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Zoom Lenses

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M.Sc., D.I.C.
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WITH A PREFACE BY

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Preface

by

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This book on zoom lenses by Mr Clark is the seventh in the Hilger series of monographs based on a selection of the project reports written by students at Imperial College as part of the work for their M.Sc. degree in Applied Optics. In my judgement this latest monograph is well up to the standard of its predecessors and in view of the dramatic extension of the use of zoom lenses in television, in motion picture photography, in amateur photography, and in microscopy, it should be of interest to a very wide audience indeed.

Some of these monographs have had their critics, so that it may be useful to explain how they have come to be written and why I for one was prepared to encourage Hilger's to publish them. In the first place, they are not just a printed version of the authors' M.Sc. report. This needs to be said because the reviewer of one of the monographs even wondered whether the student was aware that his report had been published. Once the student has chosen the subject of his M.Sc. report, he embarks on an extensive study of the literature in that branch of optics and sometimes undertakes some experimental work as well. He then writes his report, giving a survey of the development of the subject and the present state of the art as he sees it.

Subsequent to obtaining his M.Sc. degree the student usually takes up employment in the optical industry, in Mr Clark's case in a firm renowned for very many years for the manufacture of an extensive range of photographic lenses. If a student's report is chosen for publication, it is then expanded and re-written, new material is added in the light of the author's widening experience, and the author finally hands over the text to the publisher some years after obtaining his M.Sc. degree (nearly four years has elapsed since Mr Clark obtained his M.Sc.).

Nevertheless, the monographs are still the work of young men and, while this necessarily means that they cannot carry the authority of a text-book written by an expert who has worked in the field for many years, they do have a freshness of outlook and a lack of bias which has a value of its own.

They are also of a modest length, so that they are likely to be read right through rather than be put on a shelf for future reading in those leisure moments that never seem to come.

Mr Clark has made it clear in his own preface that his book is not intended for the experienced designer of zoom lenses. Yet for someone like myself, who once had visions of becoming a lens designer but whose interests became diverted to quite a different branch of optics, it has provided a most useful survey of the history of zoom lenses and an easy introduction to the very sophisticated types of lens that are now being designed. I have studied it with much enjoyment and I am sure many readers will share the same experience.

Author's Preface

As a lens designer whose practical experience is limited to special fixed-focus lenses, I sometimes envy those fortunates who can claim their occupation to be the design of zoom lenses. I explain to casual inquirers that there is a great demand and need for specially designed lenses to give improved performance, only to be cut short normally with the exclamation, 'I thought lenses were designed years ago', as if no problems existed and I must surely be wasting my time.

However this is merely to illustrate that there is a lively interest in zoom lenses, and it is perhaps the widespread association with their use on television that is responsible. As a result I have endeavoured to write this monograph for the benefit of anyone who has an interest in basic optics and in particular the zoom lens. I have assumed that the reader has little depth of optical knowledge and have developed all the mathematical expressions from simple optical formulae.

In common with most areas of interest associated with lenses, there has been very little published material on zoom lenses, and in order to provide a broader foundation for this book I obtained additional information from some of the manufacturers of zoom lenses. As a result, there is a bias in the text towards illustration with example lenses of companies who were kind enough to supply suitable material.

Naturally most of the material used in this monograph is based on the work and reporting of others and I hope that I have made adequate acknowledgment to all concerned.

I should like to express my thanks to Prof. C. G. Wynne, Dr M. Kidger and D. Freeman of the Imperial College Applied Optics Group, London, for their help and guidance with my M.Sc. thesis on zoom lenses which led to my involvement with this monograph, and in addition to the other directors and colleagues at J. H. Dallmeyer Ltd, who have helped in different ways with the preparation of this publication. Finally I should like to thank my wife, Barbara, for the encouragment given and assistance in the final preparation of the manuscript.

LONDON
April, 1973

ALAN D. CLARK

Contents

1

Introduction

A zoom lens is an image-forming optical system with such properties that an axial movement of certain components will produce a change in the equivalent focal length of the system, while keeping the resultant image fixed with respect to the desired image plane. The word *zoom* is descriptive of the effect produced by the lens as the focal length changes. The image appears to *zoom* nearer or further away as it changes in size owing to the magnification variation with focal length. The ratio of the maximum focal length to the minimum is called the *zoom* ratio, while the *zoom range* refers to the range of focal lengths available.

Basically a zoom lens may be thought to consist of three main units: a front focusing unit, a zoom unit and a fixed rear unit. The focusing unit operates as its name indicates, and in most zoom lenses, as discussed in Chapter 6, has no other function. The zoom unit provides the variable focal length facility by axially moving groups of lenses which in the following text are called *zoom elements*. For example, a zoom unit may consist of two independently moved zoom elements, each element consisting of a group of lens components. The rear unit is a special fixed focus lens that is designed to reduce the aberrations of the other two units.

The zoom lens has found extensive applications, as discussed in Chapter 7, but these lenses are generally used at the expense of image quality. As Chapter 5 illustrates, there are many additional problems associated with the design of zoom lenses compared with the design of fixed focus lenses and it is difficult, if not impossible, to produce a zoom lens of comparable performance at all zoom positions to that provided by a series of fixed focus lenses. However it is clear that the zoom lenses currently produced provide an image quality amply adequate for the systems with which they are used, and it would appear that the ability to zoom more than compensates for the small loss of performance and large increase in cost.

2

Zoom Lenses for over a Hundred Years

Historically, it is more interesting to look not just at the first zoom lens, but rather at the progress made in optics that has led to these optical units of variable focal length. Zoom lenses have greatly improved over the years, and at a faster rate currently with the aid of computers than perhaps in the past. Thus it cannot be a surprise to find that the early zoom lenses had a poor performance and were difficult if not impossible to operate in certain circumstances.

1834–1902

Peter Barlow recorded in the *Proceedings of the Royal Society*,[1] 1834, that there were advantages in employing his negative lens in 'day telescopes' as well as in astronomical telescopes; 'for by giving an adjustment to the lengthening lens, the power may be changed in any proportion, without even removing the eye or losing sight of the object. I have no doubt these and other applications of the lengthening lens will be made.' In these last few words Barlow foreshadowed the development of the zoom lens, as well as many other important optical systems.

The next development was the telephoto lens. Today this type of lens has the specific association with a long focus lens with a back focus relatively short compared with the focal length. However this certainly was not the only interpretation or even the prime one in 1899, for T. R. Dallmeyer in his book *Telephotography*[2] clearly defined the telephoto lens in either of two ways,

(*a*) as a complete positive system of variable focal length, and therefore capable of producing images of different size of a given object at any definite distance from it, or

(*b*) as consisting of two separate parts, a positive lens of definite focal length, whose function is to form a real image of definite size at a definite distance from the object, combined with a negative lens of definite focal length, whose function is to magnify the image given by the positive lens in variable degree.

He clearly made the point that, to him at least, the variable nature of the telephoto lens was of prime importance. The application for patents covering the telephoto lens in the autumn of 1891, by A. Duboscq in France on 7 August, Dr A. Miethe in Germany on 18 October and T. R. Dallmeyer in England on 2 October, dates this stage in the development of the variable focus lens.

There appears to be little reference to the actual use of this variable focal length facility offered by the telephoto lens. This could be attributed to the complexity of its use. Unlike Barlow's telescope, a visual instrument, the telephoto lens was intended for the photographic camera, and the photographic plate cannot reproduce the focusing agility of the eye. Thus not only was a rack and pinion mechanism needed to vary the separation between the positive and negative components, but a bellows extension was essential to compensate for the varying image distance.

In 1902, C. C. Allen[3] took out an American patent on a very different form of variable-focus lens. Fig. 1 illustrates the lens system consisting of three positive components. The outer components remain stationary while the inner component can be displaced axially between them. Unlike the telephoto lens, the image distance is identical for two positions of the centre component, and the defect of focus at intermediate points follows a parabolic law. However, with a restricted aperture it was possible to tolerate the defect of focus over a narrow range of focal lengths, thus allowing the distance from lens to image to be left constant.

It is important to note the basic difference between the telephoto lens and the Allen lens as variable focus lenses, for they represent the two classes of zoom lens that are still in general use today. The telephoto lens is an example of the mechanically compensated zoom lens. This type of lens relies on the use of cams, normally with non-linear related movements, to move the lens components and maintain the image in focus at some fixed plane. The Allen lens is an early example of the optically compensated zoom lens. This type of lens may have one or several moving components, but in each case only one controlling movement is required. Where more than one lens is axially shifted, a direct constant linkage connects the lenses together. The image plane oscillates in the vicinity of a fixed plane over the zoom range, and the shift of focus is normally taken to be small enough to ignore.

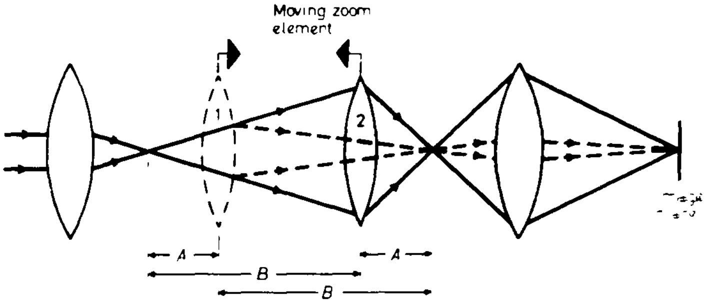


FIG. 1. Allen zoom lens. The image is formed on the same plane only when the zoom element is in position 1 or position 2.

1920–1930

It is not surprising that little recorded development of the variable focus lens took place between 1902 and the 1920s, for there really were very few, if any, applications that justified the loss of optical performance in order to obtain a variable focal length lens that was difficult to use.

Kingslake[4] refers to the need for a zoom lens felt by the motion-picture industry during the 1920s. Several designers suggested the use of a reversed telephoto lens. A large negative lens was set up at a distance in front of a camera, and the camera was focused on the virtual erect image formed by the negative component. A magnification change was achieved by moving the negative lens towards the camera, whilst continuously refocusing the camera lens to maintain focus. Another design used a positive lens set at unit magnification conjugates, with a negative component providing a virtual image at the object plane of the positive lens. The magnification change of the image was achieved by moving the positive lens in a linear fashion while causing the negative component to follow a *U*-shaped curve to maintain focus. Neither of these zoom systems became popular, as they gave poor definition at low relative apertures and were clumsy and difficult to use.

1932–1937

A paper presented in 1932 by A. Warmisham and R. F. Mitchell[6] provides proof of the serious desire to develop a successful and usable zoom lens. They described a lens which was based on the mechanically compensated inverted telephoto lens, and introduced the idea of a variable three-element system, with each movement linked by cams and operated by one control. The lens was called the Bell and Howell Cooke Varo Lens, and provided a range of focal lengths related to different stop settings. The mechanics were arranged so that the above relationships could not be upset, and thus, for example, it was impossible to use the lens at 120 mm focus and at *f* 3·5. Indeed as the paper states, 'The lens is fool-proof in this respect.' Clearly there were problems in maintaining aberration correction over the focal range.

TABLE 1

Aperture	*Focal range in mm*
f 3·5	40 to 50
f 4·5	40 to 85
f 5·6	40 to 120
f 8	40 to 120

Other new zoom lenses of this period were due to Durholz[6] and Gramatzki[7] with the Astro Transfokator. This latter lens was an afocal zoom attachment for use in front of the standard motion-picture cameras. In fact the designer, Gramatzki[7, 8] described two afocal systems in 1935. Both systems were of the optically compensated type and based on the Allen lens. In one design, a positive lens was moved between two outer negative components; in the other, a negative lens was moved between two positive outer components. As with the Allen lens, the operating range of the magnifications was very small.

In 1937, R. Richter[9] of Carl Zeiss patented a microscope-illuminating device, using the basic principle that later became the basis of the Zoomar lenses designed by F. G. Back. In this unit, as in the ones just described, three components were used; in Richter's device, however, the two outer lenses were moved while maintaining the centre component stationary with respect to the light source. In optical design, this unit was so poor that its application to an imaging device was apparently not considered feasible by the inventor.

The Busch Vario-Glaukar lens[10] was a notable zoom projection lens of this period. Indeed, zoom projection lenses were apparently a popular innovation. Baynham Honri[11] recalls the use of zoom projection lenses in a few super cinemas for the climax sequences of spectacular silent films.

> 'When, for instance, the earthquake or fire climax sequence commenced, a separate large screen was lowered in front of the usual screen and a Magnascope projection lens slowly adjusted to present a picture which gradually increased to double the normal area. Aided by heavy dramatic musical accompaninment (from a large orchestra) and sound effects (garden rollers hauled across the stage) the cumulative effect was dynamic. Large audiences packed the Stoll picture theatre, Kingsway, and the Regal, Marble Arch, both of which were able to provide additional impact on their mighty Wurlitzer and Jardine organs respectively. (The fact that the Jardine's keyboard was usually slightly in advance of its beautiful religious tones called for presynchronized precision by the organist!).'

The design of zoom lenses was not the only problem of the period.

Other problems occupied the optical designer's time over the next few years; for it was not until after World War II that a record of further development of zoom lenses is found.

1945–1950

The optically compensated zoom lenses were the subject of development by Zoomar Incorporated, USA, and SOM-Berthiot, France. F. G. Back of the former company, designed first a positive vari-focal viewfinder[12] for motion-picture cameras in 1945 and a zoom lens for motion-picture cameras in 1946.[13] The viewfinder was based on a three-positive-component system, with the outside components stationary and the inner component axially variable, plus a fixed rear eyepiece unit to complete the configuration. The zoom lens for motion-picture cameras consisted of five positive-component groups, the second and fourth being linked together and the only lens groups to move. Again, a fixed rear unit completed the configuration. This Zoomar lens contained twenty-two optical elements arranged in positive optical groups, and suffered from a severely curved image plane owing to an inability to correct for the Petzval sum (see Appendix B). Table 2 lists some early Zoomar lenses and illustrates the different fields of interest in zoom lenses and their gradual progress.

TABLE 2

Name	*Year*	*Zoom range*
Zoomar A	1946	3:1
Television Zoomar	1947	4:1
Newsreel Zoomar	1947	4:1
Super Zoomar	1949	5:1

The Super Zoomar lens, although of larger zoom range than the others, had a basically smaller defocus defect, but this was achieved by adding another moving lens group to the previous two; the extra components prevented the achievement of satisfactory aberration control and the lens never progressed beyond the prototype stage.

However, 1949 did see the development of the Pan-Cinor 16 zoom lens, manufactured by SOM-Berthiot and designed by R. H. R. Cuvillier.[14] This lens comprised two positive outer lenses, linked together and moved axially about a fixed negative lens. The zoom lens proved to be far superior in performance to the Zoomar lenses because of its ability to provide better aberration correction with the negative component, including the reduction of the Petzval sum.

In the period 1945–1950 the mechanically compensated zoom lenses progressed, notably through H. Hopkins[15] who designed a zoom lens, manufactured by W. Watsons and Sons Ltd, for the television image orthicon cameras. The forms of lenses developed at this stage were to become the fundamental basis of zoom lenses for many years and these are discussed in greater detail in chapter four.

1950–1972

A notable advance in the optically compensated zoom lens was made in 1953 by L. Reymond.[16] He reversed the powers of the Pan-Cinor lens, giving a system consisting of two negative lenses moving around a stationary positive element and added a further stationary positive element to the front of the unit. This four-lens zoom unit reduced the oscillations of the image plane and gave four points of correct focus through the zoom range. This type of zoom lens is discussed in chapter five.

The development of zoom lenses expanded rapidly and by 1956 a number of inexpensive 8 mm camera zoom lenses were produced. In 1958 several lenses appeared for the 35 mm still camera and in 1960 the first range of amateur zoom projection lenses were available. The lenses in these different areas of optics have continued to be developed and some recent patents are listed in Table 3. The gradual increase in focal range and aperture is most impressive when compared with the early lenses of 2:1 focal range and *f* 8 aperture.

It is important to remember that the use of computer optimization programmes in the late 1950s for optical design, had a great impact on the ability of the designer to cope with the large number of parameters of the lens under his control during design. This was applicable not only to fixed-focus lenses, but even more so to the complex twenty-element zoom lens. Thus, the last ten years have seen enormous strides in the development of zoom lenses. G. H. Cook and F. R. Laurent[17] in 1971 commented on the radical changes in the utilization of zoom lenses over the previous twenty years, and suggested that zoom lenses had improved to the point where they were used as a prime tool in broadcast television and more particularly in the television studios. This had resulted in new techniques of operation and viewer presentation evolving. Their comment that the motion-picture industry was following similar trends is indicative of the early lack of enthusiasm shown by this industry for zoom lenses after the very early experiences of the 1920s and 1930s. The

TABLE 3 A SELECTION OF ZOOM LENS PATENTS

Type	*Patent Number*	*Year*	*Inventor*	*Focal Range*	*Aperture*
Mechanically Compensated					
1	3 143 590	1964	T. Higuchi	2–1	
1	3 059 535	1962	Cox, Johnson	2·5–1	f/1·9
1	3 059 536	1962	Cox, Johnson	3·25–1	f/1·8
1	3 170 984	1965	Rosenberger, Korones	12–1	
1	3 027 805	1962	K. Yamaji	4–1	f/1·4
1	3 030 861	1962	Mortimer, Seidenberg		
1	3 030 863	1962	Schwartz, Ziegler	3–1	
1	3 220 307	1965	Thurow	4–1	f/2
1	3 044 355	1962	Cox, Johnson	4–1	f/1·8
2	2 847 907	1958	Angenieux	4–1	f/2·5
3	1 064 323	1963	Cook	10–1	
3	3 044 356	1962	Cox, Johnson	2–1	f/1·9
3	3 074 318	1963	Yamaji	4–1	f/2·8
3	3 393 958	1968	Takano	12–1	f/1·8
3	3 160 699	1964	Yamaji	4–1	f/1·8
3	3 267 803	1966	Marcher, Klemt	5–1	f/1·8
5	3 192 829	1965	Yamaji	6·5–1	f/4
Optically Compensated					
three-lens	3 063 341	1962	J. Beck	2·1–1	f/6·3
three-lens	3 094 581	1963	F. Back	1·7–1	
three-lens	3 307 898	1967	Hudson	3–1	f/1·0
four-lens	750 550	1954	Reymond	4–1	f/2

pattern now recognizable in television studios is related to the present state of the optical art, and it becomes apparent that many of the types of zoom lenses in current use may well have revealed the limits of modification and improvement. Cook and Laurent continue by describing a new family of zoom lenses, and further reference to these is made in chapters three and seven.

The interest shown in zoom lenses today and the importance attached to them, cannot be better demonstrated than by the fact that Rank Taylor Hobson estimate one hundred thousand pounds to have been invested in research to produce the Varotal 30 television zoom lens, the first of the above family. With television zoom lenses costing between four and five thousand pounds, and a world-wide market to supply at an estimated turnover of three million pounds a year, zoom lenses have come a long way in over a hundred years.

3

Mechanically Compensated Zoom Lenses

There are several methods used in mechanically compensated zoom lenses to achieve the variation of focal length. Five basic types of zoom units are considered here and all have been used in commercial zoom lenses in one form or another since 1950.

The description 'mechanically compensated lens' applies to all the types of zoom lenses that have two or more zoom elements that move independently of each other, forming the zoom unit of the lens as defined in the introduction.

3.1. CALCULATION OF ZOOM ELEMENT MOVEMENTS

Before looking back at the different types of zoom units it is interesting to describe one form of the calculations used to evaluate the zoom element movements. Specifically, the zoom unit consisting of two moving elements is considered; for the majority of mechanically compensated zoom lenses are of this type.

Let Fig. 2 represent a general two-component zoom unit, with the zoom elements in their mid-zoom positions. Small letters indicate the mid-zoom values, and capital letters the values at some other general zoom position. Thin-lens theory is used to investigate the zooming properties and the sign convention used is explained in Appendix A.

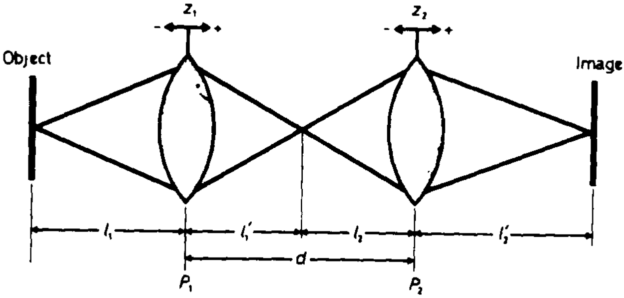


FIG. 2. Two-component zoom unit.
The zoom elements are in midzoom positions

For the first lens:

$$\frac{1}{l_1'}-\frac{1}{l_1} = P_1$$

where P_1 is the power of the lens and equal to the inverse of the focal length of the lens.

This becomes:

$$l_1' = \frac{l_1}{1+P_1 l_1} \tag{3.1}$$

Likewise for the second lens:

$$l_2' = \frac{l_2}{1+P_2 l_2} \tag{3.2}$$

But

$$l_2 = l_1' - d \tag{3.3}$$

therefore using equations (3.3) and (3.1) in (3.2):

$$l_2' = \frac{\dfrac{l_1}{1+P_1 l_1} - d}{1+P_2\left[\dfrac{l_1}{1+P_1 l_1} - d\right]} \tag{3.4}$$

Rearrangement gives:

$$l_2' = \frac{1 - \frac{d}{l_1} - dP_1}{\frac{1}{l_1} + P_1 + P_2 - dP_1P_2 - \frac{dP_2}{l_1}}$$

and as the power of the combined system P is given by

$$P = P_1 + P_2 - dP_1P_2 \qquad (3.5)$$

the above simplifies to:

$$l_2' = \frac{1 - \frac{d}{l_1} - dP_1}{P + \frac{[1 - dP_2]}{l_1}} \qquad (3.6)$$

As the two components move, the following conditions must hold:

$$Z_2 - Z_1 = D - d \qquad (3.7)$$

and

$$-L_1 + L_2' + D = K \qquad (3.8)$$

where

$$K = -l_1 + l_2' + d$$

and is the object to image distance.

Equation (3.8) specifies that the final image plane remains fixed. By using equations (3.5), (3.6), (3.7) and (3.8) the movements of the zoom elements can be calculated, given the mid-zoom, or any other starting position, and the selected values of P, the power of the complete system.

Equation (3.5) gives:

$$D = \frac{P_1 + P_2 - P}{P_1P_2} \qquad (3.9)$$

and by combining equations (3.6) and (3.8):

$$L_1^2a + L_1b + c = 0$$

where

$$a = -P$$

$$b = D[P_2 - P_1 + P] - KP$$

and

$$c = KP_2D - K - P_2D^2$$

D is calculated by using equation (3.9), and the above values of a, b and c can then be evaluated.

So

$$L_1 = \frac{-b \pm [b^2 - 4ac]^{\frac{1}{2}}}{2a} \tag{3.10}$$

As $L_1 = Z_1 + l_1$, Z_1 the motion of the first zoom element may be evaluated, and using equation (3.7) Z_2 the motion of the second zoom element may also be found.

Usually only one of the two solutions for L_1 in equation (3.10) is sensible. A notable exception to this rule is the type three zoom unit described later in the chapter, and the above equation will be used to illustrate the form of solution obtained. The above equations are applicable to the first three types of zoom units to be described.

3.2. FIVE TYPES OF MECHANICALLY COMPENSATED ZOOM UNITS

Zoom units with the same number of zoom elements, with powers of identical sign, and arranged in the same order, will belong to the same *type* of zoom unit. It is possible in practice that, within a particular type, the movement of the zoom elements may differ fundamentally from one lens to the next, but this particular property will be discussed for each type of zoom unit. For simplicity, the zoom elements have been shown as single-lens components in the diagrams illustrating the form of movements applied to them. Where possible, a realistic arrangement of the lens components is shown.

Mechanically compensated zoom type one

A simple type of zoom unit is illustrated in thin-lens form in Fig. 3. The front component is of positive power, the second of negative power, and they both move to achieve the variation of focal length.

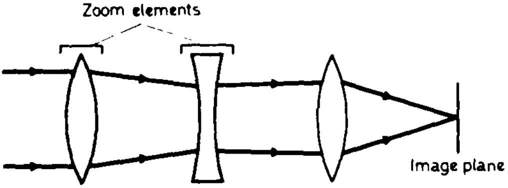


FIG. 3. Mechanically compensated zoom Type 1.

It is usually found that the movement of the middle component is linear, and that the front component has to be driven by some form of cam to hold the image in focus. An afocal zoom telescope is given as an example by Kingslake[4] and a typical form for the zoom movements is shown in Fig. 4.

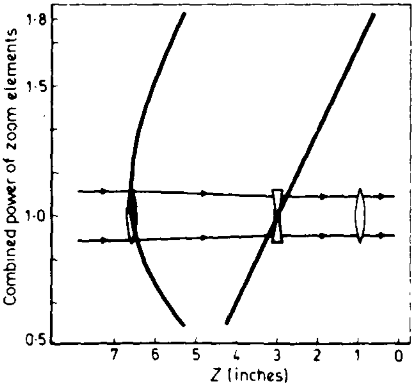


FIG. 4. Zoom-element movements for Type 1 zoom units.

A design using this type of zoom unit was patented by A. Cox and W. Johnson[18] in 1962. The lens has a zoom ratio of 4:1, and for this particular example, a focal length range of 0·32 in. to 1·28 in. Surprisingly the recommended full aperture was *f*/1·8, which seems rather large for this type of lens. Another peculiarity is that the lens is focused by moving the front zoom element and, as explained in Chapter 6, this will destroy the ability to hold a fixed image plane over the zoom range. Really, this lens can operate correctly for only the one preselected object distance for which the lens is designed. Fig. 5 shows the zoom motion of the two zoom elements and in this example the second zoom element group has a non-linear movement. The movements of the zoom elements are shown by curves z_1 and z_2 and represent the variation of axial position either side of the mid-zoom positions. Fig. 6 illustrates the construction of this lens in more detail.

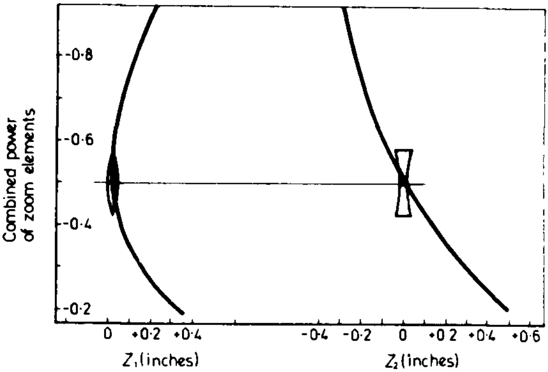


FIG. 5. Zoom-element movements for A. Cox and W. Johnson Type 1 zoom unit.

Mechanically compensated zoom type two

Angenieux, a French optical company named after the designer, were the originators of this type of zoom lens and have used it extensively. The system is illustrated in Fig. 7 and consists of a front section, stationary during zooming but moved for focusing, a zoom section consisting of a negative lens group and a positive lens group, together with a fixed rear unit.

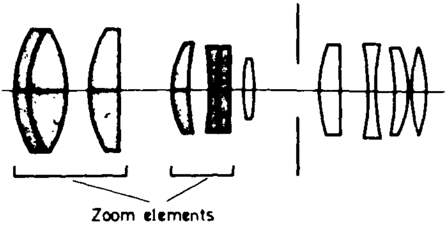


Fig. 6. Type 1 mechanically compensated zoom lens as designed by A. Cox and W. Johnson.

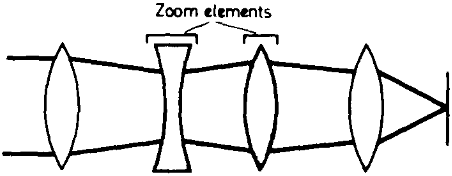


Fig. 7. Mechanically compensated Type 2 lens.

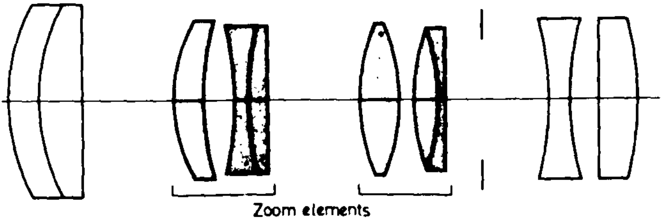


Fig. 8. Angenieux zoom lens Type 2.

An analysis of the mode of operation of this type of lens is given by P. Angenieux[19] in a 1958 patent. Fig. 8 shows one form of the lens comprising of ten components, and Fig. 9 demonstrates the zoom movements for this lens. The zoom ratio of 4:1 is operated over a focal length range of 0·8 in. to 3·2 in. and the lens was designed at an *f*/2·5 aperture. Angenieux suggested that in the initial study and design of a lens of this type, the movement of the positive zoom element could be considered fixed, thus leaving the negative lens moving between two positive lenses. It will be clear in Chapter 4 that this arrangement is a fundamental form of the optically compensated zoom lens. However, Angenieux was only concerned in easing the calculations needed to design the lens, and pointed out that the negative zoom element moved to produce the change in focal length while the positive zoom element moved over small

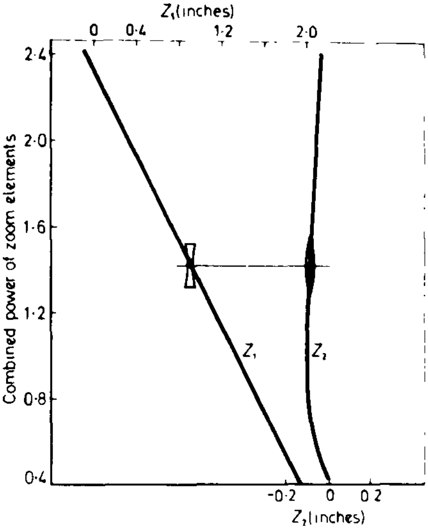


FIG. 9. Zoom-element movements for Angenieux lens.

distances to maintain a fixed image plane. It is therefore not surprising to find that the negative zoom element has a linear movement while the positive zoom element operates on a cam over a small distance for the complete zoom range.

A feature of the lens illustrated in Fig. 8 is that the rear section consists of only two components; it suggests that the aberrations of the zoom unit must have been very well corrected. It is certainly one of the more simple rear lens groups encountered in the various types of zoom lenses considered. Fig. 10 shows a second form of Angenieux zoom lens described in the 1958 patent, that really belongs to the next zoom lens, type three.

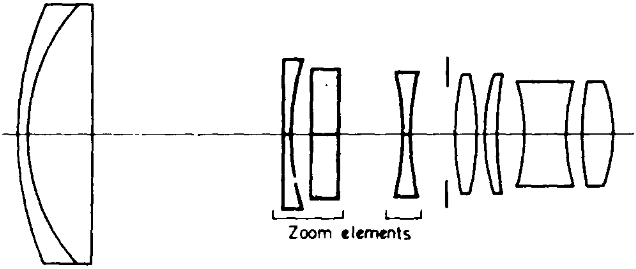


FIG. 10. A second form of Angenieux zoom lens.

Mechanically compensated zoom type three

This type of zoom unit comprises of two negative zoom elements, and the basic form of the lens is shown in Fig. 11. There are two systems within this type that are basically different in design.

The first form, is in principal, similar to the Angenieux lens just described as zoom type two. K. Yamaji[20] of the Canon Camera Co., Japan, first made use of this system in 1962, and as for the type two lenses, the front negative zoom element controls the focal length change, while the rear negative lens element keeps the image in focus. Fig. 12 illustrates the arrangement of the elements used in this ten-component zoom lens and Fig. 13 demonstrates the zoom movements used over the 4:1 zoom ratio. This lens provides a focal length range of 0·4 in. to 1·6 in. with a maximum aperture of *f*/2. The first negative zoom element follows a near linear relationship while the rear negative zoom element works on a cam.

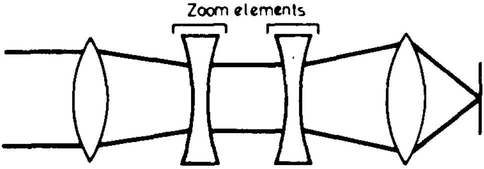


FIG. 11. Mechanically compensated Type 3 lens.

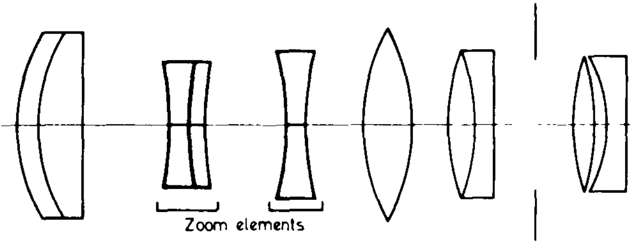


FIG. 12. Yamaji zoom lens Type 3.

In comparison with the Angenieux type two zoom lens, the ten optical components of the Yamaji design are used in a completely different way. Both designs have a doublet lens at the front of the zoom, but while Angenieux uses six moving lenses in the type two lens, Yamaji uses only three. This leaves in the latter case, five components forming the rear fixed section and suggests that the negative zoom unit has stabilized aberrations, but at higher levels throughout the zoom range, these stabilized aberrations being reduced to an acceptable level by the rear optics.

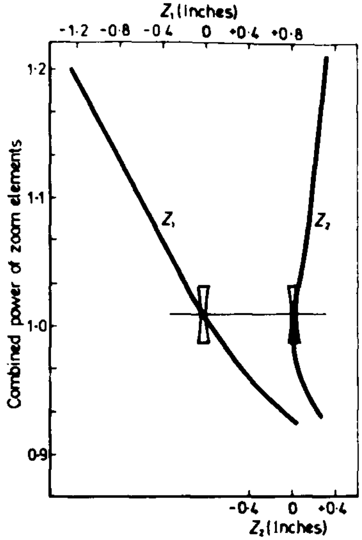


FIG. 13. Zoom-element movements for Yamaji lens.

The second form of this lens type was invented by H. H. Hopkins[21] in 1951. The system is basically symmetrical and both the negative zoom elements of the zoom unit play an equal part in the variation of focal length and in maintaining the fixed image plane. Fig. 14 illustrates an example of the form of zoom lens produced by this approach, and Fig. 15 shows the movement of the zoom elements. It was seen when considering the calculation of the movement of the zoom elements, that in general there were two solutions to the value of L_1 in the equation (3.10) and generally only one solution is sensible. A discontinuity occurs when the specified object to image distance K, which must remain fixed, equals the minimum distance for the image to stay in focus. At this point:

$$K = \frac{4}{P}$$

and the two zoom elements are working at unit magnification.

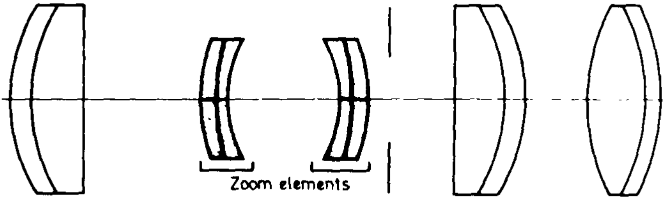


FIG. 14. Hopkins zoom lens Type 3.

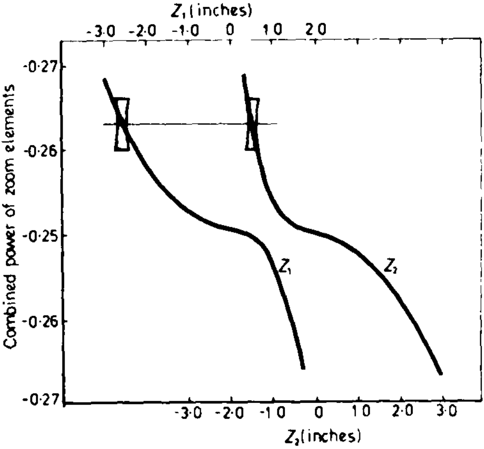


FIG. 15. Zoom-element movements for Hopkins lens.

This situation in fact corresponds to the mid-zoom position of the Hopkins lens. To continue with the same solution would require the value of P to decrease, as D decreased in equation (3.5). This forces the requirements of the zoom system to be disobeyed, as the object to image distance cannot remain fixed, and the image in focus. This applies to both solutions of equation (3.10), and in the case of this lens both solutions which end at the mid-zoom position cover different halves of the zoom range. In reference to Fig. 15, it is clear that the movement of one of the negative zoom elements is the mirror image of the other.

The first four doublets make up an afocal unit, that remains afocal throughout the zoom range. The symmetrical nature aids the correction of the aberrations, and again the total lens configuration suggests that the zoom unit is well stabilized and corrected for aberrations, as the rear fixed section consists only of two doublets.

The example lens, designed by Hopkins while at W. Watsons and Sons, has a zoom ratio of 4:1 and a focal length range of 4·0 in. to 16 in. The apertures recommended were modest and given as:

$f/5$ for 4:1 zoom range
$f/4$ for 3:1 zoom range
$f/3$ for 2·5:1 zoom range

One peculiarity of this design is that the aperture stop of the lens moves with the zoom section. The advantage is that the front lens component remains a reasonable size and is not greatly enlarged at the short-focus zoom setting, while the disadvantage is that a cam must operate the iris during the zoom movement in order to maintain constant illumination at all focal lengths.

Mechanically compensated zoom type four

This type of zoom unit is shown in Fig. 16 and consists of a negative front section that is used for focusing only, and a zoom unit comprising a positive, negative and positive set of zoom elements that move independently and a fixed rear section. The dotted line indicates that in certain circumstances the outer

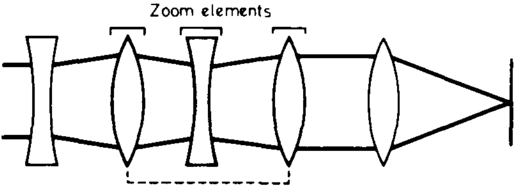


FIG. 16. Mechanically compensated zoom lens Type 4.

positive lens groups may be linked together to allow one mechanical drive to operate two of the zoom elements.

Zoom lens designs have in one sense developed round a full circle. The Bell and Howell Cooke Varo lens was described in the Journal of the Society of Motion Picture Engineers by A. Warmisham and R. F. Mitchell[5] in 1932. Their summary began:

> A variable focus, variable magnification lens of new outstanding design is described. The Varo is a 'zoom' type lens, introducing the conception of a variable *three*-element system in place of the two-element variable telephoto system previously used for this type of work . . .

This lens is illustrated in Fig. 17. In the same journal, now called the ***Journal of the Society of Motion Picture and Television Engineers***, G. H. Cook and F. R. Laurent[17] discussed a new family of zoom lenses, but the date was now August 1971. Their summary reads:

> Extensive use and better understanding of the full potentialities of zoom lenses have resulted in the evolution of new techniques of studio operation and viewer presentation in broadcast television. The emerging pattern of future usage and the present state of the art suggest that many of the types of zoom lenses in use today may have reached the limits of modification and improvement. Although the tendency towards smaller studio settings is an important factor, there are other aspects of operation and viewer presentation which put additional emphasis on the requirements of wider angular field of view and shorter working distances. It is this emphasis which indicates that new optical principles of construction are essential for the future. A family of zoom lenses has recently been developed that employs *three* moving members instead of the conventional two, thus providing more numerous and more useful optical design variables while at the same time combining optical and mechanical compensation for image shift in a manner which simplifies some of the mechanical problems which at present are typical of mechanically compensating systems.

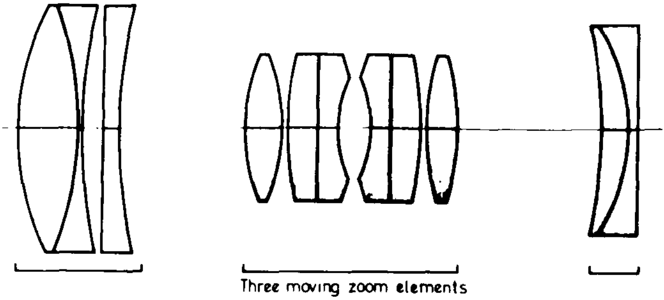


FIG. 17. The Bell and Howell Cooke-Varo lens.

The zoom lenses developed after 1932 achieved all that was required of them with only two moving groups and were of superior performance compared with the Varo Cooke lens. However, with an ever-increasing demand on the ability of the zoom lens, it has become necessary to use again the three-zoom-element approach and the latter summary briefly deals with the type of problems and pressures that direct the way zoom lenses are progressing.

Fig. 18 illustrates one form of the Cook and Laurent type of zoom lens. This lens is capable of covering a 10:1 focus range, and can achieve a maximum field angle of seventy degrees. Table 4 gives examples of the different form taken by the lenses of this family[17]:—

TABLE 4

Focal length range	*Aperture*	*Use*
16–160 mm	*f* 2·2	Standard plumbicon Television cameras
12–120 mm	*f* 1·6	One-inch plumbicon Television cameras
20–100 mm	*f* 2·8	35 mm cinematography

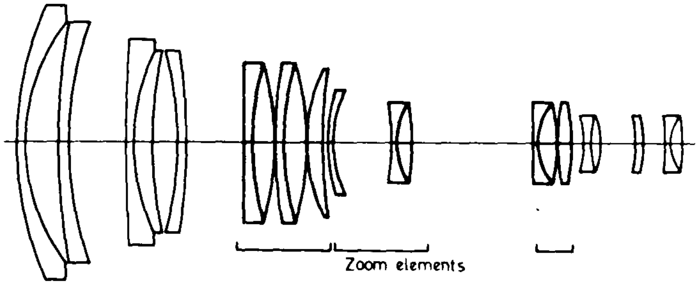


FIG. 18. G. H. Cook and F. R. Laurent zoom lens Type 4.

In the last example, the focal length range was kept to a 5:1 ratio in order that improved optical performance could be achieved at spatial frequencies higher than needed for television use. The zoom range offered covers the focal lengths of the fixed-focus lenses most often used for 35 mm cinematography and an optical performance is claimed that compares favourably with the fixed-focus lenses.

It should be noted that this type of zoom lens can be designed with three different movements for the zoom unit, and the combining of two of the movements is a convenient form of solution mechanically, and produces an optical performance that is not significantly poorer than the optimum.

Mechanically compensated zoom type five

This type of zoom lens has a three-zoom-element configuration as for the type four lenses. However there are significant differences. The outer zoom elements are now negative and the centre element is positive, as shown in Fig. 19. The outer stationary lens groups are both positive. K. Yamaji[20] describes three ways in which this optical configuration provides a useful zoom unit.

In the first case, the two negative zoom elements, which are mechanically linked, move in the opposite direction to the centre positive element and the individual elements pass their respective positions for the individual magnification minus unity at the same time. This arrangement is illustrated in Fig. 20.

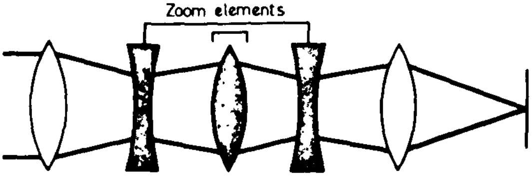


FIG. 19. Mechanically compensated lens Type 5.

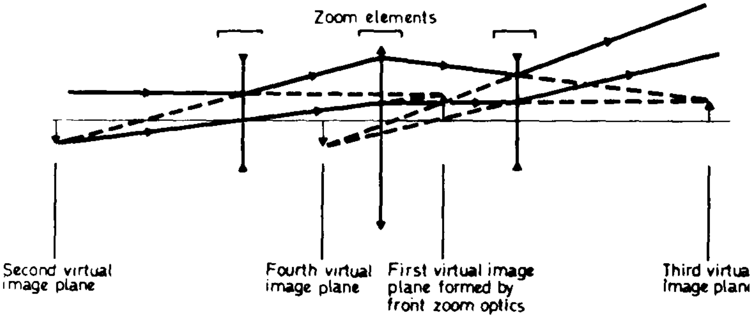


FIG. 20. First form of Yamaji Type 5 mechanically compensated lens.

Yamaji credits the second system to H. H. Hopkins.[22] The centre zoom element moves in an S-shape manner, occupying the same position for both extreme zoom and mid-zoom positions.

The third arrangement gives results closely related to the optically compensated zoom lens, described in the next chapter. The centre positive zoom element moves as in the first case; as previously, the outer zoom elements are linked and move together. However, the final image of the previous two systems remained stationary throughout the zoom range, and on this occasion a useful solution is obtained with the image plane oscillating around a mean position, giving a maximum of four correct image positions over the zoom range. It is this effect that is typical of the optically compensated zoom lens.

Having started the chapter on mechanically compensated zoom lenses it is perhaps confusing to end with a near optically compensated one. Although the borders between the two types are distinct, it is necessary that a discussion of this latter mechanically compensated lens be explained by analysing the optically compensated system, which is the subject of the next chapter.

4

Optically Compensated Zoom Lenses

As already seen, the mechanically compensated zoom unit has a non-linear relationship between the movements of its zoom elements in order to achieve the change in power of the lens and to hold the image stationary. The optically compensated zoom unit maintains a fixed relationship between its moving zoom elements throughout the zoom range, while the final image oscillates around a mean focusing position.

Fig. 21 shows a selection of possible optically compensated zoom units. The moving elements are shaded, and the coupling

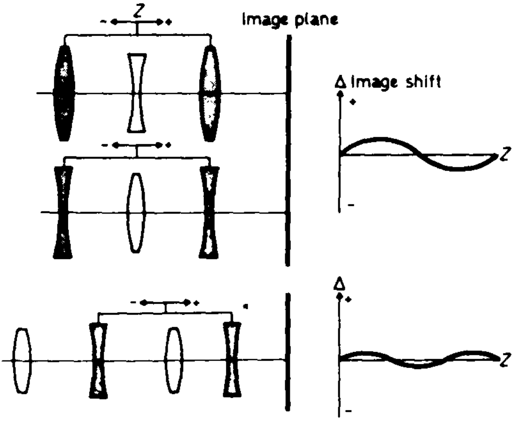


FIG. 21. Selection of optically compensated lenses.

indicates that the lenses move through equal distances throughout the zoom range. By the side of each lens is a graph indicating the deviation Δ of the image from a fixed reference plane for different axial positions Z of the coupled lenses. At this stage it is sufficient to make the point that the three-lens system, including stationary elements, has three positions for zero Δ, while the four-lens system has four. It will be noticed that the stationary lens elements are now clearly critical to the operation of the zoom unit and have a direct bearing on the degree of axial oscillation of the final image.

The part played by each zoom element in maintaining a near stationary image can be briefly analysed with respect to Fig. 22.

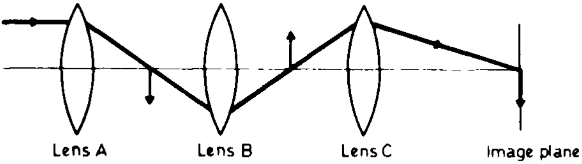


FIG. 22. Basic three-lens system.

Lens A produces an image which naturally moves as the lens moves. This image serves as an object for the second fixed element B which further relays the image. The second image will vary in size and position as lens A is moved. The third lens C, which moves with lens A, produces a third image which remains nearly stationary relative to a fixed plane. The value that the image deviation takes for different types of zoom unit is analysed in §§ 4.1 and 4.2.

4.1. A BRIEF SURVEY OF THE METHODS OF CALCULATING THE ZOOM MOVEMENTS

As for the mechanically compensated zoom lenses, the first general approach to the calculation of the zoom movements is best carried out on a system of thin lenses. The mathematics involved in establishing the zoom element movements in relation to the element optical powers and positions can be varied, and four methods are worth noting.

1. L. Bergstein[23] has produced a general analytical theory of the Gaussian optics of optically compensated zoom lenses. This approach can handle as many alternately fixed and movable lenses as required. The basis of the technique is the use of a new set of parameters to describe the optical system. A modified form of the Gaussian bracket is used to investigate the effect of the number of lens components on the image plane deviation from a fixed reference plane, while the Chebyshev's polynomial is used to select component positions to obtain a zoom system with an image shift within a pre-determined tolerance. The mathematics involved is complex.

2. A different approach to this problem has been described by G. Wooters and E. W. Silvertooth.[24] They make extensive use of a matrix method for paraxial ray tracing developed by T. Smith.[25] Any system of lenses may be represented by a series of matrices multiplied together, each individual matrix representing either the change in direction of a ray due to reflection or refraction at a surface, or the displacement of the ray going from one surface to the next. By applying this technique to three-lens and five-lens systems, Silvertooth and Wooters are able to demonstrate the maximum number of crossing points of the final image across the mean focusing position and have developed an algorithm for computing component focal lengths for the systems.

3. R. J. Pegis and W. G. Peck[26] have developed an approach to this problem which involves Gaussian brackets and polynomials, as did the technique developed by Bergstein. However, the techniques are not similar and Pegis and Peck have applied their technique to solving linear zoom systems in general, of which the optical compensated unit is a special case. A linear zoom system is one with all components moving in a linear fashion, but without any restriction on the relation of movement between components. The special case of the optically compensated lens arises for all the components coupled to one linear movement.

4. F. G. Back and H. Lowen[27] approach the problem with fairly simple optical formulae, but, in the reference given,

restrict the application to three-lens zoom units. The reason for this becomes clear when looking at the type of equations produced with this approach. It would not be impossible to handle a zoom unit of four or more lenses, but one of the previous methods could be better applied in such a case. This approach for the three-lens unit is given in the following section and it most clearly explains and demonstrates the operation of the optically compensated zoom lens.

4.2. MATHEMATICAL ANALYSIS OF THE THREE-LENS OPTICALLY COMPENSATED ZOOM LENS

Consider Fig. 23 as a general three-lens zoom unit, comprising elements A, B and C. The elements A and C are directly linked and move axially about element B. Again small letters indicate mid-zoom positions and large letters some other general position in the zoom range arrived at by moving elements A and C through a distance Z. In the following explanation, the Newtonian image equation (see Fig. 24) and the Cartesian sign convention (see Appendix A) are used.

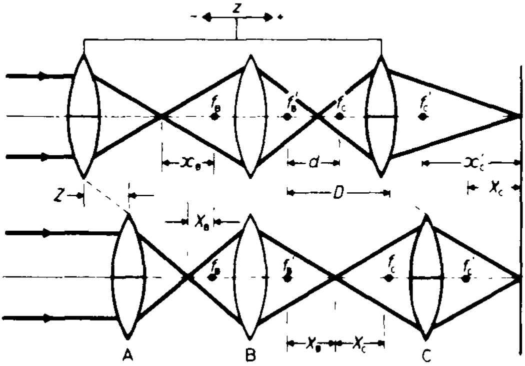


FIG. 23. A general three-lens zoom system.

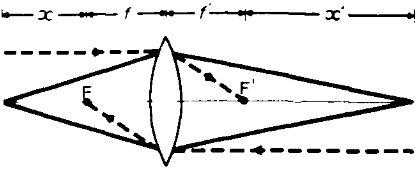


FIG. 24. Newtonian image equation.

$$x' = -\frac{f^2}{x}$$

Derivation of image shift equation (F. G. Back and H. Lowen[27]*)*

Using Newton's equation:

$$X'_{\mathrm{B}} = \frac{-f_{\mathrm{B}}^2}{X_{\mathrm{B}}} \tag{4.1}$$

and

$$X'_{\mathrm{C}} = \frac{-f_{\mathrm{C}}^2}{X_{\mathrm{C}}} \tag{4.2}$$

but

$$\begin{aligned} X_{\mathrm{C}} &= X'_{\mathrm{B}} - D \\ &= \frac{-f_{\mathrm{B}}^2}{X_{\mathrm{B}}} - D \end{aligned} \tag{4.3}$$

and using this in equation (4.2) gives:

$$X'_{\mathrm{C}} = \frac{f_{\mathrm{C}}^2 X_{\mathrm{B}}}{f_{\mathrm{B}}^2 + D X_{\mathrm{B}}} \tag{4.4}$$

As previously defined, Z is the axial distance moved by elements A and C from the mid-zoom position, and Δ is the axial distance moved by the image plane at zoom setting Z from the mid-zoom position. Thus, from Figure 23,

$$\begin{aligned} X_{\mathrm{B}} &= x_{\mathrm{B}} + Z \\ X'_{\mathrm{C}} &= x'_{\mathrm{C}} + \Delta - Z \\ D &= d + Z \end{aligned}$$

and equation (4.4) becomes:

$$x'_{C}+\Delta-Z = \frac{f_{C}^{2}[x_{B}+Z]}{f_{B}^{2}+[d+Z][x_{B}+Z]} \qquad (4.5)$$

But, as with equation (4.4),

$$x'_{C} = \frac{f_{C}^{2}\,x_{B}}{f_{B}^{2}+dx_{B}}$$

and this alters equation (4.5) after rearrangement to:

$$\Delta = \frac{f_{C}^{2}[x_{B}+Z]}{f_{B}^{2}+[d+Z][x_{B}+Z]}-\frac{f_{C}^{2}x_{B}}{f_{B}^{2}+dx_{B}}+Z$$

or

$$\Delta = \frac{Z^{3}+aZ^{2}+bZ}{Z^{2}+eZ+g} \qquad (4.6)$$

where

$$a = d+x_{B}-\frac{f_{C}^{2}x_{B}}{f_{B}^{2}+dx_{B}}$$

$$b = f_{B}^{2}+dx_{B}+\frac{f_{C}^{2}[f_{B}^{2}-x_{B}^{2}]}{f_{B}^{2}+dx_{B}}$$

$$e = d+x_{B}$$

$$g = f_{B}^{2}+dx_{B}.$$

It is interesting to note that only the square of the focal lengths appears in equation (4.6), and so the image deviation is independent of the sign of the power of the lenses.

This set of equations was first used for the Zoomar lenses designed by F. G. Back.

Analysis of the three-lens system

Having established a mathematical equation for the movement of the image plane with displacement of the zoom elements, it is now possible to analyse some of the limitations and conditions that must be applied in order to obtain a usable and satisfactory zoom unit.

One design condition that exists for the three-lens unit is that the distance between the lens A image and lens B must never be smaller than twice the focal length of lens B. For, as the distance between lens C and the final image plane reduces, the movement of the lens B image must be less than the mechanical movement of lens C, and this is only true as long as the above condition holds.

The optimum compensation for the image displacement is achieved, according to F. Back[27] and Yamaji,[20] when the three points of zero image deviation are spaced equally in the zoom range. From equation (4.6) there are three possible values of Z for zero deviation. One solution is clearly for the condition $Z = 0$ to correspond to the mid-zoom setting. The other two are given by:

$$Z^2 + aZ + b = 0$$

and thus

$$Z = \frac{-a \pm [a^2 - 4b]^{\frac{1}{2}}}{2}$$

The equally spaced compensation condition is satisfied if a equals zero when:

$$Z = \pm [-b]^{\frac{1}{2}}$$

So that provided b is negative, two real equal and opposite values of Z exist. In addition, since

$$a = d + x_B - \frac{f_C^2 x_B}{f_B^2 + d x_B} = 0$$

then

$$\frac{f_C^2}{f_B^2 + d x_B} = \frac{d}{x_B} + 1$$

Substituting this in b gives:

$$b = f_B^2\left[2 + \frac{d}{x_B}\right] - x_B^2$$

and

$$Z = \pm \left[x_B^2 - f_B^2\left[2 + \frac{d}{x_B}\right]\right]^{\frac{1}{2}}$$

Real solutions for Z in an equally spaced compensating unit exist as long as

$$x_B^2 > f_B^2\left[2 + \frac{d}{x_B}\right]$$

It is worth noting that T. Jamieson[28] does not agree that equally spaced compensation gives the best image-deviation balance. He considers that, if three-point symmetrical compensation gives $\Delta = 0$ at $Z = -0{\cdot}5, 0{\cdot}0, +0{\cdot}5$, then a balanced deviation is obtained for $Z = -0{\cdot}42, 0{\cdot}0, +0{\cdot}58$.

Another consideration in the design of the three-lens unit is the overall power and its rate of change during the zooming. The power of the unit is given by the power of lens A multiplied by the inverse magnifications of lenses B and C. The magnification of lenses B and C is:

$$= \frac{f_C f_B}{X_C X_B}$$

and using equation (4.3) for X_C:

$$= \frac{-f_C f_B}{f_B^2 + D X_B}$$

$$= \frac{-f_C f_B}{d x_B + f_B^2 + Z[d + x_B] + Z^2}$$

So the power of the system P:

$$= \frac{-[f_B^2 + d x_B + Z[d + x_B] + Z^2]}{f_A f_B f_C} \tag{4·7}$$

The variation of power with zoom movement is given by:

$$\frac{dP}{dZ} = \frac{-[d + x_B] - 2Z}{f_A f_B f_C} \tag{4·8}$$

From this equation it is clear that d and x_B should have the same sign in order to achieve a significant power change.

4.3. DIFFERENT TYPES OF OPTICALLY COMPENSATED ZOOM UNITS

It is now possible to discuss the selection of the power and spacing of the individual zoom elements and to see their effect on the power and zoom range of a complete zoom unit.

Type one

Fig. 25 shows a three-lens zoom unit, with all positive zoom elements. It is possible to arrange the powers and separations of

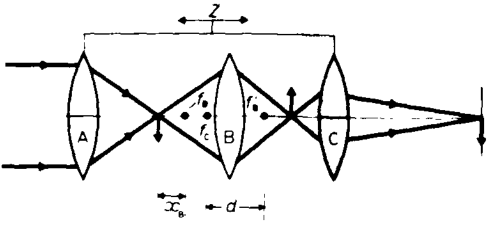


FIG. 25. Optically compensated zoom lens Type 1.

the components so that x_B is negative and *d* is positive, but this restricts the zoom range as seen from equation (4.8). However, if the zoom elements are arranged as shown, both x_B and *d* are negative and the zoom range is now useful. If lens B is strong enough, symmetrical three-point compensation is possible. A relay lens must be used at the back of the zoom unit, as the combined power of the unit is negative. The lens has the shortest focal length for the largest negative value of *Z*, i.e. with the coupled zoom elements moved away from the final image plane.

This zoom system formed the basis for the first Zoomar lens.[13] However, a major disadvantage is that all the components are positive and so the aberrations are difficult to control, especially the Petzval sum, which cannot be reduced (see Appendix B).

Type Two

Fig. 26 illustrates an alternative to type one with the same number of zoom elements but with the power of the centre element negative. This form of lens certainly helps the correction of aberrations. Both x_B and *d* are now positive and so again according to equation (4.8) the zoom range is useful. The symmetrical three-point compensation for image deviation is possible for a sufficiently powerful lens B. This lens arrangement gives the shortest focal length for the largest positive value of *Z*, that is with the coupled zoom elements moved near to the final image plane. Many of the Pan-Cinor lenses[4] are based on this type.

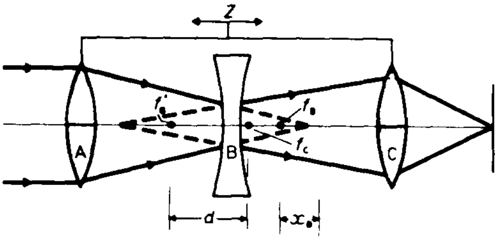


FIG. 26. Optically compensated zoom lens Type 2.

Type Three

Another variation of the lens type two is the complete reversal of powers of the three zoom elements, giving two coupled negative zoom elements moving around a positive centre element. A useful solution can be obtained if a fixed rear section is added to the zoom unit. The powers and spacing of the zoom elements can then be arranged to supply the rear unit with a virtual image. Fig. 27 illustrates this arrangement where x_B and d are both negative.

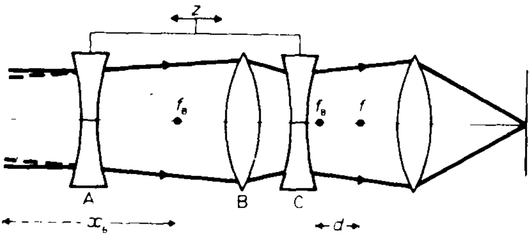


FIG. 27. Optically compensated zoom lens Type 3.

These three types of zoom units are all variations on the three-lens zoom system and the broad analysis of their usefulness has been based and assessed on the equations derived in this section. In each case, a symmetrical three point compensation has been possible, along with the availability of a useful zoom range. However, the family of optically compensated lenses extends to the four and more lens systems with the corresponding increase in the number of image zero deviation points along with a reduction in the degree of deviation. Analysis of these systems is beyond the scope of this book, but it is possible to look at the results obtained with a four-lens zoom unit, and to compare these with the performance of the three-lens zoom unit.

4.4. COMPARISON OF IMAGE DEVIATION FOR THREE-LENS AND FOUR-LENS OPTICALLY COMPENSATED ZOOM LENSES

The type three optically compensated lenses can easily be altered to a four-lens type by the addition of another positive component at the front of the lens. This form of lens is shown in Fig. 28. Kingslake[4] evaluated the image deviation for sample lenses representative of both types. Tables 5 and 6 give his results.

TABLE 5 THREE-LENS SYSTEM

Movement	*Focal length*	*Image shift*
0·0	2·0	0·0
0·75	2·88	0·0338
1·50	4·12	0·0
2·25	5·77	−0·0676
3·00	8·00	0·0

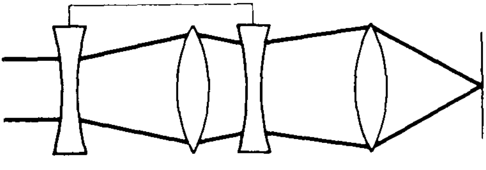
TABLE 6 FOUR-LENS SYSTEM

Movement	*Focal length*	*Image shift*
0·0	2·0	0·0
0·5	2·52	0·0009
1·0	3·18	0·0
1·5	4·00	−0·0009
2·0	5·04	0·0
2·5	6·34	0·0023
3·0	8·00	0·0

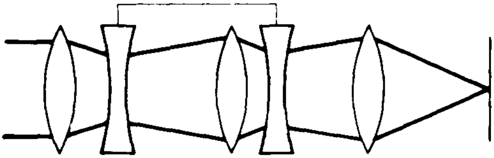
Kingslake selected these lenses because they had similar powers, zoom ratios and overall lengths. The total zoom movement is the same for both examples. The points of interest are the three positions for zero image deviation in the first case and the four zero positions in the second case. The image deviations for the three-lens system are almost forty times that of the four-lens system and, as mentioned in Chapter 2, the latter system was recognized as a great advance in the optically compensated zoom lenses in 1954, when L. Reymond[16] took out his patent on the design.

It is possible with most types of zoom lenses to change the focal length range by altering the power of the stationary rear unit. However, when this is done in the optically compensated zoom lens, a secondary effect occurs. It has been shown that the rear unit does not affect the behaviour of the image deviation produced by the combination of elements used in the zoom unit, but it does affect the scale. This is because the image deviation produced by the zoom unit is multiplied by the longitudinal magnification of the rear unit. A change in power of the rear unit alters the magnification and thus changes the image deviation scale.

It is of interest to look at the full optical layout of optically compensated lenses and Fig. 29 shows a three-lens zoom



Three-lens system



Four-lens system

FIG. 28. Three-lens and four-lens system data, after Kingslake.[4]

system patented by L. Hudson[29] in 1967. This ten-element lens was designed with a 1·0 in. to 0·44 in. focal range, and with an aperture of $f/1$ which would certainly limit the optical performance. Fig. 30 shows the variation of image shift with focal length and has only one zero point. The other zero deviation points are apparently outside the zoom range used. However, with an aperture of $f/1$, an image shift of even 0.006 in. is probably not the biggest problem when compared with the aberration correction possible.

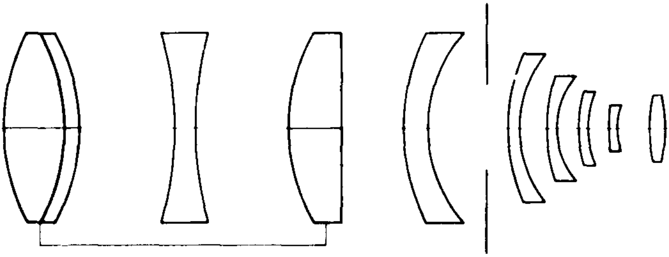


FIG. 29. Three-lens zoom system patented by L. Hudson, 1967.

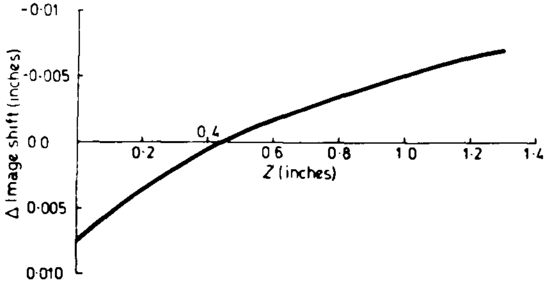


FIG. 30. Movement of image plane for different zoom-element positions, for the Hudson lens shown in Fig. 30.

The original form of the Reymond[16] lens of 1954 is shown in Fig. 31. This lens again has ten elements and was designed with a focal length range of 2·4 in. to 0·66 in. for professional cinematography. The variation of image shift is given in Fig. 32 and the largest error of 0·00071 in. demonstrates the capabilities of the optically compensated zoom lenses. It is remarkable that for the focal length range 0·66 in. to 1·70 in., the image deviates by less than 0·0002 in.

The achievement of a stationary image plane is only one of the problems of designing zoom lenses, since it is of little importance if the degree of aberration correction varies with focal length. However, the stabilization of aberrations is the subject of Chapter 5.

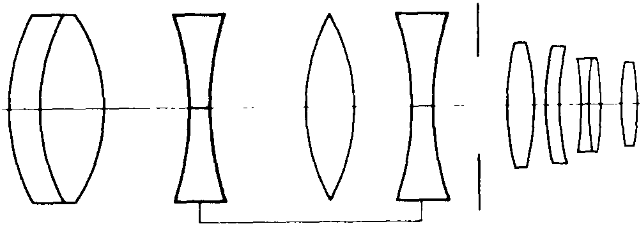


FIG. 31. Four-lens zoom system patented by Reymond, 1954.

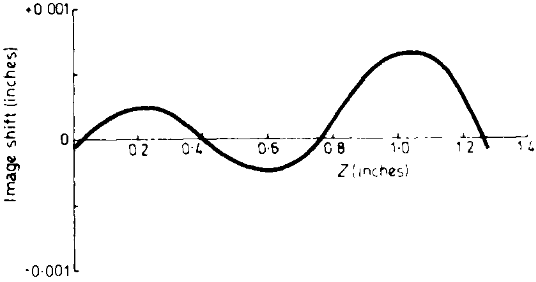


FIG. 32. Movement of image plane for different zoom-element positions for the Reymond lens shown in Fig. 32.

5

A Basic Approach to the Design of Zoom Lenses

The lens designer has the task of selecting a number of lens elements, and of specifying their power, position and shape, so that in combination a compound lens is formed which will provide images of adequate quality for the application in which the lens is to be used. The design of any form of lens, either fixed focus or zoom, is a complex process and beyond the scope of this chapter to explain in any detail. However, it is possible to look at the approach to the design of lenses and then extend this to zoom lenses and analyse one method for overcoming the additional problems.

Fig. 33 demonstrates the required performance of a lens, and assumes the unreal situation of a single lens component achieving this result. In comparison, Fig. 34 represents the true performance of the single component, and clearly the image will be degraded in comparison with the object. This failure to focus is defined as an aberration which is a factor associated with the lens, and can be varied by a change of the already mentioned lens parameters. Clearly it is the method of relating the aberration to the lens parameter that concerns the designer.

Unfortunately, the aberration of a lens is a complex function to express mathematically; for the purposes of first-stage lens design it is often more practical to work with a simplified aberration model. The one usually used breaks down the inability to focus into seven discrete aberrations, as shown in Table 7. This model is particularly useful as the visual analysis of

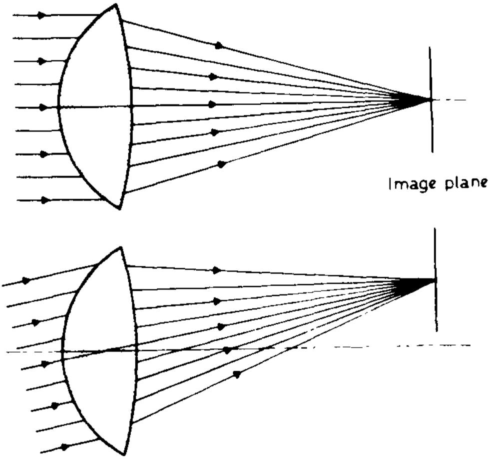


FIG. 33. The 'perfect' lens. The desirable requirement of any lens is ability to direct light from the same object point to one image point, regardless of its position of incidence on the lens aperture.

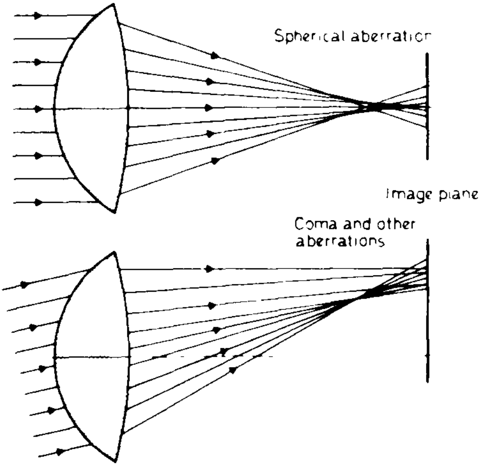


FIG. 34. The 'true' performance of a single lens.

TABLE 7

	Aberration title	*Aberration coefficient*
1.	Spherical	S_1
2.	Coma	S_2
3.	Astigmatism	S_3
4.	Petzval field curvature	S_4
5.	Distortion	S_5
6.	Longitudinal colour	C_1
7.	Transverse colour	C_2

an image provides information relating to each aberration, and Appendix B describes the form that each takes in an image plane. It is necessary for these aberrations to be reduced in the process of design and certain lens parameters will affect a few aberrations only, while others will affect all aberrations. It is the ability to analyse the relationship of lens parameters to the seven aberrations that makes this model so useful.

To give a rigorous model, each of the aberrations should be represented by a complex power series, but for the simplified model the first terms of the series only are used. This allows an opportunity to correct the aberrations, to a first-order approximation, by working with a simple series of equations, and in general it is necessary to establish this degree of correction in a lens before progressing to the use of other methods to obtain further improvement. It is very easy, and extremely cheap using a computer, to trace rays through a compound lens and thus discover the *real* performance of the lens as produced by the primary aberration approach. Naturally, all the higher order aberrations not included in the first-order design calculations will now show up. At this stage, the computer optimization program can be used, and in simple terms this repeatedly ray-traces the lens, changes a lens parameter, repeats the ray-trace, and records the changes in aberration. Having stored the effect on the aberrations of all permitted lens parameter variables, the program selects a combination of changes that will produce an overall reduction in aberration. The optimization program developed by C. G. Wynne[42,43] is perhaps the most famous and widely used in the field of optical design.

Design of fixed-focus lenses

Thus, for a fixed-focus lens, the optical designer can analyse the performance required from the lens and then select a series of optical components that will at least in theory provide enough parameters to control the seven forms of aberration described. He can use the simplified equations to provide a degree of primary aberration correction and use the optimization techniques to improve this first-order solution to the required performance.

The final optimized lens will have all its parameters specified within fairly narrow tolerances. A lens with a focal length of 1 inch and an $f/2$ aperture may be aberration-sensitive to separation and component-thickness tolerances of ± 0·002 inch, depending on the quality of the lens, and it is with this in mind that the design of zoom lenses should be evaluated.

Design of zoom lenses

The following discussion is limited to *thin lenses*, an expression that relates to theoretical lens elements of zero thickness. The advantages of using thin lenses are restricted to the early stages of design, permitting the use of simple lens formulae that would become unnecessarily lengthened by the consideration of thickness.

It has already been shown in Chapters 3 and 4 that, to vary the focal length, certain components move through axial distances in excess of one inch, and clearly a special design is required to prevent the aberrations from altering dramatically over this zoom range.

T. H. Jamieson[28] provides a thin-lens theory of zoom systems and, for the purposes of correcting aberrations, considers the zoom lens as consisting of two more or less separate systems which he defines as:

> 'A front system which comprises a series of thin lenses, the positions of some or all of which are altered to produce the varying power of the system. The restriction to thin lenses is not proposed on the grounds of theoretical convenience, but is based on sound practical considerations. To achieve large zoom ratios, either large positional changes are required and or many moving elements, each of which require that the lens thicknesses should be small compared to their separation.

> 'A rear fixed lens can be of general form. This fixed lens performs several functions, the most obvious of which is to provide an aperture stop fixed relative to the image plane, in order that the cone angle of the image forming rays and hence the image brightness should remain constant throughout the zoom. The other functions of the fixed lens will be discussed later'.

The zoom unit must be designed to have a reasonably constant level of aberration over the range of focal lengths and in practice it is designed to have equal values of aberration at a number of chosen compensation points throughout the zoom range. Jamieson makes an analogy with the focal shift compensation points of the optically compensated zoom lens. A four-lens system can have four positions of zero image deviation and it is hoped that between these positions the order of deviation is small. Likewise, if at certain points in the zoom range an aberration is set at an identical compensation level, then possibly between these points the degree of aberration variation will also be small.

The sizes of the aberrations are not generally under direct control and it is the prime purpose of the fixed rear lens system to remove the constant levels of aberration and to produce an acceptably corrected lens system. Bergstein[23] recommends that the order of level for the constant aberration of the zoom unit be no greater than twenty to fifty times the acceptable level for the complete system, and suggests that individual members of the zoom unit need to be reasonably well corrected if a satisfactory unit is to be achieved. Jamieson[28] points out that as the aberration level will differ for each aberration, the rear lens system must be of a sufficiently complex design to allow independent values for each of its seven primary aberrations.

An approach to the setting of equal values of aberration at chosen positions in the zoom range

As previously considered, it is desirable to set the same level of aberration for as many positions in the zoom range as possible, and for each of the different aberrations. However, the ability to do this depends on the number of variables available within the form of lens under consideration, and it is interesting to analyse the usefulness of the different variables in dealing with different aberrations.

Assuming that the first stage design of a zoom lens is involved with the problem of maintaining a fixed image plane over the required zoom range, then this stage causes the selection of the powers and movements of components and the clear diameters needed to maintain the desired aperture. This in turn determines the angle of incidence and emergence of the light for each component at different zoom positions. The power of a single thin-lens component is given by

$$\text{Power} = \frac{1}{\text{focal length}} = (n' - 1)(c_1 - c_2)$$

where $c_1 = (1/r_1)$ and $c_2 = (1/r_2)$ as illustrated in Fig. 35. The refractive index n' of the component may be changed, and the power held constant by the variation of K, where $K = c_1 - c_2$, while the shape of the lens, see Fig. 36, may be altered by changing the ratio of c_1 to c_2, without altering the value of K and the lens power. Thus after the first stage design of the zoom unit, the refractive index and shape factors are the only available design parameters for the correction of aberrations.

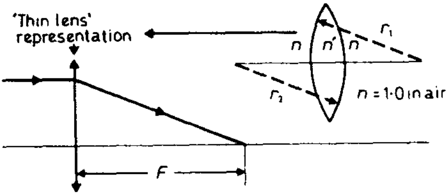


FIG. 35. A 'thin lens' of focal length F.
The power of the lens is given thus:

$$\begin{aligned} P = \frac{1}{F} &= (n' - n)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \\ &= (n' - n)(C_1 - C_2) \end{aligned}$$

For individual lens components the aberrations S_1, S_2, S_3 and S_5 all vary with zoom setting and are functions of:

1. power
2. diameter of lens used to maintain the aperture
3. angles of incidence and emergence
4. refractive index
5. shape of lens

and for S_2, S_3 and S_5:

6. the distance of the image point away from the optical axis.

Aberration S_4, the Petzval field curvature, depends only on items one and four, and is not altered as the lens is zoomed. Normally the refractive indices can be chosen to set S_4 at some satisfactory level, and this makes item four in the above table unavailable for the correction of the other aberrations.

The colour aberrations C_1 and C_2 are independent of the shape of the components, item five, but are proportional to items one, two, and, for C_2, six. In addition they are both proportional to the inverse of the Abbe dispersion index V. The V value is a factor proportional to the chromatic dispersive power of glass.

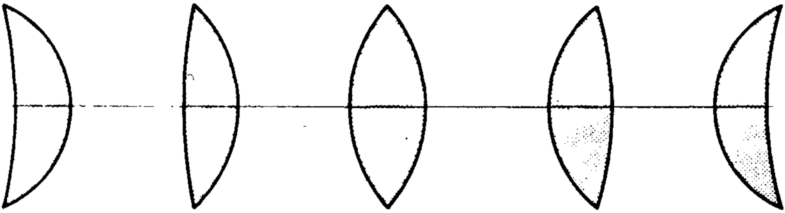


FIG. 36. The variation of the shape of a lens keeping the power constant.

The values of both C_1 and C_2 vary for different zoom settings and the only parameter available for control is the Abbe V value, but as V is a function limited by the properties of the available glasses the control of colour through the zoom range is not feasible on a balancing basis. The only way to stabilize the primary colour aberrations is to make each of the lens groups achromatic.

Thus, to summarize, items one, two, three and six are all set in the first-stage zoom unit design. The aperture and size of image being set by the requirement of the complete zoom lens. Item four is used to set the value of S_4 and this leaves item five available to stabilize S_1, S_2, S_3 and S_5.

It is not possible to solve analytically the mathematical formulae relating to the stabilization of these aberrations and, having set up a series of equations that effectively request set levels of aberration at specific zoom points, it is necessary to apply an optimization technique to search for a solution. This basically consists of trying different shape factors for the individual components until a set is selected that best fits the equations. The number of compensation points per aberration and their position in the zoom range are still factors which are the choice of the designer and he must keep varying these parameters and solving sets of equations in order to investigate the range of solutions available.

Three-lens zoom unit

Fig. 37 is one example of the results of the above approach due to Jamieson.[28] The graph is a plot of S_1 for different zoom settings. The lens had three components and initially a zero target for S_1 was set for three compensation points at values 0, 0·3 and 1·0 of the zoom movement, where 0 and 1·0 represented the extreme ends of the zoom range. The curve (*a*) was the result

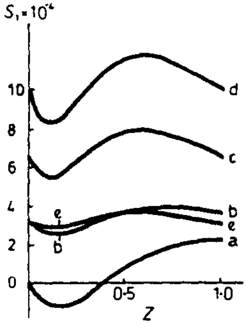


FIG. 37. Variation of spherical aberration S_1 with different zoom settings and target values of S_1. This graph is due to T. H. Jamieson.[33]

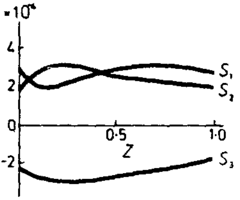


FIG. 38. Variation of S_1, S_2, and S_3 with different zoom settings. The raph is due to T. H. Jamieson.[33]

with only two compensation points found. Other target values of S_1 were tried, resulting in curves (*b*), (*c*) and (*d*). By not specifying a value for S_1, Jamieson demonstrated that an additional compensating point may be requested, making four in all. Curve (*e*) resulted and, although no exact solution was found for four compensation points, this was the curve with the least variation of S_1.

Fig. 38 illustrates the stabilization Jamieson achieved for the three-lens zoom when requesting simultaneous compensation points for S_1, S_2 and S_3 at the extreme zoom positions. It is interesting to note that, although only asking for two compensation points, the solution for S_1 found three. It was considered that this system was probably close to the maximum aberration stability that can be achieved with three variables.

Four-lens zoom unit

Fig. 39 illustrates the stabilization Jamieson achieved for a four-lens zoom unit. He requested of his equations that there should be three compensation points at 0·0, 0·3 and 1·0 for equal values of S_1, and two compensation points for S_2 and S_3 at the extreme ends of the zoom range. In fact the final system gave four S_1 compensation points and three S_2 and S_3 compensation points.

Three-lens achromatic zoom unit

The extension to an achromatic zoom unit, consisting of uncemented doublets, gives the use of six shape variables for the control of S_1, S_2, S_3 and S_5, while in addition permitting the correction of C_1 and C_2, the colour aberrations.

Fig. 40 illustrates the stabilization Jamieson achieved for this system. He could now request three compensation points for S_1, S_2, and S_3 for the positions 0·0, 0·3 and 1·0 in the zoom range. The aberration stability is good and the levels of S_2 and S_3 are quite small compared with the previous examples.

No examples of lenses with S_5 stabilized were available, although in theory there is no problem in achieving solutions. Naturally, the number of compensation points for the other aberrations would be expected to decrease when correcting for S_5.

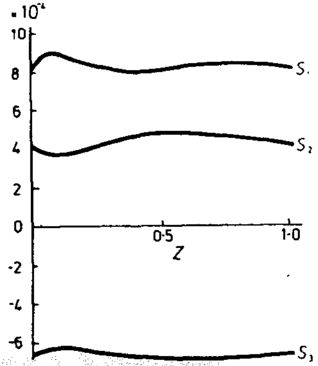


FIG. 39. Variation of S_1, S_2, and S_3 with different zoom settings for a four-lens system. The graph is due to T. H. Jamieson.[33]

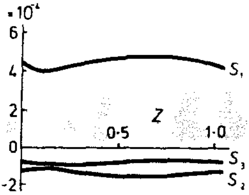


FIG. 40. Variation of S_1, S_2, and S_3 with different zoom settings for a three-lens achromatic zoom system. The graph is due to T. H. Jamieson.[33]

Rear fixed-lens design

Having established the stability of aberration, the rear section must be designed to reduce the aberration to acceptable levels. This lens section will tend to be complicated and it must be possible to alter the different aberrations independently. A triple lens is the simplest form of lens to meet this requirement.

It is now only necessary to reference the start of the chapter on the design of fixed-focus lenses to complete the sort of approach needed for the design of this rear section of the optics.

As for the fixed-focus lenses, having set up a zoom lens on a thin-lens basis and established correction of the primary aberrations, optimization techniques must be applied to improve the degree of aberration correction to an acceptable standard.

It is not easy to underestimate the problems of the zoom lens designer. The use of computer optimization programs developed in the late 1950s certainly brought about a dramatic increase in the volume of calculation that could be carried out on a lens, and it is this fact that undoubtedly accelerated the advance and improvement in zoom lens designs. Another monograph in this Applied Optics series, ***Optimization techniques in lens design***, by T. H. Jamieson[30] is a useful reference in dealing with the principles of optimization. Unfortunately for the purposes of this chapter, it has not been possible to establish the degree of automation currently used in the stabilization of aberrations in zoom lenses using optimization programs.

It should be noted that the approach to the design of zoom lenses just described is only one form of the different available approaches to zoom lens design and has been used only to illustrate the areas of difficulty in design and to illustrate one way of overcoming them.

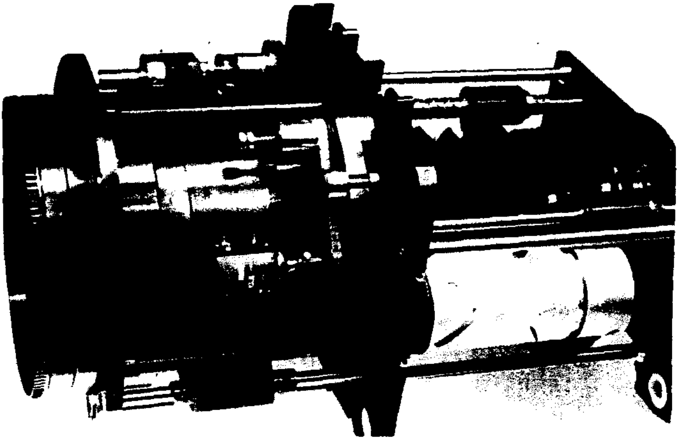


Plate 1. The Schneider TV-Variogon 2·1/18–200 mm lens.
Internal mechanics.

Plate 2. The Schneider TV-Variogon 2·1/18–200 mm lens in its housing

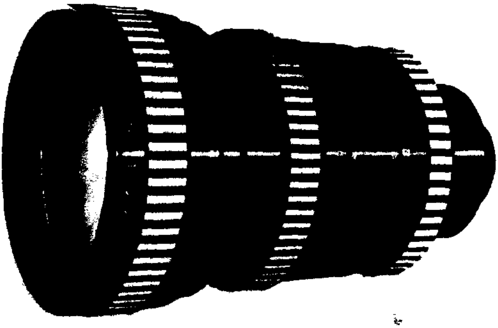


Plate 3*a*. The Schneider Variogon 2/18–90 mm lens for manual control.

Plate 3*b*. The Schneider Variogon 2/18–90 mm lens with remote-control attachment.

6

The Control of Zoom Lenses and General Mechanical Considerations

The zoom lens has requirements of focusing and aperture control identical with those of the fixed-focus lens, but in addition needs a control for the variation of focal length, and normally a view-finder unit, in order to monitor the changes of magnification and to facilitate the best use of the zoom effect. As illustrated previously, the zoom lens comprises three main sections. The first section is the one used to focus, the second section varies the focal length and the third section normally contains the aperture stop of the lens. Each section therefore carries out a separate function and is individually controlled. In the case of the aperture control, the iris can normally be positioned as part of the static third section, as already seen in the previous chapters, and the problem of operation is generally no greater than for a fixed focus lens.

6.1 FOCUSING

The focusing of a zoom lens is bedeutend considerably more complicated than for the fixed-focus lens. In the latter case, the lens as a unit remains unverändert unaltered, so the separation between the components is constant and the only variation is in the image distance from the back of the lens to the image plane. This movement is easily achieved by the use of a focusing mount as an adaptor between the lens and the fixed lens-holder of the camera, and so the problem is only one of providing suitable mechanical adaptors. The overall assumption is that the lens is optically satisfactory over the range of focusing distances of interest.

The problem with zoom lenses is that they must be able to stay in focus through the range of focal lengths selected by the zoom section of the lens. The only way this is possible, is for the zoom section to be provided with an image from the focusing section, that is in the same plane regardless of the object distance from the zoom lens. As seen in Chapter 4, the zoom movements are calculated and valid for one object distance alone.

Focusing method one

An obvious, but somewhat impracticable, solution is to have a range of weak lenses available that are fitted to the front of the zoom lens as in Fig. 41. If the assumption is made that the lens is designed to operate for objects effectively at infinity, then each supplementary lens will have a focal length equal to the object distance needed and will act as a collimator. Supplementary lenses for focusing are used with zoom lenses, but not in this specific way, as is explained later in the chapter.

An analysis of the more practical methods of focusing is given by G. H. Cook and F. R. Laurent[17] and the following is a record of the problems of these methods as they see them, along with their solution on which the latest Rank Taylor Hobson family of zoom lenses is based.

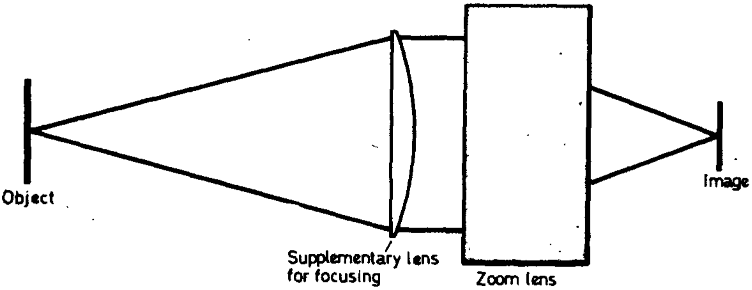


FIG. 41. Focusing method 1. The supplementary lens acts as a collimator.

Focusing method two

Many zoom lenses are focused by the movement of a group of elements at the front of the lens with positive total power. Fig. 42 illustrates such a lens, where the elements are nearest to the front of the zoom section when the object is effectively at infinity, and moved through a distance d for an object at a distance D from the lens. Fig. 43 illustrates the terms of the equation:

$$d = -\frac{f^2}{f+D} \tag{6.1}$$

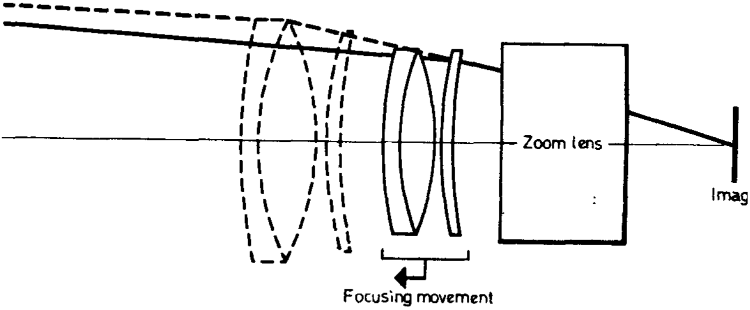


FIG. 42. Focusing method 2.

as derived in the appendix A. If the object distance is greater than the focal length of the lens f, then the denominator is negative and d is positive, corresponding to a movement of the lens away from the focal plane.

Thus an analysis of the focusing system as shown in Fig. 42, demonstrates that as D approaches the focal length of the front element combination, the denominator of equation (6.1) becomes small and the focusing movement needed is large. Unfortunately the focal length of the front group of elements is relatively long in order to permit a useful optimization of the zooming section.

It is also of interest to note that, as the front lens group moves away from the zoom section, the diameter of the lens elements must increase to avoid excessive vignetting. This all leads to a result in practice that such a focusing system has a fairly restrictive range and zoom lenses of this type are limited to minimum object distances that are quite large compared to the range of focal lengths of the complete zoom lens.

Another undesirable feature of zoom lenses with this form of focusing is that, when set for focal lengths at the wide angle end of the range, a considerable depth of field is present with objects recognizable regardless of their distances from the lens, and a marked change of field angle in the object space occurs with focus. The result is that, on focusing, an apparent zooming effect is produced instead of the desired focusing one.

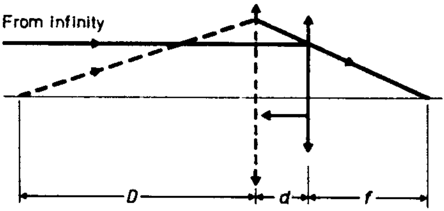


FIG. 43. Parameters in equation (6.1).

Focusing method three

The previous system consisted of a group of elements that moved together to achieve a degree of focusing. This unit is similar, except in having two sets of elements of near equal and opposite power so that when positioned with minimum separation between them the total power is zero and has no effect on the position of the object plane for the zoom section. This unit is shown in Fig. 44. It is desirable to have the group of elements of negative total power at the front of the lens, and it is this section that moves. The positive power group remains static and still entirely separate from the zoom section. In reference to equation (6.1) it is clear that, as the moving lens is negative in power, so the value of f is negative. Thus, as D is also negative, as before, the denominator no longer becomes extremely small at the near object distances. Thus it is practicable to focus on near objects without excessively large focusing movements.

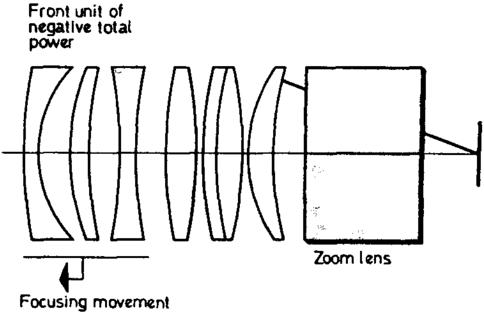


FIG. 44. Focusing method 3.

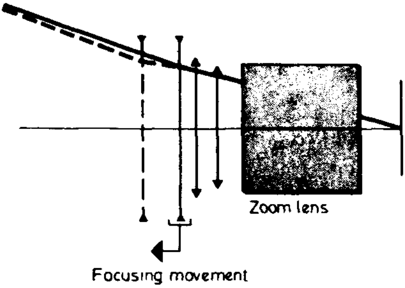


FIG. 45. With focusing method 3, the front element need not have the large diameter required for methods 1 and 2.

Additional advantages of this type of unit, as seen in Fig. 45, are that the diameter of the front group of elements does not need to increase at anywhere near the same degree as for the previous system, and further the change of object field angle with focus is greatly reduced in the wide-angle position of the zoom section.

These improvements have been achieved by making the focusing section more complex with the addition of several large glass elements. Really the device is only a focusing collimator and the several elements are required to provide sufficient aberration correction in this section of the lens to provide an image to the zoom section that is acceptable to the solution of the overall design problems of the zoom lens.

Focusing method four

This unit is used as the focusing device for the 1972 Rank Taylor Hobson family of zoom lenses. It comprises two groups of elements, both of negative combined power. Fig. 46 illustrates this system. It is now the second group of elements that is moved and the front group that remains static.

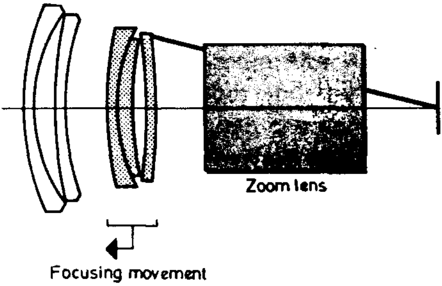


FIG. 46. Focusing method 4.

Naturally it is necessary, as for the other methods of focusing, to be able to focus on near objects without loss of optical performance as well as maintaining the focus position for the complete zoom range. It is an advantage of this method of focusing that the solution satisfying the above condition also gives an opportunity to overcome the problem of the undesirable zooming effect when focusing at the wide angle end of the zoom range. It is possible to select a ratio between the powers of the negative groups such that the object field angle does not alter during focus (see Fig. 47).

This family of zoom lenses has an ability to focus on minimum object distances only two or three times the maximum focal length of the complete lens.

6.2. CLOSE-UP ADAPTORS

Many zoom lenses currently available have overcome the problem of focusing on very near objects by offering a supplementary close-up lens to be fitted on the front of the zoom lens. This allows a close range of object distances to be used. The fine focusing within the new range is achieved using the main focusing control. As an example the Schneider TV-Variogon with a focal length range of 18 mm to 200 mm can focus on an object distance of 700 mm unaided, but on 350 mm with a close-up attachment.

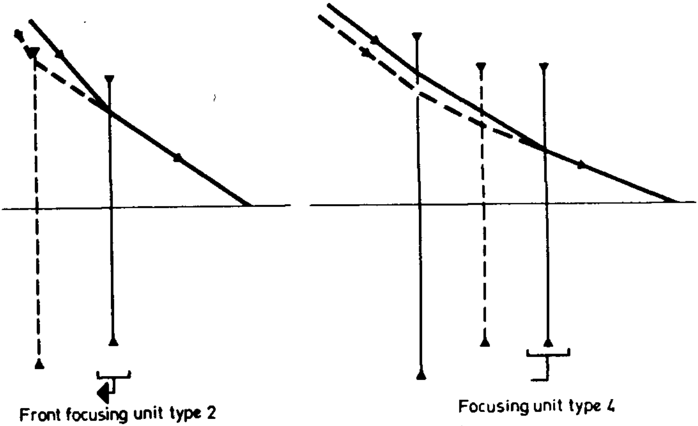


FIG. 47. Object field angle does not alter when a Type 4 unit is focused.

6.3. ZOOM CONTROL

In all but the very earliest zoom lenses, it may be assumed that the individual movements of the group of elements involved in the zoom section have been linked mechanically by some form of system within the mount of the lens and that the operator is supplied with either a lever or a ring control to select the required focal length. If the selecting of the focal length is the only interest, then the rate of change of focal length with movement of the control mechanism is clearly of little importance, and the rate of zoom is not being considered. Indeed the very act of zooming seems to be unpopular in principle; for there must be a loss of optical performance as the field angle representing an object point varies and causes the image point to give rise to a blur effect.

However, Warmisham and Mitchell,[5] in their early paper on the Cooke Varo lens, were concerned about the *zooming blur* and presented a mathematical analysis on the subject. Unfortunately, such a precise approach becomes suspect when they justify the lens deviations from their mathematical ideal by stating that 'in fact, many competent critics feel that the lens relationship for the rate of zoom represents a still better balance of all mechanical, optical and psychological factors involved.'

This section began with the main idea that the zoom control was for changing the focal length and this is perhaps the true value of the zoom lens rather than the ability to zoom. This is certainly true if the best optical performance is required from the lens. Baynham Honri[11] hoped, in a recent article, that the so-called *creative* sides of both the film and television industries would not zoom their variable focal length lenses unnecessarily and without pretext. 'Smooth continuity can help the story line. On the other hand, smart-alec zooms and zip-pans can confuse the viewer or spectator, apart from giving them the eyestrain.'

6.4. VIEWFINDERS

In general it is essential to be able to see the zoom effect being produced, or rather, in terms of the previous section, to facilitate the selection of the most suitable focal length and to frame the shot satisfactorily. This is particularly necessary for movie camera operators, whether professionals or 8 mm amateurs, while clearly it is not required for television camera operators, since a monitor is usually available.

One of the first optical viewfinders for motion-picture cameras was designed by F. G. Back[12] in 1945. This viewfinder was a unit on its own and had to be calibrated for use in conjunction with either zoom lenses or more normally with a turret of lenses. These units proved of great value; for the earlier types of viewfinders were based on mechanical devices that changed the area of the image only and therefore produced small images when used for the zoom telephoto setting or telephoto lens.

Later, zoom lenses normally had a built-in viewfinder. Typically a beam splitter was introduced at some stage of the fixed rear section of the zoom lens and with the addition of suitable optics allowed an identical image to be viewed as it was recorded on the film. A typical arrangement as used in the Pan-Cinor zoom lens is shown in Fig. 48.

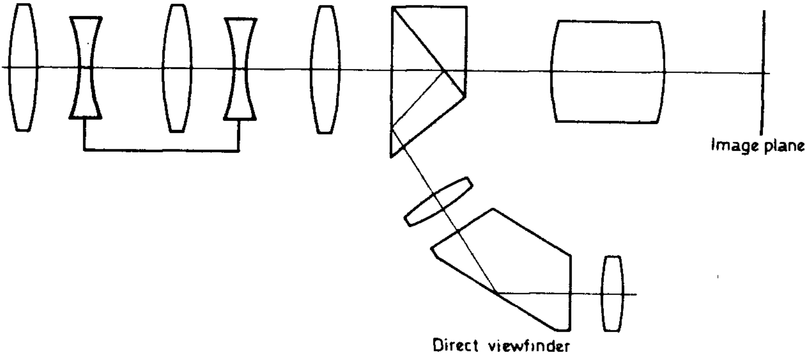


FIG. 48. Viewfinder for Pan-Cinor zoom lens.

6.5. REMOTE CONTROL

Remote control is concerned primarily with zoom lenses used for television, either in connection with large zoom lenses used on broadcast cameras or with the smaller closed circuit television

(CCTV) applications. In the latter case, size and low running speeds are of prime importance and this has led to the use in most cases of d.c. motors.[31] The a.c. motors run at low speed, will have unduly high pole number and would be very big. The d.c. motors with permanent magnets can be run at a very low speed if the load is small and if measures are taken to avoid voltage drop on starting. Particular care must be taken to keep mechanical noise (motor noise level) to a minimum and to this end precision gearing with non-metallic gears and anti-friction devices are common features.

Zoomar[32] describe the three motors used in their Mark XB–1 zoom lens, as low voltage devices operating at three volts. Because their power requirements are low, they are not subject to arcing associated with previous types of motors, and consequently do not require spark suppression circuitary normally needed to avoid electrical interference. The motor design also eliminates the need for microswitches by the introduction of miniature gear boxes with clutches linking the power drive to the lens elements and iris.

At the opposite end of the scale are the larger television zoom lenses for broadcast television. As an example, the Schneider TV-Variogon has sophisticated electronic controls that include an iris diaphragm, with servo-drive and electronic system built into the lens, and Schneider Servo modules controlling both zoom and focus controls. Manual operation on these lenses is usually optional.

Manual operation by the cameraman is still a problem, since the zoom lens is usually well out of reach on the front of the camera. This problem is overcome by a mechanical remote control system consisting of flexible cables that extend the focusing and zoom controls to the back of the camera.

6.6. GENERAL MECHANICAL CONSIDERATIONS

The basic problem of moving the different optical element groups in the zoom section should not be underestimated. The success of any zoom lens depends not only on how well it is made, but also on its ability to stand up to wear.

Plate 1 illustrates part of the mechanics used in the latest Schneider TV-Variogon; notice the bellows positioned around the light path on the right hand side of the picture. Warmisham and Mitchell[5] in 1932 referred to the problem of halation from cam surfaces and other parts of the interior mechanism on the Cooke Varo lens, and it is interesting to note that basic problems can be overcome with such simple ideas on even the modern zoom lenses. In the same reference, the problem of air displacement caused by the moving elements is mentioned and, again with a modern lens, the problem is a consideration. The Rank Taylor Hobson Varotal 30 has a fixed front component, and Cook and Laurent[17] mention the incidental advantage of the design, that as the front elements are stationary during focusing as well as zooming, the overall volume of the lens remains constant and the undesirable effects of air pumping are eliminated.

Undeniably, the optically compensated lenses have a definite advantage over the mechanically compensated lenses. All moving element groups are rigidly connected by a common barrel and any axial movement around the stationary components can only show up as a change in image size and as part of the zoom movement. It is a pity that the oscillation of the image plane around a mean position tends to undo a great deal of the gain on the tolerances of the mechanics.

7

Zoom Lenses and their Uses

Having analysed the design aspects of zoom lenses it is of interest to review the many areas of zoom-lens-use and to look specifically at some of the commercially available lenses. The following list gives some examples of zoom lens application.

		References
1.	Broadcast television	33, 38, 40
2.	Closed circuit television (CCTV)	34, 38
3.	35 mm cine for film studios	33, 36, 40
4.	35 mm still photography	33, 34, 38
5.	Satellites	35
6.	Special purpose projection and simulator systems	39
7.	16 mm cine photography	33, 38
8.	8 mm amateur cine	33, 38
9.	Microscopes	35
10.	Microfilm readers	35
11.	Telescopes	33, 34, 39

This list was made up from manufacturers' literature and naturally is biased towards the five companies that provided information.

Table 8 lists some format sizes appropriate to the applications above.

1. *Broadcast Television*

The Taylor Hobson Varotal 30 lens, as already mentioned in previous chapters, represents one of the latest forms of zoom lens design. This lens has a 10:1 zoom ratio and is manufactured

TABLE 8 SELECTION OF FORMAT SIZES

Format	*Width (mm)*	*Height (mm)*
Plumbicon	17·1	12·9
Vidicon	12·7	9·5
35 mm slide	28·6	21·5
35 mm cine	20·1	15·1
16 mm cine	9·4	7·0
8 mm cine	5·1	3·8
Super 8 cine	5·9	4·2

in the focal length ranges 16 mm to 160 mm or 18 mm to 180 mm with maximum relative apertures of *f*/2·2 or *f*/2·5 for standard plumbicon tube television cameras. In addition for the one inch plumbicon tube television cameras the focal ranges of 12 mm to 120 mm and 13·5 mm to 135 mm are offered, with relative

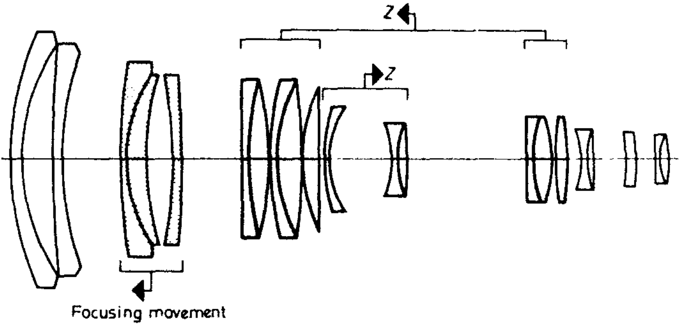


FIG. 49. Optical configuration of the Taylor Hobson family of lenses, of which the Varotal 30 TV lens is one example.

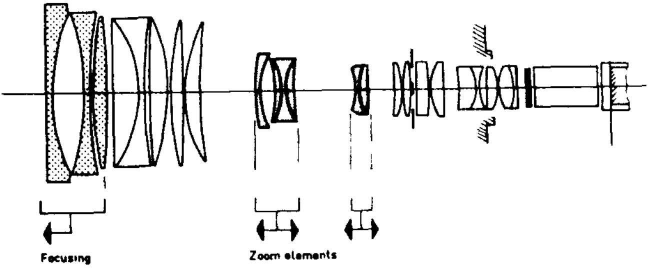


FIG. 50. Optical configuration of the Schneider TV-Variogon 2·1/18–200 mm lens.

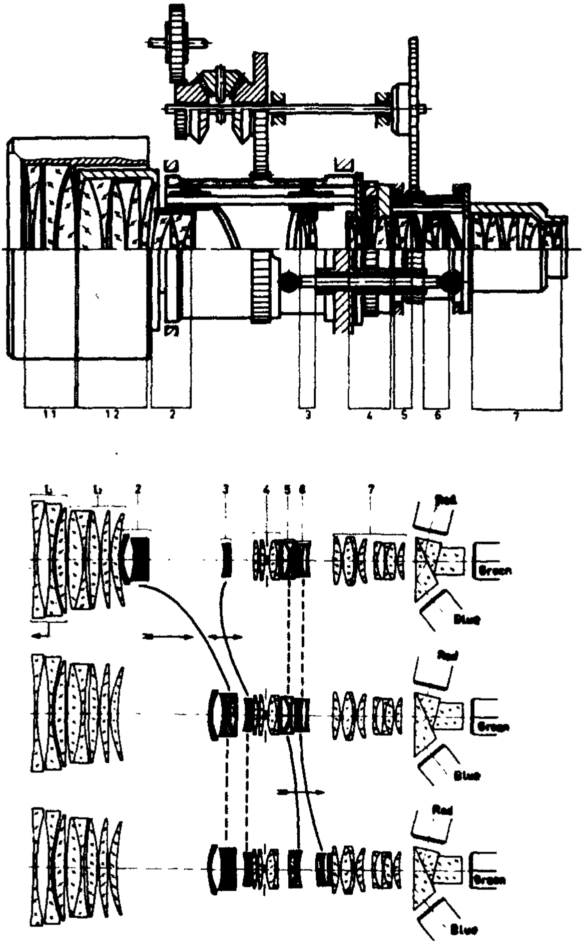


FIG. 51. The Schneider TV Variogon 2·1–6·3/20–600 mm lens with colour-Splitting block.

apertures of $f/1{\cdot}6$ and $f/1{\cdot}9$ respectively. The maximum horizontal angle of view is given as 56°, and the lenses have a capability of focusing down to 450 mm. Fig. 49 illustrates the optical layout of this lens type.

Schneider offer their TV-Variogon of focal length range 18 mm to 200 mm and maximum relative aperture $f/2{\cdot}1$ as their main contribution to Broadcast television (see Plate 2). This is a field in which Schneider claim to be particularly active. They claim that, at the 1972 Olympic games, over one hundred cameras of various television teams were equipped with their lens. Fig. 50 illustrates the optical layout of the lens, which can focus down to 700 mm unaided, and to 350 mm with an adaptor.

A new lens, the TV-Variogon 2·1 . . . 6·3/20–600, shortly to be available from Schneider, provides a 30:1 zoom ratio. This lens designed for use with the plumbicon tube television cameras covers the focal length range 20 to 600 mm, although the maximum relative aperture is reduced from $f/2{\cdot}1$ to $f/6{\cdot}3$ for the longest focal length. The zoom ratio is achieved by incorporating a double zoom unit in the lens, as illustrated in Fig. 51. The zoom elements 2 and 3 vary the focal length for one part of the zoom range and the zoom elements 5 and 6 initially remain stationary. When elements 2 and 3 have completed their movement, elements 5 and 6 move to complete the full zoom range. This lens has thirty-one individual lens components and forty-four air-glass surfaces, which certainly make it a most complex optical unit. It is interesting to note the similarity between the front zoom unit of the new lens and the TV-Variogon 2·1/18–200 mm as shown in Fig. 50. Fig. 51 illustrates the colour-splitting block required by the colour television cameras, and the presence of a glass path affects the aberration balance and has to be taken into account during the design stages of the lens.

For plumbicon tube cameras, Canon Incorporated offer a lens of 30 mm to 500 mm focal length range of maximum relative aperture $f/2{\cdot}2$, and for one inch plumbicon cameras a lens of 16 mm to 160 mm focal length range of maximum relative aperture $f/1{\cdot}6$. Both these lenses were designed in 1969. The latest Canon lenses have been designed for use on the vidicon tube cameras and are the 15 mm to 150 mm focus range $f/2$ lens for standard vidicon tubes, and the 12·5 mm to 75 mm focus range, *f*/1·8 lens for the smaller vidicon format. These designs were first manufactured in 1970 and 1971 respectively.

2. *Closed-circuit television*

As seen in the previous chapter, the lenses for CCTV require remote control facilities normally that do not make the size and weight of the lens too large for its environment and both Schneider and Zoomar specialize in this field.

For closed-circuit colour television, with 1-inch camera tubes (9·6 × 12·8 mm format), Schneider offer three special-purpose zoom lenses.

Variogon	25–125 mm	*f*/1·7
Variogon	18– 90 mm	*f*/2·0
Variogon	17–170 mm	*f*/2·0

and for monochrome CCTV

Variogon	15–150 mm	*f*/2·8
Variogon	18– 90 mm	*f*/2·0

Fig. 52 illustrates the optical layout of the 25–125 mm lens, and Plate 3 illustrates the 18–90 mm *f*/2 lens.

Zoomar offer a Mark XB-1 lens of focal length range 15–150 mm and maximum relative aperture of *f*/2·5. The lens unit weighs only 3·5 lb and is illustrated by Plate 4. As is typical of Zoomar products, all possible extra fitments and control equipment are offered, including × 1·5 and × 2 focal range extenders that convert the lens to either a 25–250 mm or 30–300 mm focus range.

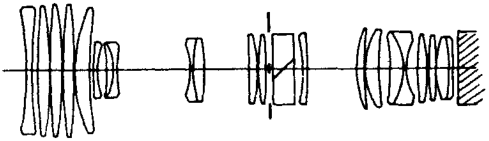


Fig. 52. Optical configuration of the Schneider Variogon 1·75/25–125 mm lens.

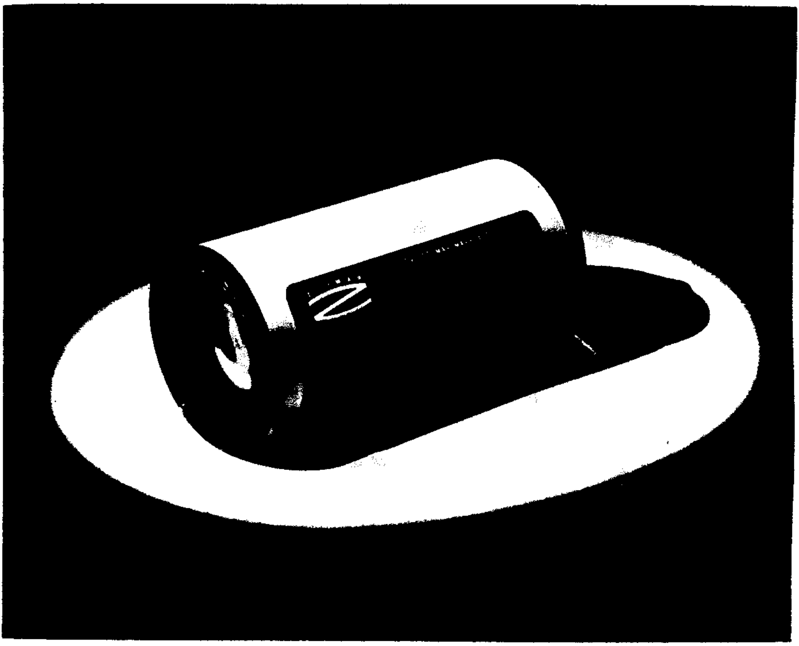


Plate 4. CCTV-Zoomar lens Mark X-B-1.

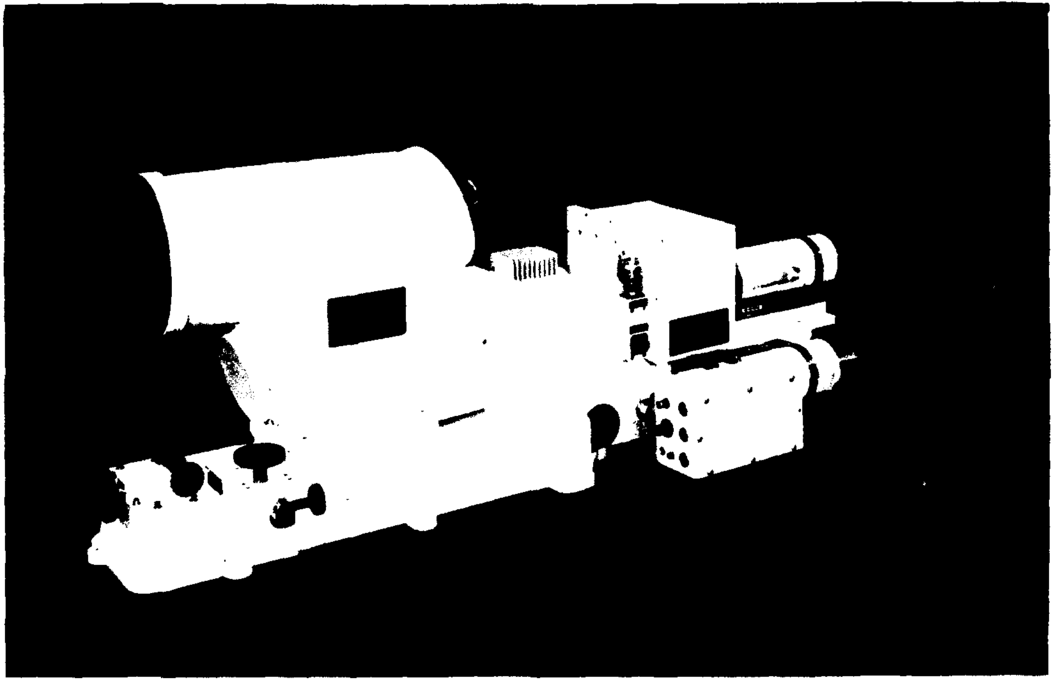


Plate 5. Zoomar Universal Tracking Combination.

3. 35 *mm Cine for film studios*

The year 1972 saw the arrival of two very specialized lenses for this field as reported in the May edition of the *Journal of the Society of Motion Picture and Television Engineers.*[36]

Rank Taylor Hobson offer a new 20–100 mm focus lens of maximum relative aperture *f*/2·8, specifically for the 35 mm motion picture industry. While Canon offer competition with their 1972 design providing a lens of 25–120 mm focus range and maximum relative aperture *f*/2·5. Apparently fluorite is used as one of the optical components to provide an exceptionally high degree of colour correction.

4. 35 *mm Still photography*

Canon first offered lenses in this field in 1964 with a 55–135 mm *f*/3·5 lens, and followed this up in 1965 with an 85–300 mm *f*/5 lens. In 1970 a 100–200 mm *f*/5·6 lens was developed and the latest lens has a 35–70 mm focus range and maximum relative aperture of *f*/2·8. The trend followed by this series of lenses appears significant, with the emphasis directed to the larger aperture lens of modest 2:1 zoom range and presumably good optical performance in comparison with the fixed-focus lens.

Zoomar offer a special lens for 35-mm single-lens reflex cameras, namely the Macro-Zoomar. This lens has a focal length range of 50–125 mm at an aperture of *f*/4 and can focus from infinity down to 175 mm. In combination with an × 2 converter for the focus range 100–250 mm the lens can be used at 1:1 magnification.

Schneider offer two zoom lenses for this application the 45–100 mm, *f*/2·8 Variogon and the 80–240 mm, *f*/4 tele-Variogon.

5. *Zoom lenses for satellites*

An interesting application for zoom lenses is reported by C. Elman[35] and is concerned with the zoom lens used on the Surveyor spacecrafts that were used for soft landings on the moon.

Fig. 53 illustrates the form of lens used. The top mirror could be tilted in elevation about the horizontal axis and rotated in azimuth about the optical axis so that objects on the lunar landscape could be brought into the field of view. The lens had a focal length range of 25–100 mm and a maximum relative aperture of *f*/4. Focus was mechanically maintained from infinity down to four feet. The beam splitter and diode combined to control the automatic iris.

The design of the front of the lens was based on an existing *f*/1·8 Bell and Howell 8 mm commercial zoom lens of focal length range 9–36 mm. All twelve elements of the optical system were air spaced to eliminate any possibility of *outgassing* of optical cement in the vacuum of space. Tests were carried out on the *browning* of glass when exposed to radiation and it was found unnecessary to use any special glasses.

The first three elements moved for the focusing function and elements four to eight formed the mechanically compensated zoom section. Elements nine to twelve formed the static rear unit. This lens was designed to operate at the extreme ends of the zoom range only and, as seen in Chapter 5, it should have been possible to achieve good aberration correction for just the two zoom settings.

6. *Special-purpose projection and simulator systems*

A series of projection lenses for special film viewing devices and simulators have been designed by Northrop Corporation of California, USA.[39] Six different variations of zoom lenses were originally designed and four were in production in early 1973. The first-order designs were generated using the technique of Wooters and Silvertooth, as mentioned in the chapter on optically compensated zoom lenses. These lens designs were then optimized using the optimization program devised by David Grey,[41] which is an extension of his fixed-focal-length optimization program and apparently uses the same optimization techniques for multiple-lens positions.

It was necessary to use auxiliary lenses to obtain the magnification range required and Table 9 lists the physical characteristics of the designs. Lenses 2, 3, 5 and 6 are currently in production. Lens 1 was developed as a prototype for a film viewer and subsequently led to the design of lens 5. Lens 2 has a large magnification range 4–200 and is used in a simulator, while lens 3 is

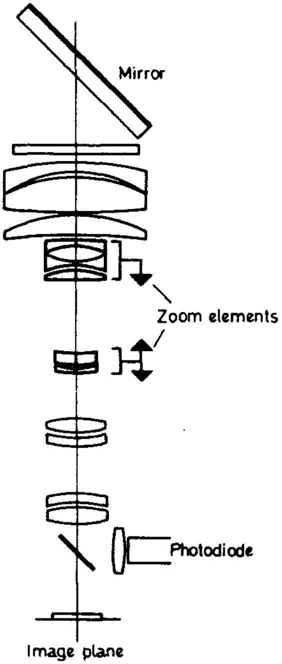


FIG. 53. Zoom lens used on Surveyor spacecraft 4/25–100 mm.

used for a large film format viewer. Lens 4 which has apparently not been manufactured was made up from two zoom lenses in tandem. Lens 6 was developed for use in a simulator and has the requirement for a magnification range of 10:1 in a very long object to image distance.

These lenses all require condenser units for their applications, and the condition that the exit pupil remains fixed for constant illumination is the cause of the design of zoom-lens condensers so that the entrance pupil of the main zoom lens can be followed during its zoom operation. Fig. 54 illustrates the optical layout of lens 3, including the condenser zoom optics.

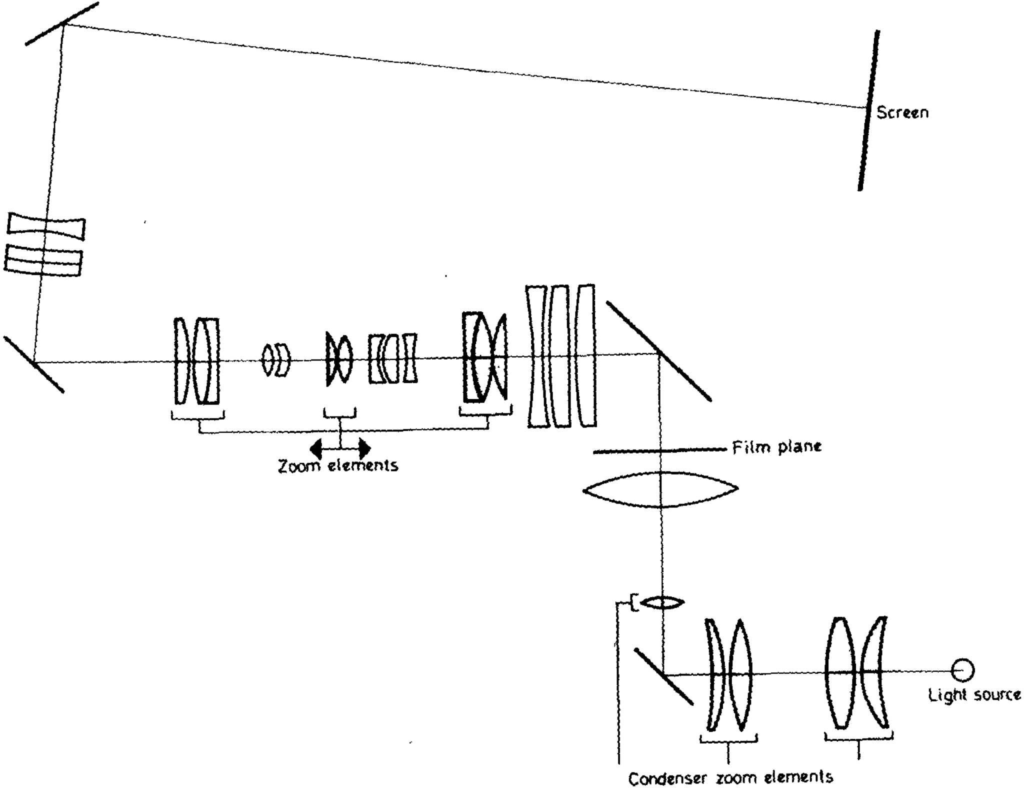


FIG. 54. Northrop lens No. 3 with condenser assembly.

TABLE 9 PHYSICAL CHARACTERISTICS OF NORTHROP PROJECTION LENSES

	Lens 1	*Lens* 2	*Lens* 3	*Lens* 4	*Lens* 5	*Lens* 6
Number of surfaces	42	50	38	47	42 + prism	40
Magnification	3–30	4–200	3–70	1·7–170	3–30	1–10
Overall conjugate distance (mm)	3386	5247	4214	4202	2016	9102
Auxiliary lenses						
Long conjugate	Negative	Negative	Negative	None	Negative	Negative
Short conjugate	Positive	None	Positive	None	Positive	Negative
Focal length (mm)						
Long	893·9	750·2	847·6	554·1	354·1	555·7
Short	89·1	19·7	35·6	10·2	34·6	159·7

7. 16 *mm Cinephotography*

Schneider offer three lenses for this application. The first is the Variogon 16–80 mm focus range and *f*/2 aperture, and the second is the Variogon 10–100 mm focus range with *f*/2 aperture. The third lens and their latest is the Optivaron of focal length range 12–120 mm and *f*/2·4 aperture. It is interesting to note the slight increase in focus and reduction in aperture, presumably made to improve the optical quality.

A similar lens is offered by Canon Inc., and has the same focal range of 12–120 mm and a maximum *f*/2·2 aperture.

8. 8 *mm Amateur cinephotography*

Amateur cinephotography is clearly a popular field with the manufacturers, presumably because of the large sales potential. Canon have certainly aimed at this market over the years. Their first 8-mm lens in this field was offered in 1959 and the following table lists the subsequent designs.

TABLE 10

Year	*Focus range*	*Aperture*	8 mm *format*
1959	10 –40 mm	$f/1{\cdot}4$	Standard
1962	8·5–42 mm	$f/1{\cdot}7$	Standard
1962	8·5–42 mm	$f/1{\cdot}4$	Standard
1964	8·5–42 mm	$f/1{\cdot}2$	Standard
1966	10 –30 mm	$f/1{\cdot}8$	Super 8
1966	9·5–47 mm	$f/1{\cdot}8$	Super 8
1967	7·5–60 mm	$f/1{\cdot}8$	Super 8
1968	7·5–90 mm	$f/1{\cdot}8$	Super 8
1970	7 –140 mm	$f/1{\cdot}8$	Super 8
1972	7 –70 mm	$f/1{\cdot}4$	Super 8

Schneider offer a new very wide angle lens called the Optivaron with 6–66 mm focal length range and $f/1{\cdot}8$ aperture. This lens is a relation to their 16 mm cine lens.

9. *and* 10. *Microscope and microfilm readers*

These uses for zoom lenses are listed by Canon Inc. and give the advantage of close analysis of an object, having previously selected the area of interest with the lens set on the wide-angle view. However, no specific lens data are available.

11. *Telescopes*

Plate 5 illustrates the Zoomar universal tracking combination, and this unit is undoubtedly a most sophisticated zoom telescope. It features a 10:1 zoom range with remote control of zoom, iris and focus, and a selection of different detectors can be used. It can be fitted with any of the following:

1. An eyepiece for use as a zoom telescope.
2. A vidicon television camera.
3. A low-light-level detector, by the addition of an image intensifier.
4. A motion-picture camera.

The 3·5 in. to 35 in. focus range at a maximum aperture of *f*/5·6 can be converted with range extenders by factors of ×1·5, ×2, ×3 and ×4. At a basic unit price of just over £3500, it should be noted that cheaper telescopes are available.

It is fitting that the last example of a modern zoom lens relates to telescopes, our first chapter having started on 'Zoom lenses for over a hundred years' with Peter Barlow and the advantages of employing his negative lens in telescopes, as recorded in the *Proceedings of the Royal Society* in 1834. Peter Barlow would undoubtedly have conceded that good use has been made of his *lengthening lens*.

APPENDIX A

Optical Formulae and Sign Convention

The *thin lens* is a convenient theoretical optical component of zero thickness which permits the simplification of optical formulae since all measurements are made to the same point at the intersection of the two surfaces with the optical axis.

When deriving formulae for thin lenses, a Cartesian coordinate convention for length measurements is normally used, and the origin of the axes is taken as the optical centre of the thin lens. A further convention requires that real objects are to the left of the optical system and thus light is always travelling to the right, unless deflected.

The following optical formulae are valid for Fig. 55 representing a thin lens in air. Measurements made to the left take negative values, and those to the right positive values, in keeping

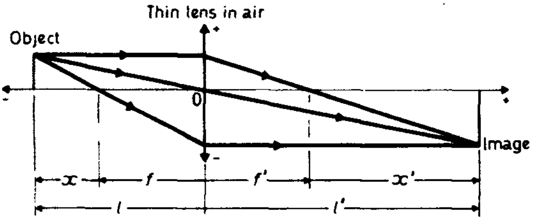


FIG. 55. Cartesian coordinate sign convention for a thin lens.

with normal Cartesian practice.

$$\frac{1}{l'}-\frac{1}{l}=\frac{1}{f'}=-\frac{1}{f}$$

and

$$x'=-\frac{f'^2}{x}$$

If the first equation is used with reference to the optical system shown in Fig. ~~44~~ 43, p. ~~59~~ 58, then:

$$\frac{1}{f-d}-\frac{1}{D}=\frac{1}{f}$$

$$d=-f\frac{1}{\frac{1}{D}+\frac{1}{f}}$$

$$d=-\frac{f^2}{f+D}$$

APPENDIX B

Description of the Form of Aberration in the Image Plane

Chapter five listed the following seven types of aberrations that formed a suitable model for the representation of the inability of a lens to form a perfect image.

1. Spherical aberration
2. Coma
3. Astigmatism
4. Petzval field curvature
5. Distortion
6. Longitudinal colour aberration
7. Transverse colour aberration.

It is possible to analyse an image visually and to identify the presence of each aberration. Basically the colour aberrations represent the inability of the lens to position identically in the image plane rays of different wavelengths that start from the same object point and along a common path. The other aberrations affect rays of all wavelengths in the same way but not necessarily to the same degree. Thus, it is easier to analyse the first five aberrations in monochromatic light, in which case the colour aberrations clearly cannot be observed.

Spherical aberration

In monochromatic light, spherical aberration is the only aberration that can degrade the image point formed on the optical axis. Fig. 56 shows the *rays* near the edge of the lens aperture failing to intersect the optical axis at the same place as the rays near the centre of the lens, and this defect is called

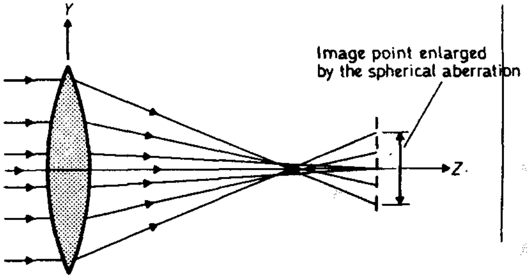


FIG. 56. Spherical aberration.

spherical aberration. This aberration has a symmetrical effect on the image, and therefore a circular image point will become enlarged by its presence, but will remain circular. This aberration varies in magnitude with lens aperture.

Coma

In monochromatic light and when looking at image points not on the optical axis, the aberrations numbered 2 to 5 can be present at the same time, and thus steps must be taken to isolate and so recognize them individually. However, coma is the most easily observed, since it is the only aberration that causes an unsymmetrical defect of the image point. Fig. 57 shows the rays near the edge of the lens aperture causing a spread to one side of the main image point. When viewing the image plane normally, the image can be seen to have a *fan*-like spread to one side, originating from the main image point. This aberration also varies in magnitude with aperture, and is the most prominent of the aberrations just off axis.

Astigmatism and Petzval field curvature

Astigmatism and Petzval field curvature may be grouped together; for the Petzval curvature adds to the overall visual effect of the astigmatism. As these aberrations do not vary in

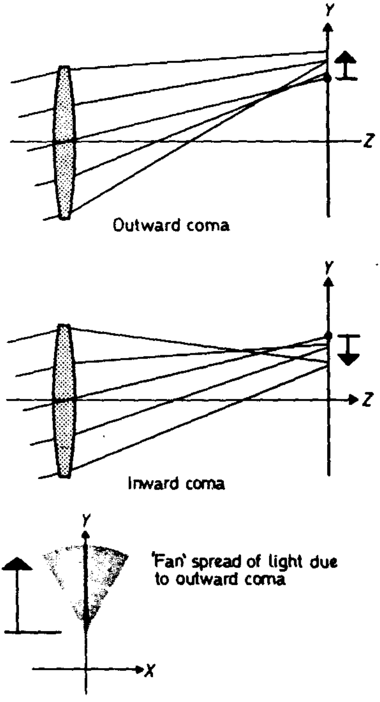


FIG. 57. Coma.

magnitude with aperture, they can be analysed and isolated from the effects of the spherical and coma aberrations by reducing the effective aperture of the lens. Fig. 58 shows that, in the presence of astigmatism, the rays coming from the vertical *Y*-axis, a tangential plane of the lens aperture, have a different focus position from those coming from the *X*-axis, a sagittal plane of the lens aperture. Thus, the image of an object point is found to have two focus positions and forms a horizontal line at the tangential focus and a vertical line at the sagittal focus.

The Petzval field curvature will alter both the sagittal and tangential focusing positions. If there is no astigmatism, the

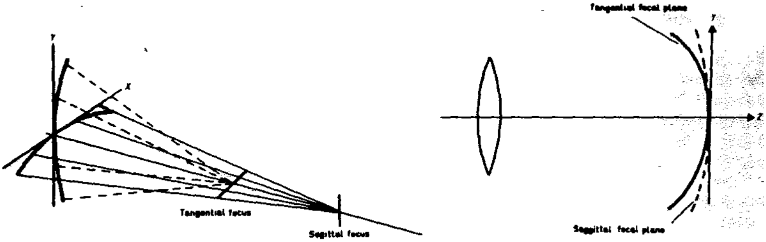


FIG. 58. Astigmatism.

image point formed will be circular and only one position of focus will be found that lies on a spherical image plane.

Distortion Verzerrung

Distortion causes the lens to vary the magnification ratio of the lens with lateral image position. Thus, in the case of *barrel* distortion the magnification decreases with increasing field angle, and, in the case of *pin cushion* distortion, the magnification increases with field angle, as illustrated in Fig. 59.

Longitudinal colour aberration

Longitudinal colour aberration is the only colour aberration that exists for the image point on the optical axis. Fig. 60 illustrates the aberration, and shows as an example where green and blue rays focus at different axial positions from the red rays. Thus, when the green-blue focus is at its best, a red symmetrical halo surrounds the image point.

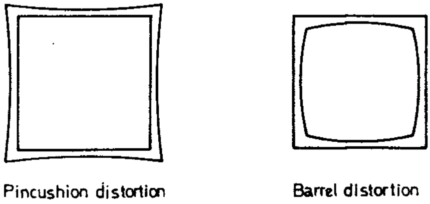


FIG. 59. Distortion.

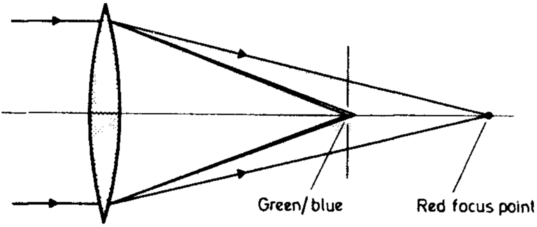


FIG. 60. Longitudinal colour aberration.

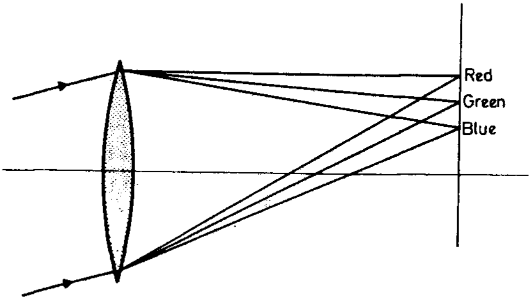


FIG. 61. Transverse colour aberration.

Transverse colour aberration

Transverse colour aberration causes the lens to have different magnification ratios for different wavelengths of light. Fig. 61 illustrates the effect. In the example, the red, green and blue images are focusing at separate lateral positions in the image plane, although originating from the same object point.

Unlike the longitudinal colour aberration, the transverse colour will produce an unsymmetrical effect with both sides of the image point having a different prominent colour.

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Index