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1920 Trans. Opt. Soc. 21 113

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TRANSACTIONS OF THE OPTICAL SOCIETY

VOL. XXI.

1919-20

No. 4.

THE OPTICAL THEORY OF PORTABLE DAYLIGHT SIGNALLING LAMPS

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Lecture delivered, 11th March, 1920

THE *ideal* signalling lamp for use by day should fulfil the following conditions: The whole equipment should be easily carried by one man from place to place—the actual signalling lamp should be easily aimed and operated by one hand. The beam projected should be of uniform and great intensity within a reasonable angle to allow for errors of aim; and of zero intensity for all angles of divergence outside that tolerance. It should be provided with a good optical sight to ensure accurate aim, and the source should be standardised in some way at the focus of the projector, so that the operator cannot interfere with it or throw the beam and sight out of alignment. The device for interrupting the beam should be easily operated by one finger, have the minimum of movement and noise, and enable the beam either to occult from maximum intensity or to flash out again to maximum intensity in less than a tenth of a second.

Now it is difficult to satisfy all these conditions, but it will be the purpose of this paper to deal with certain simple geometrical methods of dealing with the purely optical problems presented, viz. to afford a beam of maximum intensity within definite angular limits from apparatus of minimum size and weight.

In the first place, it is necessary to point out that the stimulus to the eye of the receiver of the message is, in really efficiently designed apparatus, strictly proportional to the product of the area of the clear aperture of the lamp into the intrinsic brightness of the source. If suitably designed and focussed, what the eye sees is the whole aperture of the lamp filled with a brightness equal (except for transmission losses) to the brightness of the source. Of course, signal lamps

are operative by day at ranges far beyond those at which the eye can see the lamp as a *disc* of light, but the fact remains that the increase in candle power as contrasted with the naked source is only due to the increase in apparent size of the source effected by the optical device employed in the lamp. The optical device cannot make the source look brighter; it only makes it look larger. In all that follows this distinction as to what the eye really sees will be ignored and for scientific exactitude the reader can imagine the image as being transmitted to the eye by a really good telescope.

It will be convenient to define the apparent shape and size of any small incandescent source, corresponding to any particular view point, as the actual shape and area of a flat, cut out sheet which, held with its plane perpendicular to the line of vision, just completely obscures the source as seen from that view point.

Now the condition of portability imposes a definite upper limit for the size of lamp and in all that follows it will be assumed that a lamp of known maximum allowable clear aperture is being used. It is, therefore, at once evident that a source must be chosen of as high an intrinsic brightness as possible, and that the optical device employed in the lamp must be so related to the source that the receiver of the message sees the whole clear aperture of the lamp as filled with a flash of that intrinsic brightness. This is termed "complete flashing"; "partial flashing" means that the receiver sees certain parts of the clear aperture as either without any flash or as only filled with a *coloured* flash, due to the optical device failing over those zones to bend *all* the useful light energy into the receiver's eye.

The subjoined table shows the intrinsic brightnesses of various sources.

Table of relative intrinsic brightnesses.

	Candle power per square inch
The sun at zenith through air	1,000,000*
The crater of the ordinary carbon arc	110,000*
Tungsten filament in argon (·65 watts per candle)	7,500†
Oxy-acetylene with pastille	3,000*
Ordinary tungsten filament (in vacuo)	960*
Acetylene flame (burning in air)	36‡
Paraffin flame (enclosed in glass chimney)	10‡

* National Physical Laboratory.

† Langmuir.

‡ G. A. Shakespear.

In daylight signalling from aircraft a source of very high intrinsic brightness is absolutely essential, because unlike night signalling it is not merely a question of producing a certain candle power in the beam but it necessitates that a certain minimum of *contrast* shall be afforded when seen against such a comparatively bright background as is afforded by the sky in broad daylight. Unlit, the lamp is a *black* dot in the sky and a certain amount of light energy is used up in (so to speak) obliterating this negative effect. The table makes it at once evident that the electric arc must be employed for really powerful apparatus, but that the tungsten filament incandescent in argon offers far and away the most effective and convenient source

for readily portable signalling outfits. The figure given as originating from Langmuir's investigation of the (so-called) half-watt lamp was communicated by Mr Paterson when he was at the N. P. L.; but the writer's investigations which led up to the design of the Aldis Daylight Signalling Lamp, show that a mean intrinsic brightness of over 17,000 candles per square inch of surface has been attained with the lamp run at an efficiency of $\cdot 4$ watts per candle. This was only the *mean* intrinsic brightness, however, and the photograph (see Fig. 1) of the incandescent filament shows that different parts of the wire are actually very much brighter than other parts. The illustration is from a photograph of the incandescent filament made by projecting this on to a sensitive plate, so that an accurate, highly enlarged record was obtained both of the apparent size and shape of the filament from the view point of the lens used for projecting the image and also of any variations in brightness in different parts of the filament.

As there is a great danger, when dealing with the subject of signalling lamps, of introducing ambiguity by referring to the electric incandescent sources as "electric lamps" these latter will always be referred to as "electric bulbs," and in what follows, as a matter of fact, the term electric bulb will always be supposed to mean a high efficiency, so-called half watt (or preferably gas-filled), incandescent electric lamp.

The only source that can compare with an electric bulb for convenience in a self-contained really portable outfit is the acetylene flame, and from the data supplied above it is evident that the intrinsic brightness is only about $\frac{1}{100}$ of that possible in the electric bulb. It would appear, therefore, that for an acetylene projector to attain to the same range as a 5" diameter electric signalling lamp it would have to be made over 7 feet in diameter. This comparison, however, assumes complete flashing in both cases. The electric bulb, therefore, is the best source to employ in a hand signalling lamp provided a complete flash can be afforded.

As regards the optical means employed for projecting the beam it may be remarked that the well known property of a parabola, viz. that rays emanating from the focus are rendered parallel after reflection, has caused this optical device to receive (as will be shown later on) an undue amount of attention from those responsible for the design of such lamps. Again and again inventors appear to hanker after that impossible abstraction a "point source" used in conjunction with a parabola. As a matter of fact, it is at the present time easier to approximate to a point source than it is to approximate to a true point focus for a parabolic reflector suitable for such a source. In other words, with any parabolic reflector commercially obtainable the spreading of the projected beam due to local imperfections of shape is quite as great as that due to the source having appreciable size when the best types of the so-called point sources are utilised.

It will be found convenient to describe the illumination produced in different

Fig. 1. Incandescent coils shown magnified 8 times.

parts of the signalling beam in terms of the light patch received on a distant white screen—this being the way in which such beams are practically tested for uniformity and angular size. To investigate the theory of the parabolic projector for affording a complete flash within a certain predetermined angle α it is convenient to consider what each tiny element of the parabolic reflector contributes to the light patch received on a distant screen. It is evident that any such tiny element throws on to the screen a patch whose apparent shape and size is exactly the same as the apparent shape and size of the light source as seen from that portion of the reflector. Its position on the screen is such that the axis of the reflector intersects this light patch at a point corresponding to the apparent position of the focus in the source as viewed from that portion of the reflector. Thus the ideal shape and size of the smallest possible source to fulfil the required conditions is a sphere surrounding the focus as centre whose angular diameter as seen from the forward edge of the parabola is equal to α , and that this forward edge should be in the plane containing the source, i.e. the latus rectum of the parabola should be made equal to the assumed limit of clear aperture imposed for the signal lamp. It is bad practice and wasteful to employ a parabola of shorter focal length than this. It is true that it collects more light energy from the source, but this is scattered over a wider angle in the projected beam. Complete flashing is actually confined to a narrower angle.

Now it is impossible to dispose the filament in an electric bulb so that it shall appear as a continuous incandescent spherical source. Fig. 2 is from a photograph of an incandescent filament forming one of the best approximations to an incandescent sphere which the electric lamp makers were able to produce before the introduction of the drawn wire filament. The photograph was made by projecting the incandescent filament exactly as in the case of Fig. 1. This is known as a "crown pattern" filament, the filament being zig-zagged up and down, and the zig-zags disposed on the surface of a cylinder; in fact the filament is made to follow the shape of the upper edge of the paper crowns so popular with children.

Fig. 2. Incandescent filament shown magnified 8 times.

The best approximation to a spherical source, of course, is obtained by including as many zig-zags as possible disposed on the cylindrical surface and making the height of the zig-zags equal to the diameter of this cylindrical surface. The image of this crown pattern filament, as projected by a good lens in a direction approximately at right angles to the axis of the crown pattern, forms of course an interlaced pattern of lines far removed from anything that could be described as a continuous incandescent sheet. Nevertheless, this pattern filament placed with its

axis coincident with that of a parabolic reflector affords quite a good signalling beam *if the reflector be made large enough*. What happens, of course, is that the reflector is only seen partially flashed everywhere within the angle of the beam, and for night signalling this suffices very well.

The introduction of the tungsten drawn wire filament made the simulation of a continuous surface in electric bulbs possible. Fig. 1 shows the progress made since pre-war days in producing such sources. When it is remembered that the two sources (Figs. 1 and 2) are shown to the same scale of enlargement (eight times natural size) and that the candle power for the gas filled bulb (Fig. 1) was over 100 and that for the vacuum type (Fig. 2) was only 12, it will be seen that the progress in increasing the actual intrinsic brightness of the wire was fully as remarkable as the progress in concentrating the wire so as to simulate a continuous small incandescent sheet. Though the projection of the coil presents the appearance of a continuous incandescent surface, it is very far from being a uniformly bright surface, because the temperature of the wire varies in different parts due to self-heating effects between adjacent rings. Remembering that the actual diameter of the filament is only a few thousandths of an inch, the variations in temperature and brightness of different parts of the surface of the wire are remarkable. The fact also that these periodic variations in brightness from ring to ring are, despite every effort of the designer to obviate them, all to a certain extent reproduced in corresponding variations in intensity in the signalling beam shows what small quantities have to be considered in modern portable daylight signalling apparatus.

Fig. 1 shows that the tungsten drawn wire filament can be wound so as to simulate a continuous incandescent cylinder. It is evident that the best approximation to an incandescent sphere for projecting a circular beam from a parabolic reflector is a close cylindrical coil coaxial with the reflector, (whose outside diameter is the diameter of the equivalent sphere) sufficiently long for the apparent shape as seen from *all useful parts* of the reflector to show no black hole due to looking right through the interior of the coil.

The reference to "all useful parts of the reflector" makes it necessary to call attention to the one great draw-back of the electric bulb used in conjunction with any reflector placed behind it for projecting a signalling beam. The glass containing bulb acts practically as an opaque obstruction in the path of the beam—it is quite impossible in fact to produce a complete flash in such a reflector; the most that can be done is to produce a complete flash in the annulus of the reflector seen surrounding the bulb. Any partial flash seen through the bulb affords always an absolutely negligible contribution to the total signalling beam. It must never be forgotten, therefore, that any reflecting system placed behind the source is to be considered as limited to the annulus enclosed between the outer edge and a central area equal in diameter to that of the glass bulb employed for the electric source; and maximum efficiency will always be attained if a complete flash can be secured in this outer annulus only. In actual practice the inner edge of this annulus subtends so large an angle at the source that it is easy to make an axial coil long enough to be seen as a continuous sheet without any hole in it due to looking right through

the coil from this inner edge. A comparatively short axial coil, therefore, can afford a complete flash in a parabolic mirror annulus.

This obstructive effect of the bulb shows how important it is for the makers of electric bulbs to provide the maximum of candle power *in the minimum size of bulb*. At present for high efficiency signalling lamps intended to be held in the hand the minimum possible size of bulb for a given filament is such that the mirror annulus cannot be brought near enough to the source to afford the necessary angle in the signalling beam. The only thing to do, therefore, is either to introduce such deformations in the parabolic mirror as will spread the beam by the necessary angle or to wind the incandescent filament as a larger and more open spiral coil. As a matter of fact, it is best to do a little of both, but this, of course, means adopting partial flashing for the whole of the signalling beam and using a lamp of larger diameter than is theoretically necessary. Thus the makers of electric bulbs have to a certain extent taken away with one hand from the designers of signalling lamps what they have given with the other. They have afforded small sources of exceptional intrinsic brightness, but put them in such large bulbs that they cannot be used to full advantage.

The most obvious way to get over this obstructive effect of the bulb is to abandon the idea of a mirror placed behind the bulb and adopt a dioptric system in front of it. Here again, however, the radius of the bulb imposes a definite limit to the possible proximity of the optical system and as a matter of fact the expense and complexity, not to mention the weight, of a system of dioptric and catadioptric rings placed in front of an electric bulb renders this system impracticable. Where a fairly wide angle is demanded in the signalling beam the designer of commercially practicable signalling lamps is forced to adopt partial flashing in a mirror placed behind the electric bulb.

Now the commercially procurable small parabolic reflectors suffer from two grave defects, first, the uncertainty of their actual shape*, and, secondly, their tendency to tarnish and so to lose rapidly in reflective power in use. A much better reflector for signalling purposes and more aplanatic too, is afforded by the Mangin mirror or lens mirror. Fig. 3 shows correctly to scale a principal section of the mirror used in the daylight signalling lamp designed by the writer. The theory of flashing in such a mirror can, as a matter of fact, be best dealt with in reference to what may be termed the focal caustic for the view point. All the possible directions in which the eye of a distant observer on the mirror axis can receive light from the mirror annulus form a system of lines all parallel to its axis. These directions can be traced optically through the lens mirror as shown in Fig. 3, and after reflection and refraction they determine in any principal plane the focal caustic surface corresponding to a beam of perfectly parallel light received on the mirror parallel to the axis. This focal caustic can be determined accurately for any given lens mirror by exact computation, and it has definite size, shape, and what may be termed colour thickness, because on *refraction* the ray directions are split up and the final

* Not so much, be it noted, the inaccuracy of their shape but the element of pure chance as to what the departures from parabolic shape are.

caustic has a red inside limit and a blue outside limit for visible light. It must not be forgotten that the central part of the mirror is obstructed by the bulb and, therefore, the only part of the focal caustic to be taken account of is that formed by ray directions incident on the useful mirror annulus, and this limitation will apply in all that follows.

In any well-designed mirror annulus the size of the focal caustic is very small

Fig. 3. Section of Aldis Signalling Mirror and its axial focal caustic, shown actual size.

in relation to the size of mirror. Unfortunately, if designed to produce minimum size, there is an inevitable tendency to increase colour thickness, which imposes a limit on what is wise in this direction. Still the fact remains that the focal caustic is small in relation to the mirror, and is also generally much smaller than the actual focal caustic afforded by any commercially obtainable parabolic reflector. It is,

however, not small in relation to any really useful electric bulb source for projecting a beam of reasonable angular size. The circle in Fig. 3 shows correctly to scale the diameter of the glass containing bulb for the electric source, not, however, in its focussed position but displaced towards the mirror. This makes plain what a comparatively small annulus is left unobstructed. The two black dots shown near the centre of the bulb indicate the actual outer diameters ($\cdot 033$ inch) and the relative location of the two incandescent coils.

The focal caustic for parallel axial rays after refraction at the front surface of the Mangin mirror is shown correctly to scale in Fig. 3, but displaced axially so as to bring it within the compass of the diagram. It will be noted how large this is in relation to the final axial focal caustic after passing through the Mangin mirror. This shows how greatly superior the Mangin mirror is for flashing small sources as compared with any simple spherical refracting or dioptric system.

What is meant by small sources is best conveyed by the section shown in Fig. 4 which shows the axial focal caustic (for red colour only) for the Aldis Daylight Signalling Lamp mirror annulus, enlarged eight times, and in the same figure a section of the two coils of the electric bulb standardized for this lamp. The section at the axial position is shown, not only correctly to scale, but also in the proper focal position (as will be shown later) for flashing the mirror to the best advantage over a predetermined angle, with a fairly abrupt occultation of the flash on the margins of the beam.

The whole caustic surface divides up into two parts, the outer part, which will be termed the "trumpet," because it is commonly shaped like the flared out end of a trumpet, and a short line forming a portion of the axis which corresponds to the intersections of ray directions coming from a succession of concentric zones of the mirror. This part will be termed the "axial part" of the focal caustic. The trumpet has colour thickness—the axial part is only coloured at its extreme ends and is in commercially obtainable Mangin mirrors of average quality an extremely good approximation to a mathematical straight line. Evidently the most obvious and easy way to insure a complete flash for axial view points is to surround this part of the focal caustic by a close spiral coil fully long enough to cover the coloured ends of this axial part of the caustic. If this is done it is at once evident that any ray direction traced from the observer's eye through the optical system ends up on the incandescent filament for every visible wave length.

The axial flash for such an axial coil is complete and quite devoid of colour, but before the angular limits within which complete flashing holds can be determined it is necessary to find out how the focal caustic for the view point alters and moves in relation to the source as the view point is moved off the axis. Now there is a point which may be termed the optical centre on the axis of the Mangin mirror, about the same distance in front of the focal caustic as the mirror is behind it, which is such that ray directions passing through it after reflection at the mirror return along themselves. If a fixed distant view point be taken, and if this optical centre be regarded as fixed, and the line joining the view point to the optical centre be termed the "axis of vision," then the ray directions all drawn from the view

point parallel to the axis of vision determine, after being traced through the Mangin mirror, a focal caustic which, as a matter of fact, is remarkably constant in shape, size, position, and colour thickness as the Mangin mirror is rotated through any *small* angle about the fixed optical centre. The chief deformations, of course, occur at the larger end of the trumpet, but they are not important.

It should be noted that this is a property of the Mangin mirror annulus not

Fig. 4. Axial focal caustic of Aldis Signalling Mirror, shown magnified 8 times.

shared by other less truly aplanatic optical devices such as a parabolic reflector whose focal caustic is a point for the axis, but something very far removed from a point the moment the axis is departed from. It is, of course, only roughly true of the Mangin mirror but quite a good rough first approximation when such comparatively small angles are dealt with as actually occur in daylight signalling lamps. It follows from this property of the Mangin mirror that the effect of imperfect aim may be described as equivalent to swinging the incandescent source about the optical centre through a small angle equal to the angular error of aim in relation to a fixed and definitely shaped focal caustic, viz. the one computed for

parallel axial ray directions. The use of this focal caustic in conjunction with the computed optical centre for the mirror is now made apparent. To be any good the source should have dimensions comparable with those of the focal caustic and quite large in comparison with colour thickness; it must be situated so as to include as large a part of the focal caustic as possible; and when rotated about the optical centre it must continue to include a considerable portion of the focal caustic, and should preferably cease contact with the trumpet and all the cone of rays enveloping the same abruptly and simultaneously. Since small angles only are to be considered, the nature of the illumination produced off the axis of the lamp can be derived by considering how the source cuts the axial focal caustic when it is laterally displaced perpendicular to the axis a distance proportional to the angle of divergence under consideration. The two displaced coil positions corresponding to the extreme limits of the beam are shown in Fig. 4, and indicate an adjustment in which the angular size of the halo produced by the forward coil is the same as the outer angular size of the *annular* beam projected by the coil nearer the mirror.

The point to note is that the light patch projected has angular size as much due to the spherical aberration of the mirror as to the source having size. It has already been pointed out that the real problem presented by the electric signalling lamp is that when the filament coil is wound close enough to present the appearance of a continuous incandescent cylinder the size of the bulb prevents any reflecting optical annulus placed behind it being brought close enough to project a beam of useful angular width. Thus the designer is compelled to adopt a relatively large mirror annulus, and this means that spherical aberration plays an important part in determining the size and distribution of light in the projected beam.

Chromatic aberration also may play a fatally important part in reducing the equivalent intrinsic brightness of the flash, and it is very important to keep down colour thickness in the focal caustic to a mere fraction of the coil diameter if efficiency is to be attained. The way colour thickness goes up when spherical aberration (or the size of the trumpet) goes down is made clear by Fig. 5, which shows enlarged eight times actual size the axial focal caustic for the Aldis Daylight Signalling Lamp mirror, and that for a mirror of similar size but designed to give minimum spherical aberration *for the useful annulus only*. It will be noted that the trumpet is folded back upon itself. The colour thickness in both cases is indicated by shading. The section of the incandescent coils as used in the Aldis Lamp, shown correctly to scale on the left, makes it at once evident that the focal concentration has been carried too far for such a source, considering the colour thickness introduced.

To consider specific cases in more detail, the axial coil method of obtaining a complete flash from a mirror annulus when considered in the light of the foregoing shows that only a comparatively narrow beam can be afforded by such means, though this will be greatly improved if the diameter of the coil be made more than large enough to bridge the gap between the axial part of the caustic and the small end of the trumpet. For wide beams, however, and especially for transmitting beams affording a rectangular or oval light patch it is best to use coils placed at right angles

to the axis of the mirror. If one coil be placed with its axis in the plane of the circle of least confusion of the focal caustic it will project a good rectangular-shaped light patch showing fairly even illumination and surrounded by no halo, because the coil ceases contact with the focal caustic and the extreme cone of light rays enveloping the caustic simultaneously. If this coil is moved away from the mirror the bright portion of the light patch contracts and a large and weak halo surrounding it is

Fig. 5. Axial focal caustics of different 4 inch diameter Mangin Mirrors, shown magnified 8 times.

seen rapidly growing in size. As it is moved inwards towards the mirror the light patch grows rapidly in size, its edges become brighter and fringed with colour, and ultimately it shows a dark centre. All these effects can be deduced by a careful consideration of the focal caustic, noting how in the various axial positions the coil approaches and leaves the caustic surface as it is moved laterally across the system of rays, and not forgetting the effect of colour thickness.

The adjustment aimed at in the Aldis Daylight Signalling Lamp was to use two coils, the one nearer the mirror located so as to project a light patch having a dark rectangular centre with a bright ring surrounding it, the other located so as

to project a light patch having a bright rectangular centre *coinciding with the dark centre of the former beam* surrounded by a halo of *just the same size* as the outer ring in the former beam. Obviously this means a very nice adjustment, but the interesting point to note is that, given the focal caustic and the optical centre, the size and disposition of the two coils can be laid down on paper to fulfil this condition, and the angular limits of the beam predicted with tolerable accuracy.

Fig. 4 shows in addition to the axial position of the incandescent coils the

Fig. 6. Focal caustics of 4 inch diameter Mangin Mirror, shown magnified 32 times.

position displaced off the axis by an amount which corresponds to the extreme limits of the projected beam on the assumption, however, that the focal caustic remains unchanged for such comparatively large departures from the axial view point. Making this assumption, it would be asserted that, provided only the light passing forwards from the naked source were cut off by a shield placed in front of it, Fig. 4 would determine the theoretical angular limit outside which no light would be received by any observer.

As a matter of fact, there are two very important practical reasons causing light to be projected outside the margins of the beam, both attributable to the glass containing bulb surrounding the source. This is approximately spherical in shape and is generally of variable thickness, being thinnest at the drawn off pip end. This has two effects; the first by reflection causes an inverted image to occur generally near to, but unfortunately seldom in, the plane of the coils forming the original source. In the second place the computed focal caustic for any lens mirror differs from the one actually effective in practical use owing to deformations introduced by refractive effects in passing through the containing bulb. The former defects result in the projection of a separate "ghost" beam which militates against secrecy, and the latter defect spoils the shape and evenness of the beam and throws out an irregular halo surrounding the light patch.

The effects of ghost images of the source due to reflections at the front or refracting surface of the Mangin mirror can, to a very large extent be obviated by placing an annular stop at a suitable distance in front of the source, and it has been found in practice that the really serious sources of lack of secrecy have been due to the two above-mentioned causes, both attributable to the glass containing bulb. It has already been pointed out that, provided a certain amount of colour thickness in the focal caustic can be tolerated, the spherical aberration can be reduced to a remarkable extent and in this case the part of the focal caustic that has been termed the trumpet is so to speak folded back upon itself. Fig. 6 shows, enlarged 32 times, the axial focal caustic and the rays enveloping it for a mirror annulus carefully designed to afford large angular aperture with minimum spherical aberration. This mirror annulus has practically the same clear aperture as the mirror shown correctly to size in Fig. 3 and hence this caustic is shown at four times the enlargement used for Figs. 4 and 5. The specification for this mirror annulus is

Radius of first refracting surface	...	...	...	...	2 $\frac{1}{2}$ "
" " second reflecting surface	...	...	...	...	3 $\frac{1}{4}$ "
Thickness at centre	...	...	...	...	1 $\frac{1}{2}$ "
Clear aperture of front surface	...	...	...	...	4"
Diameter of central part cut out by the glass containing bulb	...	...	...	...	2"
Refractive index of glass for red ray	...	...	...	...	1.533
" " " blue ray	...	...	...	...	1.544

The six pairs of rays actually drawn correspond to ray directions intersecting a plane containing the extreme front edge of the mirror at successive $\frac{1}{4}$ " intervals measured from the axis and starting at $\frac{3}{4}$ " distance from the axis, which includes slightly more than the useful annulus. The shaded contour indicates the colour thickness of the focal caustic which is dangerously large for such a small source as was standardised for the Aldis Daylight Signalling Lamp. In addition, of course, this focal caustic indicates that the angle afforded in the beam by this source used in conjunction with this mirror would not be large enough.

An interesting point in connection with Fig. 5 is that the second non-axial focal caustic (shown by a chain-dotted line) corresponds to accurately computed ray directions after passing through the mirror annulus initially incident upon

it from a distant view point $\frac{3}{4}$ of a degree off the axis. It will be seen that they determine a focal caustic very similar in shape and size to the axial focal caustic, though displaced from it by an amount considerably greater than its circle of least confusion. The colour thickness of this displaced caustic is not shown for the sake of clearness.

Considering the labour of computing these non-axial caustics, it is evident that for small angles the displaced axial caustic may be taken as a very good guide as to where the ray directions come for a non-axial view point. Thus a study of the complete axial caustic in relation to the optical centre of the mirror affords a very good means of judging the best type of source to employ and the best focal position for the projection of a beam of given intensity free from colour within predetermined small angular limits.

DISCUSSION

Professor Cheshire said that when he was at the Ministry of Munitions he was particularly struck by the way in which Messrs Aldis Bros. had tackled a number of pressing difficulties during the war, and he was sure that peace problems would be dealt with by them in an equally efficient manner. He thought that the lecture set out very clearly an interesting optical problem and its solution. The ray diagrams which Mr Aldis had exhibited would prove to be of great use to future designers.

Major Henrici testified that in the Lucas modification of the Aldis lamp the bulb is automatically fixed in its correct position, and that the direction of the beam of light did agree with the sight.

Mr R. S. Whipple said that it was evident from the lecture what a large amount of experimental work had been necessary to evolve what appeared to be a simple optical instrument. He would like to know whether electric light bulbs similar to those Mr Aldis had used in his signalling lamps would be available for general experimental purposes, such as galvanometer work. He asked if Mr Aldis knew whether the inert gas in the bulbs was under pressure.

The author, in reply, said he was of the opinion that the "focus" bulbs (as he called them) had a distinct future before them. He thought that Messrs Siemens must have a large number of bulbs for disposal.

The bulbs were filled with nitrogen (or, preferably, argon) at ordinary pressures. They were 14 volt bulbs which consumed $\cdot 4$ watt per candle, and had a total candle power of about 110 candles.