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A NEW ANASTIGMATIC FLAT FIELD TELESCOPE AND ITS APPLICATION TO PRISMATIC BINOCULARS

By H. DENNIS TAYLOR

Read and discussed, 13th January, 1921

THE public have become so accustomed to the usual prismatic binocular consisting of an achromatic objective, two inverting prisms, and a Kellner eyepiece that they have come to regard them as incapable of being improved upon. While there is no doubt that the best types of such instruments are by no means to be despised as regards their optical performance, yet those who are more versed in optical science than the man in the street are well aware that all telescopes are characterised by certain alternative defects which cannot possibly be got rid of, provided that present principles of construction are adhered to. In the same way, up to the year 1895 or so, it was thought by the average photographer that the lenses used by him were as perfect as it was possible to get them, as in fact they were so long as the old principles of construction were adhered to.

It was only later that it was fully realised by the photographer what a great improvement in the optical performance and rapidity of the lenses that he used could be attained by a radical departure from the old principles of construction, which consisted in the use of one or more compound achromatic lenses through which the oblique pencils were constrained to pass excentrically by means of a suitably placed stop. Now it had long previously been demonstrated by Petzval that if by the use of excentricity corrections, due to such excentric passage of oblique pencils, the astigmatism generally characterising oblique pencils is neutralised, leading to a curved but anastigmatic image, then the radius R of such image

is expressed by the simple formula $\frac{1}{R} = \frac{1}{f_n}$ in the case of a simple lens of refractive index n and principal focal length f . In the case then of a simple positive lens of refractive index 1.5 the radius of curvature R of an anastigmatic image yielded by it is $1.5f$, and if the refractive index is 1.625 then $R = 1.625f$, so that a positive lens of high refractive index has an advantage as regards flatness of field over one of the same focus but of low index. Further, in the case of compound lenses, he demonstrated that the radius of the anastigmatic image the system is capable of is expressed by the formula

$$\frac{1}{R} = \frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \dots$$

Let us now consider the usual forms of double compound lenses consisting of a positive lens of one refractive index together with a negative lens of lower power

but higher refractive index and higher dispersive power. Let D be the ratio of the principal focal lengths of the two lenses which generally is the ratio between the dispersive powers of the two glasses. Let f be the principal focal length of the positive lens and F that of the two combined then $\frac{1}{F} = \frac{D-1}{D} \frac{1}{f}$ and conversely

$$\frac{1}{f} = \frac{1}{F} \left(\frac{D}{D-1} \right) \quad \text{and} \quad f = F \frac{D-1}{D}.$$

Thus, if n be the refractive index of the positive lens and m that of the negative lens, the curvature radius of the anastigmatic image is given by

$$\frac{1}{R} = \frac{1}{fn} - \frac{1}{Dfm} = \frac{Dm-n}{fDnm},$$

in which for f we may substitute

$$F \left(\frac{D-1}{D} \right),$$

thus obtaining

$$\frac{1}{R} = \frac{Dm-n}{F(D-1)nm}.$$

If we assume $D = \frac{5}{3}$ and $n = 1.5$ and $m = 1.625$, then we get

$$\frac{1}{R} = \frac{\frac{5}{3}(1.625) - 1.5}{F(\frac{5}{3})(2.4375)} = \frac{1.208}{F(1.625)} = \frac{1}{F(1.345)}.$$

But if the lens were a simple one of refractive index = 1.5 and principal focal length F then $\frac{1}{R}$ would be $\frac{1}{F(1.5)}$. Therefore as long as we are obliged to use negative lenses of glass of higher refractive index than the glass used for the positive lenses, in order to get correction against spherical aberration, especially in the case of cemented doublets, we are handicapping ourselves when trying to obtain anastigmatic images that shall approach to the condition of flatness. It was the realisation of this fact which prompted Schroeder to bring out his photographic lens (known as the Concentric) whose lenses were composed of a positive of focal length 1.5 combined with a negative of focal length minus 1.6 while their refractive indices were 1.6 and 1.5 respectively so that here we had

$$\frac{1}{R} = \frac{1}{1.5(1.6)} - \frac{1}{1.6(1.5)} = 0.$$

This of course implied that the radius of curvature of the anastigmatic image was infinite and the image flat. But the spherical aberration was of course uncorrected so that it was barely feasible to use even an aperture of $F/16$. Then Rudolph and Goerz came forward with their more complex lenses, in which the Petzval condition

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \dots = \frac{1}{R} = 0$$

was carried out, not so completely as in the case of Schroeder's lens, but in an approximate degree which at the same time enabled them to get the spherical aberrations sufficiently well corrected for a much larger aperture.

Then the Cooke lenses were introduced, in which the positive and negative lenses involved would, if they were all in contact, yield scarcely any focal power at all and the power was obtained chiefly by the axial separation of the constituent lenses. The Petzval condition

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \frac{1}{f_3 n_3} = 0$$

was approximately, but not completely, fulfilled, for the Cooke lens was to a certain extent a compromise. The fact of the lens being composed generally of only three components, two positive and one negative, was of course an advantage on the score of simplicity, but it entailed the presence of certain excentricity corrections of the 3rd order which produced an incurving towards the lens of images of concentric circles as the pencils got beyond a certain degree of obliquity, say 23 to 25 degrees. Such 3rd order excentricity corrections would increase as the fourth power of the powers of the lenses, so that had the Petzval condition been completely carried out the result would have been a more truly anastigmatic flat field in the middle area of the field, but this would be obtained at the expense of a reduced aperture and focal power combined with a much more marked incurving of the images of concentric circles formed by the more oblique pencils. This would have practically meant a curtailment of the useful field of view. The corollary which this fact illustrates is this, that the complete carrying out of the Petzval condition

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \dots = 0$$

will only pay under conditions which will permit of the excentricity corrections of the 3rd order being practically eliminated, but, as a matter of fact, they can only be eliminated under conditions of greater complication.

And now let us proceed to consider the case of the telescope usually employed for binoculars and here we may most conveniently leave the erecting prisms out of further consideration, after pointing out that they have a slight tendency to make the red image larger than the blue, to produce slight inward coma, slightly to flatten the images in just the same way as do excentricity corrections, and lastly to produce slight barrel-shaped or negative distortion of images of straight lines projected by the objective. But from the point of view of attaining the Petzval condition the erecting prisms have no influence whatever.

Suppose we take the case of an ordinary type binocular telescope with an objective of about 6" focal length and a Kellner eyepiece magnifying about eight times and fix it up so as to point squarely at a large diagram of radial lines and circles like Fig. 1 placed at 25 feet from the telescope, and then unscrew the focussing eyepiece by 4 diopters. The eyepiece will then project a real image of the diagram subtending 40 to 50 degrees to a distance of about 10 inches behind it. Fig. 2 gives a rough analysis of this image. The field correction usually followed in the case of an apparent field of 48 or 50 degrees is to secure that an image of a concentric circle at 22 degrees or so from the axis shall be in focus at the same time as the centre point of the diagram. That is, if *AF* is the focal plane we shall

have sharp focus for a tangent line at C , 22° from the axis, simultaneously with sharp focus for the centre of the diagram at A . Nevertheless the image as a whole for the concentric circles or tangent lines is not a truly flat one, because of the excentricity corrections of the 3rd order which exist in the Kellner eyepiece. Under more exact observation it is found that the curve on which the images of

Fig. 1

Fig. 2

the concentric circles is formed is the curve $AMCP$, which bulges a little inwards to the maximum point M , about 15 degrees from the axis, then curves back and crosses the focal plane at C and rapidly recedes behind the focal plane towards P . This reversing curve is due to negative excentricity corrections of the 3rd order being counteracted by positive excentricity corrections of the 2nd order. If we now turn our attention to the image of the radial straight lines we find that it is

located along the violent curve AS at an ever increasing distance within the focal plane as the angle of obliquity increases, and obviously the reciprocals of the horizontal distances between the secondary curve AS and the primary curve $AMCP$, for the same ray, are a measure of the astigmatism existing in the oblique pencils. If the excentricity corrections were only carried far enough to give an anastigmatic image it would then be formed on the still more violent dotted curve AA' (whose radius of curvature near the vertex A is only $\cdot 78$ inches), but in order to see such an image clearly the eyepiece would have to be moved further and further in as the edge of the field was approached. Thus, if either a diagram like Fig. 1 or a natural landscape or view containing radial and tangent lines is viewed through any existing binocular, it is found impossible to see both lines in clear focus at the same time. While the image of tangent lines may be approximately flat yet that for radial lines is violently curved, while any markings of the nature of spots or dots are necessarily blurred and elongated tangentially by the astigmatism which accompanies the defect.

I have examined some binoculars made by Zeiss in which the curve ACP is curved still further back away from the focal plane, presumably with the intention of simultaneously flattening the secondary curve AA' a little more, but personally I do not think that any flattening of the field further than that shown in Fig. 2 is desirable, since it also increases the separation between the secondary and primary curved fields and therefore increases the astigmatism.

I had long ago been impressed by the obviously imperfect field corrections of all existing low power telescopes and about two years ago thought I would enter into an investigation with a view, if possible, of applying the principle involved in the Cooke lens for eliminating these defects and securing a really flat and anastigmatic field of view. I think that you will all agree that no designers who entertain a high ideal of optical science and its applications should neglect any possible opportunity that occurs to them of improving the performances of optical systems, even if it be at the cost of greater complexity in construction.

The arguments in favour of an anastigmatic and flat field of view scarcely need emphasising. It is highly desirable from an aesthetic point of view alone, and this becomes an ever stronger factor under the educative influence of improved standards of optical performance. The binocular is largely used for finding objects, sometimes minute and in unknown localities, in the landscape and to that end it is most important that the eye should be able to pick them up anywhere within the limits of the field just as readily as at the centre. A particular case of this is when they are used by officers of the Navy or Army for observation of fire, and by surveyors and naturalists when exploring new country and by sportsmen whether in looking out for game or in watching races or looking out for friends on the race course.

My enquiries and experiments, carried out with all the facilities afforded to me by the Company with which I have the honour to be associated, at last materialised in the model, first of a power 10 and then a power 7 telescope, in which I am glad to say the perfection of the optical corrections throughout an apparent field

of 52 to 56 degrees came out far higher than I was prepared to anticipate. For I expected to be up against very serious residual aberrations of the 3rd order which could not be got rid of, but eventually the power 10 model, and still more the power 7 model, only showed traces of aberrations of the 3rd order which are so small as to be practically imperceptible. Fig. 3 is a longitudinal section through the optical parts of the power 10 telescope.

I will deal first with the telescope itself and then the erecting prism *P*. *O* is the objective, which is of a type giving a little inward coma to neutralise the outward coma characteristic of the eyepiece system. *N* is a quadruple negative lens consisting of two negative lenses of fluor crown cemented to and enclosing a positive of extra dense flint and a detached negative lens also of fluor crown. As this negative system has to have a very large aperture compared with its focal length, it is necessary to use crown and flint glasses of as widely different dispersive powers as possible in order to keep the curves moderate. I tried at first to make this negative corrector lens a cemented triplet, but had to give it up for the curvatures were so violent that very serious 3rd order aberrations were introduced which could

Fig. 3

not be counteracted. This negative system is placed a little within the principal focal plane of the objective and it functions as an enlarging lens, enlarging the primary image and throwing it back on to the plane *dd* where a field stop is placed to outline the field. *F* is a meniscus shaped field lens of dense barium crown whose chief function is to collect the principal rays diverging from the negative lens and render them approximately parallel before entering the eyepiece lenses *E*₁ and *E*₂. The first eyepiece lens *E*₁ is a light baryta flint positive lens cemented between two meniscus negatives of extra dense flint glass. The eye lens *E*₂ is made of a meniscus extra dense flint lens cemented to a meniscus positive lens of the same glass as that used for the positive of *E*₁. These two compound lenses are held together almost touching and are together moved in and out by screw action, according to a diopter scale engraved on the eyecap.

The image is supposed to be formed always in the constant position *dd*, while focussing for short distances is done by moving the objective outwards, and for varying eyesight it is done by screwing the eye lenses in or out. The forms taken by these various lenses have been with a view to eliminating aberrations of the 3rd order as well as those of the 2nd order. Here then is shown the application to the telescope of the same principle of construction as was first embodied in the

Cooke photographic lenses, only in this case the principle is carried out still more thoroughly and with still more perfect results.

As I have pointed out before, one can only carry out the Petzval condition completely, provided that aberrations of the 3rd order can be eliminated completely. In the case before you the whole Petzval sum

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \dots$$

comes out not exactly zero, but with a very slight minus residue of 1.6 per cent., which enables it to present to the eye an image that is perhaps a little better than being anastigmatically flat, inasmuch as it is really not only anastigmatic but slightly curved concave to the eye, to about 19 inches radius. I would lay a little stress on this point, as I think it will be conceded that the average user of a binocular so focusses that the axial distance from his eye of the virtual image presented to his view is not infinity but generally about 20 inches and it therefore becomes desirable that when turning his eye to see an object at the edge of the field he should not have to vary the focus of his eye, and for that reason I aimed at getting the radius of curvature of the anastigmatic image about 20 inches, and concave towards the eye.

The longitudinal section of the power 7 system would not look essentially different from that of Fig. 3, the main variation being that the objective is of shorter focus and the negative lens enlarges the image in lesser degree and has a larger relative aperture, while the whole telescope is a little shorter.

From what I have already said it will be inferred that these two telescopes are of greater perfection, from an optical point of view, than was any Cooke lens hitherto worked out and this is due to the greater complication or the greater number of elements which can be intermodified in order to suit all the exigencies of the case. I remember visiting Zeiss's factory in 1894, together with Mr Wigglesworth, and having a very interesting talk with Prof. Abbe on the subject of attaining greater perfection in the performance of optical instruments, and his emphatic declaration was that, as a general rule, one should never be afraid of adopting greater complexity in construction, provided that any substantial gain in optical performance were thereby secured.

And now we have got an anastigmatic flat field telescope, but it is an inverting telescope, and means of erecting the image must be found. The ordinary pair of crossed doubly reflecting right-angled prisms placed between the objective and the negative lens might be employed, but there are very grave objections to their use in this case.

I think most of you here will agree that one seldom comes across a pair of prismatic binoculars in which a critical examination will not reveal a lobe-sidedness of the field corrections, I mean a greater amount of astigmatism or flatness showing on one side of the field than on the other or more coma on one side than the other. Nor need one be surprised, when it is considered how essentially intricate and difficult the adjustments of such prisms really are. First of all, we have lateral movements of the prisms along their lengths and parallel to themselves, which

placed by about half the length of the prism. The field of total reflection depends upon the refractive index. For a power 7 telescope which requires 8 degrees of actual field the refractive index should not be less than 1.58 and a light flint, which is one of the most transparent of all glasses, should be employed. For an objective of 1 inch aperture it is well known that the inside glass path involved in the usual double crossed prism is about 4 inches and the same applies to this new prism, although there is slightly more bulk of glass involved.

Now it will be seen that there are only two movements of this prism that can move the image in the field at all. One is an angular movement about any axis parallel to the vertical axis $a'b'$, and the other is an angular movement about any horizontal axis parallel to the top ridge aa . The first movement moves the image left or right by twice the angular movement of the prism and the second moves the image upwards or downwards by twice the angular movement of the prism. The top ridge rests in two V-cut claws V and V , one near either end, and is pressed home into the same by a counterspring C pressing on ridge bb . These two V claws are part of a flat bar resting upon a flat surface at the bottom of the prism box and this flat bar can be moved laterally parallel to itself, thus giving an angular movement of the prism about an axis parallel to the ridge aa , there being a fixed bearing point S (Fig. 4A) against which the prism is kept pushed by spring pressure opposite. That is, the lateral movement of the V bar gives an angular movement of the prism about a horizontal axis and vertical movement of the images, the prism adapting itself by rocking slightly in the V claws. The V bar is also capable of a rotation about its centre, that is, one V can be made to recede from the telescope while the other V approaches by an equal amount, and this movement of course imparts an angular movement of the prism about a vertical axis perpendicular to the ridge aa and causes horizontal movement of the images. After the prism has thus been adjusted the V bar is securely fixed. Of course none of these adjustments of the prism have any effect whatever upon the optical performance of the telescope; it is only the orientation of the images that is affected.

It will be seen that this prism and the methods of its mounting imply a great simplification in the adjustments, moreover these adjustments are so arranged that they can be operated from outside by concealed screws while the binocular is all assembled and directed on a test mark. After the adjustments are carried out the operating screws, which lie concealed in their recesses, are sealed up and fixed.

I would here point out that the form of eyepiece which has been shown in section in Fig. 3 is, with a slight modification, also applicable to the microscope. But as microscope objectives, on the dry system at any rate, may also be constructed to give anastigmatically flat images, it becomes desirable to make the eyepiece anastigmatic and with a flat field in itself. In the case of the telescope it has to be over-corrected in order to neutralise the field curvature and astigmatism of the objective and the more so in inverse proportion to the magnifying power. In the case of the microscope each different power of eyepiece should be equally usable with any power of anastigmatic and flat field objective and thus be interchangeable. I hope to bring before you more detailed accounts of such schemes of microscope

construction on some future occasion. It will be seen that these more complex constructions for telescopes imply six cemented pairs of surfaces and it becomes important that the films of Canada balsam shall be as colourless as possible as well as permanent, and here we are up against the ever recurrent balsam problem, the well-known difficulties of which I think I have succeeded in solving in a very simple and practical way, which, if confirmed by further experience, would in itself furnish material for a short paper.

Lastly, as regards complexity in construction, I would point out that there is nothing of special difficulty in it, although, of course, it must be expected that the cost of production of the optical parts will appreciably exceed the cost involved in the ordinary construction. But I have never heard yet that in the case of bicycles, motor cars, gramophone records, orchids, or potatoes a more thorough realisation of the ideals aimed at in each particular instance has been attained, without calling forth more ready and appreciative offerings from the purses of those who really want such things.

DISCUSSION

Mr L. C. Martin drew attention to a paper by Prof. Conrady in the Monthly Notices of the *R.A.S.* (April, 1918) in which the employment of an achromatic negative lens before the positive lens system of the eyepiece is suggested in order to produce an anastigmatic flattening of the field by satisfying the Petzval condition.

He would like to enquire whether, in the author's opinion, the gain in definition at the margin of the field would be sufficient to compensate for the effects of multiple reflections in diminishing the light and weakening the contrasts in the image.

Mr H. S. Ryland said that of about 4000 binoculars which he had examined 92 per cent. possessed unequal astigmatism.

He would also like to draw attention to the question of the loss of light. He thought it was better to have good definition at the centre of the field of view accompanied by good illumination than to have good definition over the whole of the field with inferior illumination, provided that the definition does not fall off too badly. In practice the periphery of the field was largely used for detecting movements of objects.

He suggested that manufacturers should publish light transmission values in their advertisements.

Instructor-Commander T. Y. Baker thought that the author was to be congratulated on introducing a new method of erecting the field of view by means of prisms.

He asked if the author could give the percentage light transmission of his telescope, as this was an important factor in service instruments used for night work. Recently attempts had been made to reduce the loss of light in prismatic binoculars by cementing the reflecting prisms together and to the flat face of the field lens, thus giving six glass-air surfaces as compared with four in the Galilean binocular. He enquired if it would be possible to simplify the eyepiece in the author's telescope so as to reduce the number of glass-air surfaces.

Mr P. F. Everitt agreed with the author that any complications in optical design were justified if they led to improvement in performance.

He thought that the question of astigmatism in binoculars was one of long standing.

Mr T. Smith said that the little prism in front of the system was very compact and could easily be seen to be achromatic. The condition for this was that the bisector of the angle between the two refracting faces should be perpendicular to the roof edge. It would be interesting to know how this was secured in manufacture.

It had been stated that the Cooke lens had been so designed that when all the lenses were placed together the combination was of zero power. In any system of separated lenses the sum of the powers of all the components enters into the aberration expressions and particularly affects the astigmatism as distinct from the curvature which depends on the Petzval sum. The sum of the powers need not be zero, but its value will affect the design considerably. He cited by way of example any system in which each successive image formed by the various lenses was free from spherical aberration and coma; the vanishing of the sum of the powers was then the condition for freedom from astigmatism. This in conjunction with the Petzval condition suggested that by the introduction of a negative field lens existing telescopes could be given a flat field free from astigmatism.

Mr J. Guild said that he would like to oppose the view that the only thing which matters is the brilliancy of the image, as he considered that the visibility in faint lights must depend largely on the accuracy of the definition.

The author, in reply, said that he did not think that the telescope could be simplified.

With regard to the loss of light he wished to draw attention to the enormous adapting power of the eye to variations in brightness. The illumination of a landscape under a full moon is well known to be at least 300,000 times weaker than in broad sunlight. In a particular submarine periscope system the light transmitted was only about 20 per cent. yet a friend had declared that objects seen through it appeared to be as bright as under ordinary circumstances. In the telescope described in the present paper about 40 per cent. of the light is transmitted when the surfaces are freshly polished. About five of the surfaces retain their polish, while the others tarnish and then transmit more light. After the instrument has been in use for some time it transmits about the same percentage of light as an ordinary prismatic binocular.

The most important question to be considered is that of the balsam, which in tropical climates dries and cracks, a certain amount of volatile constituents evaporating out and giving rise to vacuities and further trouble. He thought that he had found a way of getting rid of the brittleness of the balsam, and he hoped shortly to give a paper dealing with the balsam problem.

He estimated that the cost of the binocular would not exceed that of an ordinary prismatic binocular by more than 50 per cent.

Note added later. I was not aware of Prof. Conrady's paper in the Monthly Notices of the *R.A.S.* until after Mr Martin drew my attention to it. I then procured a copy, from which I find that Prof. Conrady was, as should be expected, fully aware of the importance of carrying out the Petzval condition in eyepieces for telescopes, but should he have proceeded to work out practically such an eyepiece, I feel sure he would have found that it cannot be efficiently carried out by the employment of only one cemented compound negative lens and one cemented compound eye lens, as suggested in his paper.