. Nelson states: 'Triple front & back and double middle. circa 1848. N.A. .818. Focus (collar to line) 0.0773 [1.96mm]. Initial power 129.4 0.1.6.3 A good example of a 1/12 of this date. Well corrected. Has resolved 90000 band Grayson. v. R.M.S. journ.1904 p.395 P.T.O. This objective is of the same date and same type as that used by Warren de la Rue in his investigations on the scale of Amathusia Florspieldii (?) Trans. Mic. Soc. London, Vol.3, 1852, p.39.' (In 1990 the cement of the back and the front element was cracked)

inv.nu.	date	thread	dwg	f	M	NA	mRP
MHS32.42.17	1/5 in.	s-scr	-	4.90	55.33	0.792	<1
SMWA601295.4	1/5 in.	s-scr	29	4.94	57.08	0.978	<1
MHS32.42.18	1/6 in.	f12.7;40	-	3.93	71.85	0.932	<1
RMS123.2	1/6 in.	f12.6;40	-	3.86	72.45	0.940	<1
SM1900-172.1	1/7 in.	s-scr	-	4.27	71.13	0.940	<1
SM1900-172.2	1/7 in. WI	s-scr	-	3.98	69.16	0.914	<1
MHS32.42.13	4/10 in.	s-scr	-	8.22	33.59	0.666	1
RMS15.6	4/10 in.	s-scr	21	8.09	33.02	0.810	1
SM1972-49.1	1/10 in.	s-scr	-	3.26	64.92	1.112	<1
SM1891-17.1	1/12 in.	m16.5;48	-	2.21	121.85	0.686	<1
RMS8.091	1/12 in.	s-scr	21	1.68	-	-	-
RMS104.5	1/12 in.	s-scr	32	2.18	118.55	0.609	0.75
MHS32.42.2	1/12 in.	f12.7;40	-	2.01	138.31	0.856	<1
RMS8.092	1/12 in.	s-scr	21	1.60	177.83	0.979	<1

15.2.9 *Ross's signatures on cans*

The signatures of Ross's objectives I found (mostly on the cans) were:

- before Ross's cooperation with Lister in 1837: A. Roßs Optician 15 St. John Sque. Clerkenwell LONDON.
- 1837–1845/1850, Andw. Roßs & Co. Opticians 33 Regent St. Piccadilly. [the & Co. might stand for Lister who provided Ross with these designs]
- from 1845/1850 onwards, when the cooperation with Lister stopped: A. Ross, London, (on can): And.w Ross, Optician, London.
- After the death of Andrew Ross in 1859, made by Thomas Ross: Ross London.

15.3 OBJECTIVES BY POWELL & LEALAND

15.3.1 *2 inch objectives*

RMS0.01 *2 inch ACHROMATIC Object Glaßses*
RMS378.01 POWELL & LEALAND
MHSC63.01 *2 inch ACHROMATIC Object Glaßses*

inv.nu.	date	thread	dwg	f	M	NA	mRP
RMS234.01	1840 (mic)	m17.4;40	-	47.34	3.56	0.057	3.5
RMS0.01	-	m17.4;28	42j	46.03	4.87	0.103	4.5
RMS2.01	1841	s-scr	-	46.39	4.94	0.104	3.5
RMS370.01	1850	m17.4;36	42a	42.61	5.14	0.108	3.75
MHS32-42.06	-	s-scr	-	41.42	5.43	0.118	3
RMS282.01	1850 (mic)	m17.4;36	43a	62.59	4.94	0.122	4.75
RMS378.01	1850	m17.4;36	42b	42.18	5.39	0.123	3
RMS168.01	1840 (mic)	m17.4;36	43b	44.18	5.33	0.123	4
MHS32-42.07	-	-	-	40.24	5.60	0.129	2.75
SM1918-17.07	1840 (mic)	s-scr	-	43.08	4.10	0.137	3
SM1907-83.01	1860 (mic)	s-scr	42b	41.42	5.53	0.144	2.75
MHSC63.01	1842, ca.	m17.5;28	-	43.49	10.27	0.214	3.75

15.3.2 *1 inch objectives*

RMS0.03 *1 inch ACHROMATIC Object Glaſses*
RMS103.1 *Powell & Lealand*
MHS0.1 R.L. [Radcliffe Library]
RMS378.2 POWELL & LEALAND
RMS256.1 POWELL & LEALAND

inv.nu.	date	thread	dwg	f	M	NA	mRP
SM1918-17.6	1840 (mic)	s-scr	-	24.23	7.60	0.163	2.75
RMS327.1	1853 (mic)	m17.4;40	-	26.04	8.69	0.168	2.5
RMS168.2	1840 (mic)	m17.4;36	43b	23.47	10.10	0.175	2.25
RMS0.03	-	m17.4;28	42c	25.61	9.03	0.199	2.25
SMWA140784	1849 (mic)	m17.336	42c	25.72	6.78	0.199	2
RMS370.2	1850	m17.4;36	43b	25.41	9.14	0.201	1.75
RMS168.3	1840 (mic)	m17.4;36	43b	24.69	9.48	0.204	2
RMS282.2	1850 (mic)	m17.4;36	43b	25.41	9.22	0.205	2
RMS297.1	1871 (mic)	m17.4;36	-	25.49	9.09	0.211	1.75
SM-A71911	1845 (mic)	m17.4;36	-	24.23	9.88	0.218	2
RMS103.1	1875?1900	s-scr	42c	22.94	10.54	0.224	1.75
MHSC63.2	1842, ca.	m17.4;36	-	22.94	10.37	0.228	2.5
MHS0.1	1864	s-scr	-	22.09	11.11	0.237	1.5
RMS2.2	1841	s-scr	-	24.22	18.97	0.246	1.5
RMS426.2	1893 (mic)	s-scr	-	21.87	11.07	0.268	1.25
RMS378.2	1850	m17.4;36	43b	21.09	11.11	0.271	1.5
SM1907-83.2	1860 (mic)	s-scr	42c	21.67	11.07	0.271	1.75
RMS256.1	1876 (mic)	s-scr	42c	19.58	12.42	0.292	2

15.3.3 *1/2 inch objectives*

RMS256.2 *Powell & Lealand*
RMS102.3 *Powell & Lealand*
MHS0.2 *Powell & Lealand* R.L. [Radcliffe Library]

inv.nu.	date	thread	dwg	f	M	NA	mRP
RMS169.1	1848 (mic)	m17.4;40	-	13.57	17.96	0.171	2
RMS234.2	1840 (mic)	m17.4;40	-	13.26	17.78	0.196	2
SM1921-181.2	ca.1845	m12;36	-	11.87	14.82	0.216	2
SM1918-17.5	1840 (mic)	m17.4;36	-	13.35	14.33	0.251	1.75
MHSC63.3	ca.1842	m17.4;36	-	13.56	18.44	0.287	1.5
RMS256.2	1876 (mic)	s-scr	43c	12.25	21.56	0.316	1.25
RMS378.3	1850	m17.4;40	43b	11.18	23.05	0.384	1.25
RMS282.3	1850 (mic)	m17.4;36	43b	10.77	23.05	0.417	1.5
RMS327.2	1853 (mic)	m17.4;40	43c	9.47	26.82	0.551	<1
SM1907-83.3	1860 (mic)	s-scr	42f	9.00	28.74	0.577	<1
RMS0.5	-	m17.4;28	43f	9.81	26.13	0.593	1
RMS102.3	1864	s-scr	43f	9.69	27.17	0.598	1
MHS0.2	1864	s-scr	-	9.81	26.35	0.600	<1

15.3.4 *1/4 inch objectives*

RMS169.4	1/5 [on can]
MHS0.3	*Powell & Lealand* R.L. [Radcliffe Library]
RMS102.4	*Powell & Lealand*
RMS370.3	*Powell & Lealand*
SM1967-41.1	1/4 inch APO

inv.nu.	date	thread	dwg	f	M	NA	mRP
SM1921-181.4	1845, ca.	m12;36	-	4.84	39.52	0.338	1.5
RMS282.5	1850 (mc)	m17.4;36	43d	4.62	64.92	0.445	<1
RMS169.4	1848 (mc)	m17.4;40	42d	5.19	49.40	0.453	1
SW-A140784.3	1849 (mc)	m17.3;36	-	5.72	35.93	0.475	<1
SM1918-17.3	1840 (mc)	m17.4;36	-	5.81	37.32	0.493	1
SW-A71911.1	1845 (mc)	m17.4;36	43e	5.39	38.11	0.494	<1
RMS282.4	1850 (mc)	m17.4;36	43d	5.54	46.10	0.496	<1
SM-A140784.2	1849 (mc)	m17.3;36	-	5.45	38.53	0.500	<1
RMS234.3	1840 (mc)	m17.4;40	43e	5.44	46.70	0.503	1
RMS2.4	1841	s-scr	43d	5.77	45.16	0.508	<1
MHS32-42.8	-	m17.4;36	43d	5.45	47.99	0.511	1
RMS169.2	1848 (mc)	m17.4;40	43d	5.33	46.70	0.514	1
MHSC63.4	1842, ca.	m17.4;36	43d	5.33	49.40	0.520	1
RMS297.2	1871 (mc)	m17.4;36	43c	5.33	49.40	0.526	<1
RMS327.3	1853 (mc)	m17.4;40	43e	5.33	48.30	0.674	0.75
RMS378.4	1850	m17.4;40	43f	5.45	49.40	0.719	<1
SM1907-83.4	1860 (mc)	s-scr	-	5.59	47.75	0.725	<1
MHS0.3	1864	s-scr	-	5.59	48.64	0.726	<1
SM1967-41.2	1874 (mc)	s-scr	-	5.81	46.43	0.733	-
SW-A601303.3	1856 (mc)	s-scr	-	5.87	37.54	0.735	0.75
RMS102.4	1864	s-scr	43f	5.49	47.99	0.740	0.75
RMS370.3	-	s-scr	43e	5.66	47.42	0.766	<1
RMS169.3	1848 (mc)	m17.4;40	43e	4.62	56.45	0.829	1
RMS0.7	-	m17.4;28	43f	5.16	51.37	0.955	0.75
SM1967-41.1	1874 (mc)	s-scr	-	6.99	39.52	0.919	<1

15.3.5 *1/8 inch objectives*

RMS370.4	*Powell & Lealand* ; [on front] 1/8 Immersion
RMS122.2	*Powell & Lealand* ; [on front] 1/8 Immersion
RMS0.9	*Powell & Lealand* ; [on front] 1/8 Immersion
RMS103.21	*Powell & Lealand* 1877
RMS103.21	*Powell & Lealand*, 1877; [on front] 1/8 Immersion
RMS426.3	POWELL & LEALAND №15, 1/8 Oil Immersion N.A. 1.29

inv.nu.	date	thread	dwg	f	M	NA	mRP
RMS2.5	1841	s-scr	43d	2.94	88.92	0.577	<1
SM1921-181.3	1845, ca.	m12;36	-	2.73	69.16	0.592	1
SM1918-17.2	1840 (mic)	m17.4;36	-	0.00	72.45	0.603	<1
MHSC63.5	ca.1842	m17.4;36	43d	2.73	96.33	0.613	<1
SM1907-83.5	1860 (mic)	s-scr	-	2.86	94.84	0.882	<1
RMS378.5	1850	m17.4;40	43f	2.67	101.62	0.908	0.75
RMS0.8	-	m17.4;28	43f	2.70	100.77	0.937	<0.75
SM1967-41.3	1874 (mic)	s-scr	-	2.57	110.09	0.970	-
SW-A71911.2	1845 (mic)	m17.4;36	43h	2.84	106.20	0.988	<1
SW-A71911.3	1845 (mic)	m17.4;36	43h	2.65	102.75	1.006	<1
RMS370.4	>18??	s-scr	-	2.43	118.55	1.044	<1
SM1967-41.4	1874 (mic)	s-scr	-	2.82	110.09	1.078	-
RMS103.22	1877	s-scr	43i	3.15	106.20	1.170	0.75
RMS122.2	1875 (mic)	s-scr	43i	2.45	104.44	1.125	<0.75
RMS0.9	-	m17.4;28	43i	2.33	110.65	1.219	<0.75
RMS426.3	1893 (mic)	s-scr	-	3.05	88.92	1.240	<0.75
RMS103.21	1877	s-scr	-	2.45	-	-	0.75

15.3.6 *1/12 inch objectives*

RMS370.8 — *Powell & Lealand* ; [on front] *Immersion* 1/12; on can: 2/3.
MHS0.4 — *Powell & Lealand* R.L. [Radcliffe Library]
RMS370.5 — *Powell & Lealand* ; on front 1/12 *Immersion*
MHS0.5 — *Powell & Lealand* R.L. ; [on front] 1/12 *Immersion*
RMS370.6 — POWELL & LEALAND №18; on front: 1/12 *Oil Immersion* ; [on can] POWELL & LEALAND LONDON 1/12 Oil Immersion , scratched: 1.28
RMS426.4 — POWELL & LEALAND №96 1/12 *Apochromatic Oil Immersion* N.A. 1.40
SW-A71911.4 — 1/12 Apo HI NA=1.4
RMS370.7 — POWELL & LEALAND №121 1/12 *Apochromatic Oil Immersion* N.A. 1.43

inv.nu.	date	thread	dwg	f	M	NA	mRP
RMS297.3	1871 (mic)	m17.4;36	43f	2.01	128.43	0.927	<1
RMS370.8	-	s-scr	-	1.59	169.93	0.956	<1
SM1907-83.6	1860 (mic)	s-scr	-	1.99	138.31	0.982	<1
MHS0.4	1864	s-scr	43f	1.86	148.19	1.052	<1
RMS370.5	-	s-scr	43i	2.88	154.78	1.136	0.75
MHS0.5	1864	s-scr	43f	1.51	165.98	1.178	<0.75
RMS370.6	-	-	43j	1.99	142.27	1.253	<0.75
RMS426.4	1893 (mic)	s-scr	43j	2.17	121.85	1.342	<0.75
SW-A71911.4	1845 (mic)	m17.4;36	43j	2.16	122.51	1.349	<1
RMS370.7	-	-	43j	2.11	132.67	1.429	<0.75

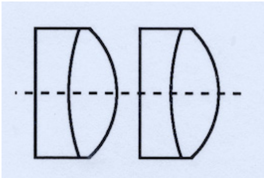
15.3.7 *1/16 inch objectives*

RMS122.4 — *Powell & Lealand* ; [on front] *Immersion* 1/16

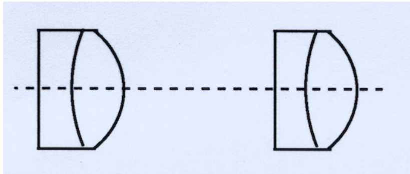
inv.nu.	date	thread	dwg	f	M	NA	mRP
SM1918-17.1	1840 (mic)	m17.4;31	42d	0.00	158.07	0.638	<1
RMS2.6	1841	s-scr	43d	1.35	193.64	0.663	<1
RMS378.6	1850	m17.4;40	43d	1.45	193.64	0.853	<0.75
SM1967-41.6	-	s-scr	-	1.45	230.52	1.10	-
RMS122.4	1875 (mic)	s-scr	43h	1.20	227.23	1.057	<0.75

15.4 DRAWINGS OF ROSS AND POWELL & LEALAND OBJECTIVES

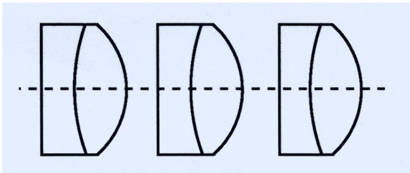
The numbers refer to the column dwg (drawing) in the tables above.



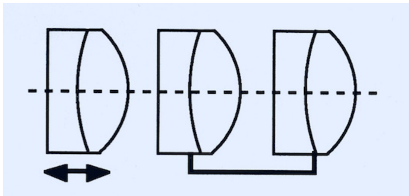
(a) 1



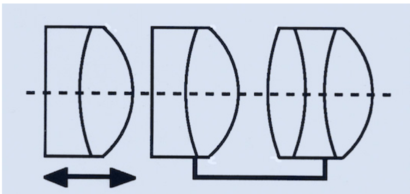
(b) 2



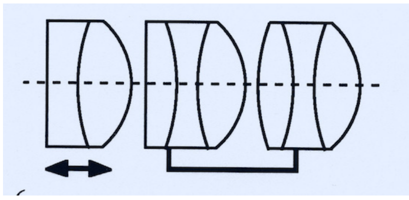
(c) 3



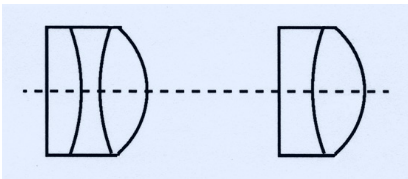
(d) 4



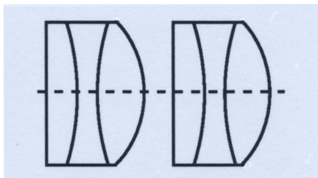
(e) 5



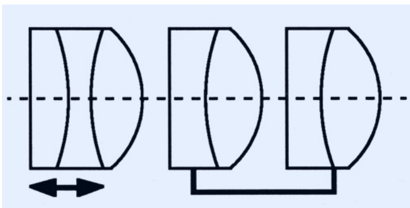
(f) 6



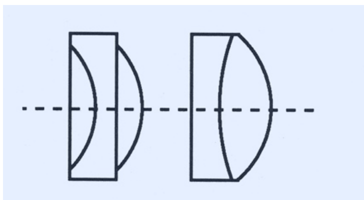
(g) 7



(h) 8

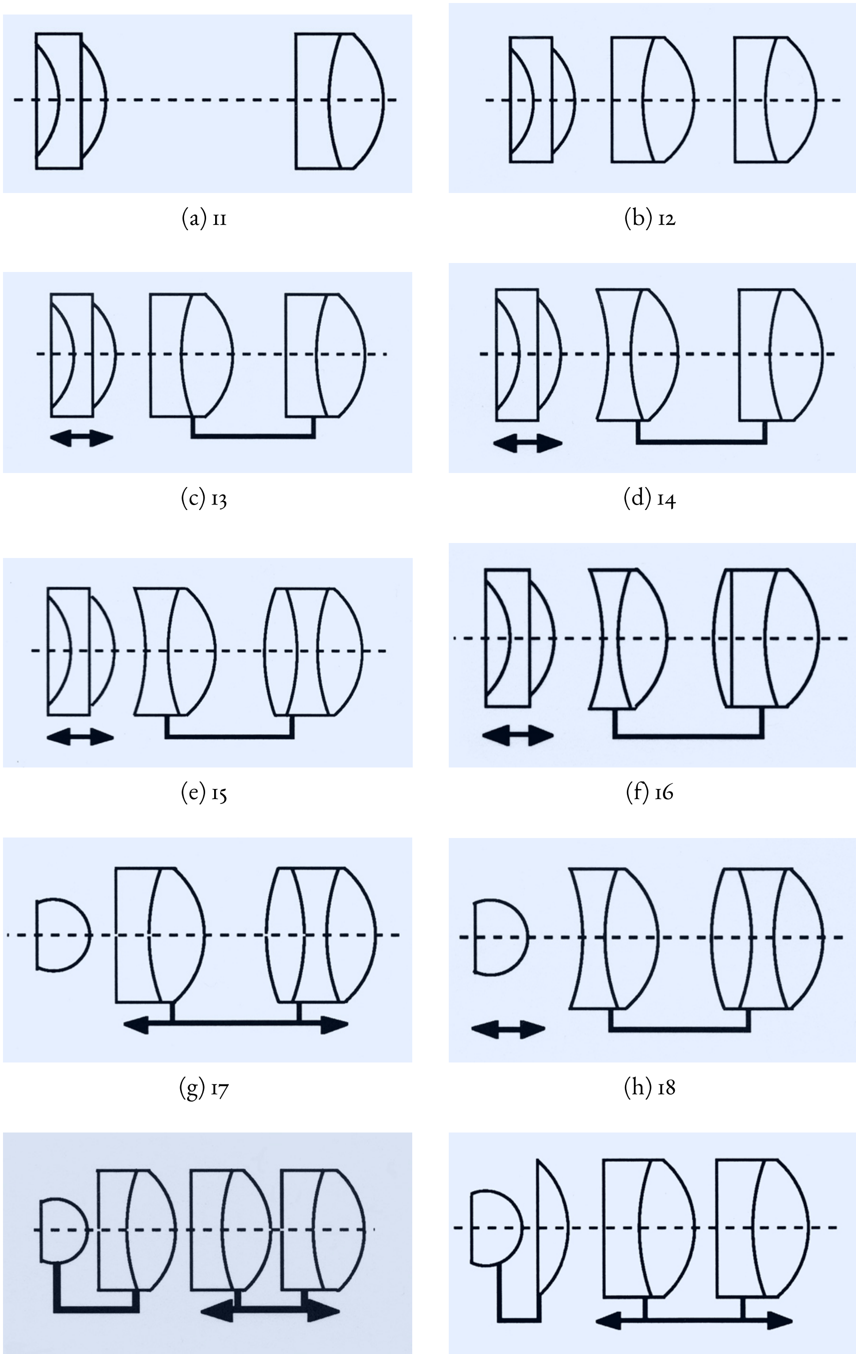


(i) 9



(j) 10

Figure 42: optical construction of objectives 1-10



(a) 11 (b) 12

(c) 13 (d) 14

(e) 15 (f) 16

(g) 17 (h) 18

(i) 19 (j) 20

Figure 43: optical construction of objectives 11-20

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