DESIGN OF A VARIABLE-FOCAL-LENGTH OPTICAL SYSTEM

FINAL REPORT

by

Douglas Ricks and
Robert R. Shannon

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Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

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INTRODUCTION

The purpose of this study was to exam the possibility of designing a zoom lens appropriate for use on a comet explorer. The system requirements were as follows:

Variable focal length	200 to 2000 mm
Image size	18.6 x 18.6 mm
Resolution MTF	50% at 28 line pairs/mm
Spectral range	500 to 1000 nm
Volume	30 x 30 x 70 cm
Back focal distance	90 mm
Object focal distance	10 mm to infinity

The general requirements were to design a system with a variable focal length ranging from 20 to 200 cm with an overall length somewhat less than 100 cm. The requirement to place the entire system within a length less than the maximum focal length placed severe restrictions upon the design. The requirement of a wavelength range of 0.4 to 1.0 μm produced an even greater limitation upon the possibilities for a design that included a catadioptric front end followed by a zooming refractive portion.

There were other requirements relating to the range of focal distances needed and the weight and specific package within which the lens would fit. These requirements were considered of secondary importance to the major question of whether a lens could be designed to fit within the length constraints.

To examine the possibility of such an optical system, some potential designs were examined by Mr. Douglas Ricks. He began the project as a class exercise and continued it through the summer period, but had to stop work and return to his employer in mid summer. Therefore, a successful design meeting all of the space and wavelength requirements was not completed. Some of the designs investigated have the potential of being carried on toward a final design, but meeting the space, wavelength, and zoom range requirements does not seem to be possible. It may be necessary to make some compromises in the specifications or the operational approach in order to obtain a useful system.

A survey was carried out of presently available zoom systems. One approach showed the possibility of meeting the requirements and should be followed up.

The requirement for the wide wavelength range necessitates the use of a catadioptric front end for the system. As a consequence, there are some limitations on what can be accomplished. To estimate the effect of the wavelength range on the design, some simple examples were considered. For a refractive system, the amount of aberration blur in the paraxial focal plane resulting from secondary residual color is given by about d/2400, where d is the diameter of the aperture of the lens, for a wavelength range of 0.48 to 0.66 μm, or a spectral width of about 0.2 μm. The requirement for this lens is a spectral width of about 0.6 μm. Since the amount of the blur is related to the square of the wavelength range, this leads to a blur of about d/400. Refocusing should lead to a reduction of the blur by about a factor of 2, leading to a factor of d/1000 as reasonable for an estimate. Table 1 shows the estimated effect of this aberration on the system at various focal lengths for a relative aperture of f/8.

Table 1. Approximate Effect of Secondary Chromatic Aberration on an f/8 Refractive Lens System.

Focal length	Aperture diameter (mm)	Color blur (mm)	lp/mm
200	25	0.025	40.000
400	50	0.050	20.000
800	100	0.100	10.000
1200	150	0.150	6.667
1800	225	0.225	4.444
2000	250	0.250	4.000

This table indicates that, if no other aberrations are present, the spectral width limits the resolution as shown. Since the likely detector will have a sample distance of about 0.02 mm, a required level of resolution at this stage is 1.04 or 25 lines per millimeter. This system would be acceptable only at short focal lengths.

If a reflective front end were to be used, the size of the blur would be reduced in direct proportion to the demagnification of the aperture entering the refractive zoom system. If a reduction of 3 times is used, then the effective multiplier in the determination of the residual color blur becomes d/3000. Table 2 shows some values for this case.

Table 2. Approximate Effect of Secondary Color on a Catadioptric.

Focal length	Aperture diameter (mm)	Color blur (mm)	lp/mm
200	25	0.008	20.000
400	50	0.017	60.000
800	100	0.033	30.000
1200	150	0.050	20.000
1800	225	0.075	13.333
2000	250	0.083	12.000

The limiting resolution for this case can now be used as a starting point. Therefore, we can see that the color requirements lead to a catadioptric system.

There is another problem to be considered. The requirement for a central obstruction means that there will be an obstruction of variable size in the system, with a proportately larger obstruction for the shorter focal lengths. This needs to be worked out as a compromise in the final design, and might be inappropriate for this set of requirements. In addition, if an object is at a finite distance, the centrally obscured aperture will produce a normally undesirable "donut" effect from out-of-focus glints.

The above discussion is only an initial one. The use of special glasses and clever trading of space versus number of elements change the results somewhat. However, these do represent material limits upon image quality and will influence the design.

In the following sections, Mr. Ricks discusses his design work on the refractive and catadioptric system. A brief survey of the state of the art follows, at least as far as could be ascertained during the time available.

The final conclusion is to look at the possible modification of an existing design before proceeding to the full design of a new type of system.

COMPUTER STUDY

The investigation of zoom lenses began with a three-lens system based on design formulas from Modern Optical Engineering. These formulas can be expressed as:

$$R = \sqrt{M},$$

where M is the zoom ratio,

$$\phi_A = \frac{(R-1)/R}{L-(3R-1)(R+1)/4\phi R};$$

is the power of the first lens,

$$\phi_B = -\phi_A(R+1);$$

is the power of the second lens,

$$\phi_C = [\phi_A(R+1) + \phi(4/R+1)]R/(3R-1)$$

is the power of the third lens, and L is the length from the first lens to the image plane.

It can be seen that for a zoom ratio of 10, the power of the second lens is more than four times the power of the first lens. When the length L is small, the denominator of the expression for the power of lens A is near zero, hence the power of lens A is large. A short zoom lens with large zoom ratio causes the powers of all the lens elements to be large. Large powers mean large aberrations that usually require splitting each lens into a number of lenses so that the power per lens is reduced. Furthermore, higher refractive indices are necessary so that higher powers can be achieved for the same surface curvature.

The three-lens system required too much power per element and was difficult to make continuous. Therefore a four-lens system was decided upon.

The function of the first lens, when positive, is to collect the light and begin to focus it. If the second lens is negative, it can create a telephoto effect. When the second lens is close to the first lens, the focal length is at a minimum. Increasing the separation of the lenses increases the focal length.

The third lens moves to keep the image plane stationary. The fourth lens balances the powers and provides control of the aberrations. In Zoom Lenses by A. D. Clark, various types of zoom lenses are categorized according to whether the image plane is held stationary by a nonlinear movement of a lens (the mechanically compensated type) or allowed to vary slightly (as in the optically compensated type). Clark lists five types of mechanically compensated zoom lenses and three types of optically compensated lenses. When the first and fourth lenses are held fixed, the second lens is negative and the third lens is positive we have a Type-2 lens; if the third lens is negative, we have a Type-3 lens.

The Type-2 design was used with the variation of having the fourth lens negative instead of positive. Later, as the lens was optimized, the last lens became positive. In the Type-4 lens there are three moving lenses between stationary lenses, though the second and fourth lenses usually move together. The Type-5 lens has negative lenses in place of the positive lenses of Type 4 and vice versa. Types 4 and 5 combine the virtues of optically and mechanically compensated lenses, but appear to be more difficult to design. Mechanically, they are also more complicated.

After finding a solution for the powers and positions of each lens to provide a 10:1 zoom ratio of focal lengths from 200 mm to 2000 mm in a space less than 70 cm, an attempt to reduce the extremely large aberrations was made by making each lens into three elements. Each positive lens was split into two positive elements and a negative element, each negative lens into two negative elements and a positive element. The purpose of adding a negative element to a positive lens group is to better control aberrations. It is also necessary to make the positive and negative elements of different glass types. The positive elements are crown glasses with low dispersion, the negative elements are flint glasses of high dispersion.

While the addition of a negative lens of high dispersion will help to control aberrations, it does require that the positive lens have even greater lens power. An increase in lens surfaces and glass types as variables creates a gain, but the stronger curvatures cause a loss. To increase the correction available during computer optimization, one surface in each lens group was made an aspheric surface.

This lens design was faced with too many problems to promise a good solution. The chromatic aberrations were very large and troublesome. The large apertures and high curvatures meant aberration control could be achieved only by balancing high-order aberrations such that a little change somewhere immediately made everything worse. Of course it is impossible to know for certain, but it began to look like the design would require more than 20 lens elements and would be very slow to correct. When the paraxial aberrations do not provide good approximations (as when the apertures are large and powers are high as in this case) real rays must be traced. When there are a lot of surfaces and several zoom configurations, the optimization becomes extremely slow. Furthermore, it becomes important to choose carefully which variables to use in the optimization and how much weight should be placed on them. Improvements do not snap into place.

The catadioptric system offers several attractive advantages. There are no chromatic aberrations in a mirror. The aberrations are generally reduced because a mirror can provide greater lens power for a given curvature than a glass element can. Furthermore, a mirror system will fold a system that would be much longer if realized with glass optics alone. On the other hand, there are difficulties with providing an iris for relative aperture control.

When the catadioptric system was designed to keep the size of the lens elements reasonable, an intermediate focal plane was needed. A lens was placed in this focal plane to "relay" the image. The mirror surfaces were aspheric and a corrector plate was placed in front.

Basically the mirror system concept seems to work well. The mirrors do most of the light collection and focusing without introducing a lot of aberrations. With the relay lens the glass elements can be kept small, so the entire system should be rather lightweight.

In the mirror system the wide angles of the shorter focal lengths becomes a problem. It was decided to concentrate on the focal range of 360 mm to 2000 mm. The extreme wavelength range made it difficult to obtain good aberration correction, so the range was reduced to 0.435 μm to 0.70 μm. This was a great improvement.

In the catadioptric design selected, the zooming is accomplished by moving glass elements after the mirror elements. The room available here is not great (about 40 cm) and the lens powers were still high. A zoom system of all positive lenses significantly reduces the powers necessary. It also presents other problems, i.e., it was necessary to add a "field flattener" just before the focal plane to reduce the field curvature.

Because of the central obscuration (from the secondary mirror) the clear aperture necessary to obtain a constant light intensity on the image plane throughout the zoom range is more complicated. At the shorter focal lengths only a small ring of aperture is available, thus reducing the MTF values.

PATENTS

Three zoom lens patents were received from the U. S. Patent Office (see Appendix A). The patent numbers were found in the book Zoom Lenses by A. D. Clark. The most recent of these patents is, unfortunately, more than 20 years old. A great deal of progress has been made in zoom lenses since then. These patents describe useful general design considerations. Two of the patents give refractive index and Abbé numbers for a representative system.

The ACCOSV zoom system described by Takeno's patent was put on. The system has 32 independent glass surfaces, and uses 13 different types of glasses—many of them exotic. Since only the refractive index and Abbé number were given, the exact glasses used were not known. Although described as compact, when scaled up to the 200- to 2000-mm focal length requirements, the system became extremely long (2878 mm). Furthermore, the correction at 0.4 μm and 1.0 μm was terrible, although this may be due to an error made in glass selection. Ray fan plots are shown in Appendix B. The lens was rescaled to conform to the length requirements, but the aberrations were tremendous with the increased element powers to achieve the desired focal lengths. No doubt further computer optimization could reduce aberrations and maintain physical length and focal lengths.

CORRESPONDENCE

Letters were sent to seven companies that manufacture zoom lenses. The names and addresses are given in Appendix C. Of these companies, replies were received from three: Celestron, Angenieux, and Zoomar. In fact, Angenieux sent two replies from separate branch offices.

The first from Angenieux said that their zoom 10×18-T2 lens might work, although the back focal length was only 50 mm. To reach a longer back focal length, the zoom 10 × 40-T1 was needed. These lenses have a maximum focal length of only 180 mm and 400 mm. The f/number varies with the focal length.

The second reply from Angenieux was from a different office that had received the inquiry via Arriflex. They claimed to be able to meet the requirements with one of their 42× zoom lenses. Table 3 lists the requirements and how well the various commercial products meet those requirements. Further information is provided in Appendix C.

Celestron did not have what was required. They do sell telescopes of the appropriate focal length and zoom oculars, but these zoom oculars would allow a zoom ratio of only about 2× and are for visual and not camera or photographic use.

The Zoomar Universal Tracker combination is a system that can be adapted to various cameras, vidicons, or other instruments. The basic unit has a maximum focal length of 900 mm, but Zoomar can provide a 2× extender to increase this to 1800 mm. Frequently Zoomar modifies their products to meet customer requirements. The Universal Tracker comes with a 4-post filter wheel and has little room otherwise between lens and image plane.

Table 3. Comparison of Some Commercial Zoom Lenses.

	Angenieux				Zoomar with 2X extender universal tracking
	10×18-T2	10×40-T1	42×24	42×32	
Focal length (mm)					
Minimum	18	40	24	32	180
Maximum	180	400	1000	1350	1800
Relative aperture	∿f/2.5	∿f/1.5	f/1.7- f/5.7	f/2.3- f/7.6	f/11
Image size diam. (mm)			16	21.4	25.4
Minimum object distance			4 m	4 m	800 ft
Size					
Height (mm)			190	190	300
Width (mm)			220	220	200
Length (mm)			∿700	∿700	700-800
Weight (lb)			∿75	∿75	60-90
Resolution					
50% MTF at center (1/mm)			∿15	∿15	∿25
25% MTF at corner (1/mm)			∿15	∿15	∿25

One requirement not specifically addressed by the commercial suppliers of zoom lenses is the performance of the lens at wavelengths other than the primary design wavelength. Angenieux shows that the transmission drops off to about 15% and 25% at 0.4 μm and 1.0 μm respectively. Neither Angenieux nor Zoomar shows how the MTF depends on wavelength.

CONCLUSIONS AND RECOMMENDATIONS

The refractive-optics zoom lens design created for this project must be improved before the aberrations can be reduced sufficiently for the required resolution. While improvements could be made with further computer optimization, an additional six or more elements would probably be required. Several of these would be large and utilize expensive, exotic glasses. Probably several aspheric components would also be necessary. It is possible that no reasonable amount of effort nor addition of lens elements would improve the lens performance sufficiently. The basic problems include too much variation of focal length, too large a focal length, too wide a spectral range, and too compact a space requirement. The present preliminary design is given in Appendix D.

A catadioptric system, that is, a system with both mirror and glass components, was also investigated. The degree of aberration control is much greater in this system. To some extent this is because more time was spent optimizing this system than was spent optimizing the refractive optics system. The catadioptric system started out with lower aberrations. Furthermore, the spectral width and the zoom ratio were reduced so further progress could easily be made. Further optimization would certainly be possible, but meeting the resolution and spectral range requirements would very likely require several more components. The catadioptric system has good chromatic aberration control and low light loss, but stray light control and relative aperture control are not as good. Details of this preliminary design are found in Appendix E.

In conclusion, the refractive optics design would be heavy, require numerous elements, be difficult and time consuming to perfect, and may be unsuitable for near-ultraviolet and near-infrared wavelengths. The catadioptric system would also require more optimization, possibly a few more elements, and would have a restricted zoom range of about 360 to 2000 mm. Of the two designs, the catadioptric system probably has the best chance of success, as long as the shortest focal lengths are not really needed.

Zoomar Corporation has an existing catadioptric with zoom that begins to approach the requirements. A suggested approach is to determine if Zoomar can modify their present lens to fit the space and weight requirements. The extent to which this can be done can be estimated from the current design work.

LITERATURE

The following is a list of some interesting sources of information on zoom lenses. A brief description of some useful ideas in each reference is included.

1. Monographs in Applied Optics No. 7. Zoom Lenses, by A. D. Clark. American Elsevier Publishing Company, Inc., New York. 1973.

   An excellent source of information on zoom lenses. The small book includes a brief history, descriptions of mechanically and optically compensated zoom lenses, design formulas, information on focusing, and mechanical factors. There are a couple of dozen patent numbers given, drawings, and information on usage of various types of zoom lenses.

   There are descriptions of five types of mechanically compensated lenses (our refractive lens design is Type 2) and three types of optically compensated lenses. Curvatures and glass types are not given.

2. Photographic Optics by Arthur Cox. Focal Press, London and New York. 1966.

   This book contains a good introduction to zoom lenses and some helpful ideas for mirror lens systems. There are descriptions of four types of mechanically compensated zoom lenses. There are three pages of tables listing zoom lenses and 38 drawings. The longest focal length given is 40 inches. Specific lens curvatures or glass types are not given.

3. <u>Lens Mechanism Technology</u> by D. F. Horne. Adam Hilger, London. 1975.

There is a wealth of useful information on the mechanical aspects of zoom lenses in this book (the details of cam movements and so forth). Several of the systems described have zoom ratios of 10:1 or more. The zoom lenses illustrated have between 14 and 31 elements. Again, no specific design information for optical design.

The book also points out some of the advantages and disadvantages of mirror or catadioptric systems: freedom from chromatic aberration, low-light absorption, wide range of wavelengths, support of optical surfaces from the back. It mentions that adjustments to relative aperture are "impossible."

4. <u>Photographic Lenses</u> by C. B. Neblette.

In many mirror systems there are glass elements that optically come after the secondary mirror but physically come between the two mirrors. Apparently with the proper baffles, you can get away with this. It might help to provide room for the movement of the glass zoom components thus reducing element powers and improving aberration control.

Another interesting point was that the last lens group frequently contains six or more elements to reduce system aberrations. Distortion is always a problem in a zoom lens.

5. The Photographic Lens, by Hans Martin Brandt. The Focal Press. 1968.

There is a rather good discussion on methods of design for close focusing. There are about 20 pages of a table listing zoom lenses. There are a few 10:1 zoom ratio lenses, one made by Fujinon goes from 80 to 800 mm for a TV format.

6. Physical Optics in Photography, by Georg Franke. Focal Press. 1966.

Some help for the design of mirror lenses and for first-order zoom lenses.

7. Journal of the SMPTE Vol. 30. "Recent trends and developments of zoom lenses," by G. H. Cook and F. R. Laurent. August 1971.

This article describes some ways to achieve close focusing. Basically, one uses a positive and a negative lens of equal but opposite power. Moving them apart affects the distance the object must be from the lens to be in focus. There is a description of a zoom lens which is somewhat between an optically compensated and a mechanically compensated lens.

8. Journal of the SMPTE, Vol. 77. "The surveyor variable and fixed focal-length lenses," by Carvyn Ellman. April, 1968.

It was found that special glasses were not necessary for use in space. The design did avoid cemented doublets to make sure outgassing would not be a problem.

9. Modern Optical Engineering, by Warren J. Smith. McGraw-Hill. 1966.

Contains a good discussion of catadioptric systems. There are also some useful formulas for the design of a Type-1 (Clark's categories) zoom lens.

APPENDIX A

OPTICAL SYSTEM PATENTS

Append.x D.1

like type 5

Feb. 26, 1957 **H. H. HOPKINS** **2,782,684**

VARIABLE MAGNIFICATION OPTICAL SYSTEMS

Filed Oct. 5, 1954 2 Sheets-Sheet 1

Fig. 1.

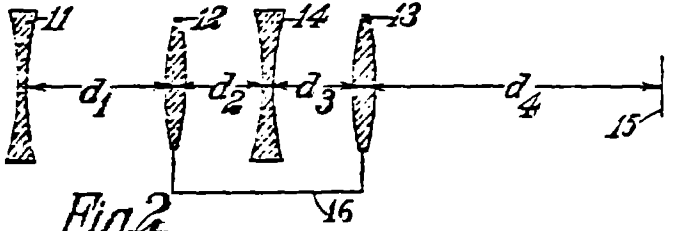


Fig. 2.

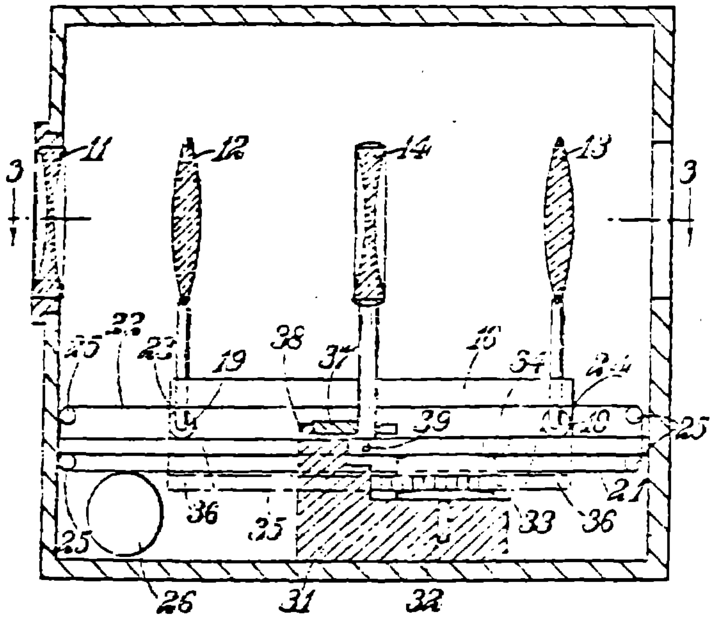


Fig. 5.

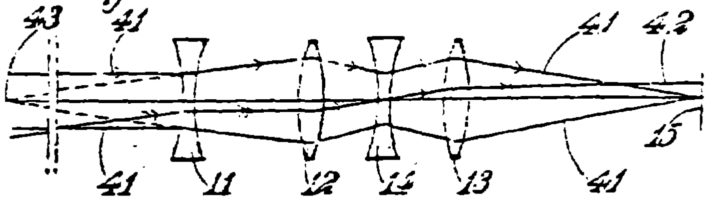
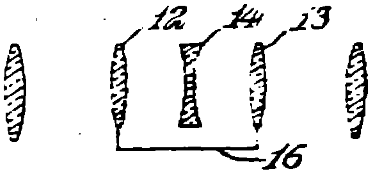


Fig. 6



INVENTOR

Harold H. Hopkins

by Watson, Cole, Grindle & Watson

ATTORNEYS

ORIGINAL PAGE IS OF POOR QUALITY

Feb. 26, 1957 H. H. HOPKINS 2,782,684

VARIABLE MAGNIFICATION OPTICAL SYSTEMS

Filed Oct. 5, 1954 2 Sheets-Sheet 2

Fig. 3.

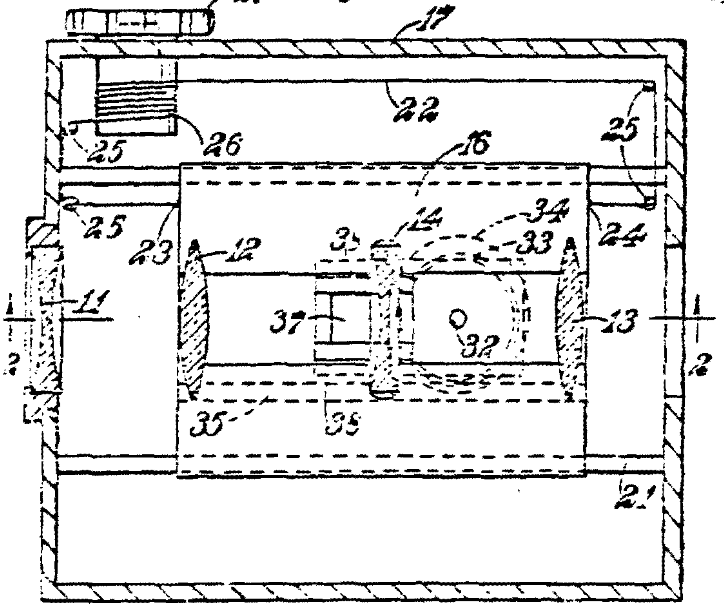
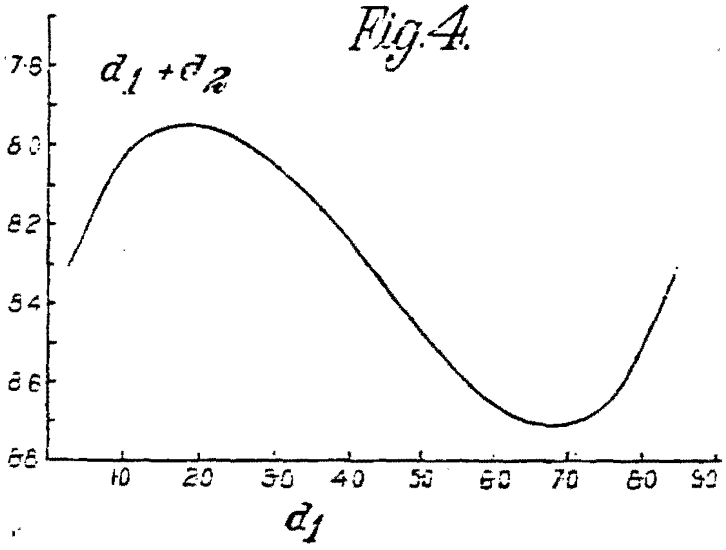


Fig. 4.



INVENTOR
Harold H. Hopkins
By Watson, Cole, Grindle & Watson
ATTORNEYS

2,782,684

VARIABLE MAGNIFICATION OPTICAL SYSTEMS

Harold Horace Hopkins, London, England, assignor to W. Watson & Sons Limited, London, England, a British company

Application October 5, 1954, Serial No. 460,361

Claims priority, application Great Britain October 9, 1953

13 Claims. (Cl. 88—57)

The invention relates to variable magnification optical systems of the kind (hereinafter referred to as the kind described) which may be used alone or in conjunction with a further optical system (e. g. the lens system of a camera) to produce an image of continuously variable size of an object at a fixed distance from the system. Such a system may be used for example in or with a stationary cine camera or television transmitting camera in order continuously to increase or decrease the size of the image, on the film or other image receiving device, of objects in the scene towards which the camera is directed and thereby to give the impression when the film is projected, or the television receiver is viewed, that the view-point approaches or recedes from objects in the scene.

Examples of variable magnification optical systems of the kind described are described and claimed in United States Patents Nos. 2,501,219, 2,566,889, 2,537,561 and 2,514,239 and United States patent applications Serial Nos. 236,482, now Patent No. 2,663,223 dated December 22, 1953, and 308,825, now Patent No. 2,741,155 dated April 10, 1956.

It is an object of the invention to provide an improved variable magnification optical system of the kind described.

The invention provides a variable magnification optical system comprising two positive (convergent) lenses and a negative (divergent) lens, all arranged on a common optical axis with the two positive lenses spaced apart and the negative lens between the two positive lenses and spaced from at least one of them, the lenses being movable axially and the positive lenses being constrained to maintain a constant axial distance between them during their axial movement, and, in combination with the lenses, magnification varying means for continuously and simultaneously moving the two positive lenses and the negative lens along the optical axis relative to a stationary base or like support according to a law such that the distance from a fixed point on the base at which the image of an object at a fixed distance from the said fixed point on the base is accurately focussed remains constant while the size of the said image is continuously varied during the operation of the magnification varying means, the distance between the image position for the rear one of the said positive lenses and the corresponding conjugate object position for the other of the said positive lenses being finite and not greater numerically than a small multiple of (e. g. 10 times, or more preferably 7 times) the focal length of either of the said movable lenses. This last mentioned condition ensures that the object distance for the front movable positive lens and the image distance for the rear movable positive lens are both finite, and consequently the individual magnifications produced by each of the said positive lenses change as the positions of these lenses are changed by the operation of the magnification varying means.

It will be appreciated that when the system includes one or more lenses interposed between the rear one of the said positive lenses and the final image position for the system, the said image position for that rear one of the said positive lenses will be the position of the intermediate real or virtual image formed by that rear positive lens, otherwise it will be the position of the final image for the system. Similarly, when the system includes one or more lenses interposed between the other (front) one of the said positive lenses and the actual object position the said conjugate object position for the front one of the said positive lenses will be the intermediate real or virtual image which acts as the effective object for that front positive lens, otherwise it will be the actual object position for the system.

Furthermore the system is preferably designed and used so that the magnifications of the two movable positive lenses are of like sign, preferably such that each movable positive lens produces an inverted image of the effective object for that lens. This preferred condition is satisfied if the object distance for the front movable positive lens is negative in sign and numerically greater than the focal length of the said front movable positive lens, and the image distance for the rear movable positive lens is positive in sign and numerically greater than the focal length of the said rear positive movable lens, an object or image distance being regarded herein as negative or positive according as the said object or image is in front of or at the rear of the lens to which it refers. When the magnifications of the two movable positive lenses are so arranged to be of like sign in any given position of the said movable positive lenses, the said magnifications change in such a manner, when the lenses are displaced as described above, that they both increase together or decrease together in numerical value (according as the said displacement of the movable positive lenses is in one direction or the other), and hence both act in the same sense so far as their effect in increasing or decreasing the size of the fixed final image is concerned. When the movable positive lenses are displaced relative to the base, by the operation of the magnification varying means, the movable negative lens is simultaneously displaced by the said magnification varying means by an amount such that the distance from an object in a fixed position relative to the base to the image of that object produced by the action of the two movable positive lenses and the movable negative lens taken together remains constant. There will be, in general, two positions of the movable negative lens for which this condition is satisfied and to distinguish between these two positions the movement of the movable negative lens relative to that of the movable positive lenses is preferably arranged such that the magnification of the movable negative lens increases or decreases numerically according as the magnifications of the movable positive lenses increase or decrease in numerical value. The individual magnifications of all the three movable lenses then simultaneously and continuously increase or decrease in numerical value as the positions of the said three movable lenses are simultaneously and continuously varied by the operation of the magnification varying means, and this constitutes a valuable preferred feature of the invention.

The ranges of movement of the lenses are preferably such that the maximum and minimum magnifications of the system are reciprocals one of the other. This is advantageous in correcting the aberrations of the system. The two movable positive lenses preferably have equal focal lengths and the movements of the three movable lenses are preferably such that during their range of movements the position of the negative lens relative to the two positive lenses changes from near one of the positive lenses (to give one limit value of magnification) to near the other of the positive lenses (to give another limit value of magnification, which limit value is the reciprocal of the other limit value). The focal lengths of the lenses of the system are preferably such as to give approximately equal amounts of positive and negative power in the system.

The maximum distance through which it is necessary for the negative lens to be moved has been found to depend upon the value of the said constant axial distance between the two positive lenses. It has been found that the necessary displacement of the negative lens, relative to a fixed point on the base, is in one sense for small values of the constant axial distance between the two positive lenses and is in the opposite sense for suitable larger values of that constant distance. To simplify the mechanical design of the magnification varying means the value of the constant axial distance between the two positive lenses may be chosen so that the distance through which the negative lens has to be moved is at a minimum or at least is small. To satisfy other conditions, however, (e. g. correction of aberrations) it may be desirable to employ a different constant axial distance between the positive lenses and consequently to move the negative lens through a larger distance. It has been found that an increase in the value of the constant axial distance between the two positive lenses results in it being necessary to move those lenses through a smaller distance relative to the base to achieve any given range of magnification, and that, alternatively, movement of the positive lenses through the same distance provides a greater range of magnification.

In conjunction with any given focal length for the negative lens, the positive lenses may have any of a range of focal lengths. An increase in the value of the focal lengths of the positive lenses enables a greater range of magnification to be achieved.

In the system of the present invention the individual magnifications of all of the three movable lenses change in one and the same direction when the magnification varying means are operated to change the magnification of the complete system. Consequently the three lenses all contribute in the same sense the desired change in magnification.

The invention enables very large variations of magnification to be obtained without the overall length of the system being excessive.

The system may include two fixed or stationary lenses positioned on the optical axis, respectively optically before and after the three movable lenses. The stationary lenses may be both of the same sign and are preferably both positive lenses. They are preferably of equal focal length and symmetrically positioned about the mid-position of the three movable lenses. The inclusion of such a pair of fixed positive lenses increases the overall length of the system but facilitates the correction of aberrations. The effect of the fixed lenses is to increase the angle of rays of the axial pencil, thereby affording the possibility of an increased relative aperture (lower F number) with the same linear lens diameters. In this case by arranging that the power of the rear fixed positive lens is greater than that of the front fixed positive lens the equivalent focal length of the system is reduced by a factor which is greater than the reduction of the overall length and, in consequence, as stated above the advantage of great reduction of overall length is lost. It remains, however, that when a large range of magnification is contemplated that advantage is obtainable and this is of considerable advantage to the designer.

The ranges of movement of the movable lenses are preferably such that at one, or each, limit of their movement the movable negative lens lies very close to one of the movable positive lens, the criterion of closeness being that the principal planes of the movable negative lens and the adjacent movable positive lens shall have a separation which is very small in comparison with their focal lengths. A fixed or normally stationary lens, preferably a negative lens, may be positioned optically in front of the movable lenses and may be adjustable along the axis to focus the system for objects at various distances from the base. The normally stationary negative lens may be of such focal length that when it is focused for an infinite object distance the position of the normally stationary negative lens is such that it just permits the full range of movement of the movable positive lenses, with a clearance determined only by practical considerations. A diaphragm stop for the system may be placed in contact with the movable negative lens and when the whole system is working in its wide angle position the separation between the normally stationary negative lens and the front one of the movable positive lenses may be of the order of the focal length of the normally stationary negative lens. If the movable negative lens is in contact with the positive lens nearest to the normally stationary negative lens, then the stop position so determined constitutes the exit pupil for the normally stationary negative lens and, in consequence, the distance of the entrance pupil for this lens will be at a distance rearwardly of it of the order of half its focal length, and this means that the incidence heights for the principal rays are small for a lens of this kind and hence permit the use of a large angle field. This is of importance in correcting the aberrations.

A specific example of a system embodying the invention will now be described by way of example and with reference to the accompanying drawings, in which:

Figure 1 is a diagrammatic longitudinal section showing the optical arrangement of the system:

Figure 2 is a longitudinal sectional view of the system, taken on the line 2—2 of Figure 3:

Figure 3 is a sectional view taken on the line 3—3 of Figure 2:

Figure 4 is a graph showing the movement of the movable negative lens relative to the base.

Figure 5 shows ray paths through the system, and

Figure 6 shows a modified system including two positive lenses respectively optically before and after the three movable lenses.

In this example the system comprises a normally stationary negative lens 11, two movable positive lenses 12, 13 and a movable negative lens 14. An image receiver, e. g. a film, is placed at 15. The movable positive lenses 12, 13 are rigidly mounted on a carriage 16, which maintains them at a constant axial distance apart.

The lenses are housed in a casing 17 having a base 18. The carriage 16 has wheels 19 which run on rails 21 secured to the casing 17, and the carriage is propelled along the rails by a taut driving wire 22 which has its ends attached to the carriage at 23, 24. The wire 22 passes over guide pulleys 25 and is wound several times around a drum 26. The drum may be rotated in either direction by a control knob 27, thereby to drive the carriage along the rails and so move axially the two positive lenses 12, 13.

A block 31 secured rigidly to the base 18 provides a stationary bearing for a vertical shaft 32 carrying for rotation together with it a gear wheel 33 and a cam 34. The gear wheel 33 meshes with a rack 35 carried by the carriage 16 and rigidly suspended beneath it by brackets 36. Thus as the carriage moves along the rails the engagement between the gear wheel 33 and the rack 35 causes the cam 34 to rotate, its angular position at any instant being determined by the position of the carriage along the length of the rails.

The movable negative lens 14 is carried by a slide 37 which is guided for movement parallel to the axial direction of the lenses by suitable shaped parts 38 formed at the upper end of the block 31. The slide 37 has a downwardly projecting pin 39 which engages with the periphery of the cam 34, the slide 37 being urged by a spring (not shown) to maintain the pin 39 in contact with the cam. As the cam rotates the slide 37, and consequently the negative lens 14, are moved axially in accordance with the required law. Thus manual rotation of the control knob 27 moves the three lenses 12, 13, 14 in the required manner.

The law of movement of the movable lenses in this example is as indicated in the following table which shows the variation in the axial distances d_1, d_2, d_3 and d_4:

F	d_1	d_2	d_3	d_4	d_1+d_2
64.738	0.3132	8.0	0.0	17.252	8.3132
53.226	0.6525	7.5	0.5	17.014	8.1525
45.122	1.0743	7.0	1.0	16.631	8.0743
34.565	1.4664	6.5	1.5	16.198	7.9664
27.000	1.9024	6.0	2.0	15.715	7.9024
20.865	2.4563	5.5	2.5	15.178	7.9563
15.9067	3.072	5.0	3.0	14.595	8.072
12.000	3.692	4.5	3.5	13.974	8.192
9.0000	4.333	4.0	4.0	13.333	8.333
6.750	4.974	3.5	4.5	12.692	8.474
5.0626	5.595	3.0	5.0	12.072	8.595
3.8015	6.178	2.5	5.5	11.4443	8.678
3.0076	6.715	2.0	6.0	10.9124	8.715
2.3446	7.395	1.5	6.5	10.4284	8.895
1.87520	7.631	1.0	7.0	10.1353	8.631
1.22272	8.014	0.5	7.5	9.6529	8.514
1.21025	8.252	0.0	8.0	9.2122	8.252

The lenses have the following focal lengths (f):

Lens	Focal Length
11	$f_{11}=-9$
12	$f_{12}=+5$
13	$f_{13}=+5$
14	$f_{14}=-2$

The above dimensions are expressed in inches.

The first table given above includes the value of the focal length (F) of the system, expressed in inches, for each of the listed positions in the movements of movable lenses. It will be seen that the ratio of the maximum to the minimum focal length (and consequently the ratio of the maximum to the minimum magnification) is about 50:1. The overall length of the system is only of the order of one third of the maximum focal length thereof.

It may be seen from the above table that in this example the movement of the movable negative lens relative to a fixed point on the base, which movement is determined by the variation in the numerical sum of the distances d_1 and d_2 is small. The variation of the sum (d_1+d_2) with the distance d_1 is shown in the above first table and is also shown graphically in Figure 4. That data defines the shape of the cam 34.

Figure 5 shows the paths of rays 41 which reach the system, parallel to the axis, from the object which in this example is at infinity i. e. a very large distance away, and a ray 42 from the object, which ray reaches the system at an angle of about 5 degrees to the axis.

The lens 11 forms a virtual image at its focus 43 and that virtual image serves as the effective object for the front positive lens 12. The axial distance between the point 43 and the image receiver 15 is 34.67 inches, i. e. just under seven times the focal length of each of the positive lenses 12, 13.

The lenses are shown merely diagrammatically in the drawings and the distances given in the above first table are calculated from the simplified theory of thin lenses. The lenses are each individually corrected for chromatic aberrations and each of them may comprise two or more component lenses cemented together or spaced apart by a fixed distance or having a combination of cementing and fixed spacing.

The field curvature may be readily made small as the absolute powers of the lenses have an algebraic sum which is small. As the changes in magnification of the complete system are contributed to substantially equally by the three movable lenses respectively the correction of the other aberrations is facilitated.

The system of this example may be employed in conjunction with a television transmitting camera, a cine camera or the like but it may alternatively be employed, for example, as a variable focal length projection lens for a film projector.

The invention is not restricted to the details of the foregoing example. For instance the three movable lenses may be employed alone, or with a pair of stationary positive or negative lenses optically before and after them, to provide a symmetrical system of variable power working about a mean magnification of minus 1, which system is suitable for lenses of the kind known as process lenses.

I claim:

1. A variable magnification optical system comprising two positive (convergent) lenses and a negative (divergent) lens, all arranged on a common optical axis with the two positive lenses spaced apart, and the negative lens between the two positive lenses and spaced from at least one of them, the said lenses all being movable axially and the positive lenses being constrained to maintain a constant axial distance between them during their axial movement, and, in combination with the lenses, magnification varying means for continuously and simultaneously moving the two positive lenses and the negative lens along the optical axis relative to a stationary support according to a law such that the distance from a fixed point on the support at which the image of an object at a fixed distance from the said fixed point on the support is accurately focussed remains constant while the size of the said image is continuously varied during the operation of the magnification varying means, the distance between the image position for the rear one of the said positive lenses and the corresponding conjugate object position for the other of the said positive lenses being finite and not greater numerically than a small multiple of the focal length of one of the said positive lenses.

2. A variable magnification optical system as claimed in claim 1, in which the object distance for the front one of the said positive lenses is negative in sign and numerically greater than the focal length of that front positive lens, and the image distance for the rear one of the said positive lenses is positive in sign and numerically greater than the focal length of that rear positive lens.

3. A variable magnification optical system as claimed in claim 2, in which the movement of said negative lens relative to that of the said positive lenses is such that the magnification of the said negative lens increases and decreases numerically according as the magnifications of the said positive lenses increase and decrease in numerical value.

4. A variable magnification optical system as claimed in claim 3, in which the ranges of movement of the said three lenses are such that the maximum and minimum magnification of the system are reciprocals one of the other.

5. A variable magnification optical system as claimed in claim 4, in which the said two positive lenses have equal focal lengths.

6. A variable magnification optical system as claimed in claim 5 in which the movements of the said three lenses are such that during their range of movements the position of the negative lens relative to the two positive lenses changes from near one of the positive lenses, at one limit value of magnification, to near the other of the positive lenses, at another limit value of magnification, which limit value is the reciprocal of the other limit.

7. A variable magnification optical system as claimed in claim 6, in which the ranges of movement of the movable lenses are such that at one, or each limit of their movements the said negative lens lies very close to one of the said positive lenses, the criterion of closeness being that the principal planes of the said negative lens and the adjacent positive lens have a separation which is very small in comparison with their focal lengths.

8. A variable magnification optical system comprising

two positive lenses and a negative lens, all arranged on a common optical axis with the two positive lenses spaced apart, and the negative lens between the two positive lenses and spaced from at least one of them, the said lenses all being movable axially and the positive lenses being constrained to maintain a constant axial distance between them during their axial movement, magnification varying means, in combination with said lenses, for continuously and simultaneously moving the two positive lenses and the negative lens along the optical axis relative to a stationary support according to a law such that the distance from a fixed point on the support at which the image of an object at a fixed distance from the said fixed point on the support is accurately focussed remains constant while the size of the said image is continuously varied during the operation of the magnification varying means, the distance between the image position for the rear one of the said positive lenses and the corresponding conjugate object position for the other of the said positive lenses being finite and not greater numerically than a small multiple of the focal length of either of the said positive lenses, and two stationary lenses positioned on the optical axis, respectively optically before and after the said three movable lenses.

9. A variable magnification optical system as claimed in claim 8, in which the stationary lenses are both positive lenses, are of equal focal length and are symmetrically positioned about the mid-position of the three movable lenses.

10. A variable magnification optical system comprising two positive lenses and a negative lens, all arranged on a common optical axis with the two positive lenses spaced apart and the negative lens between the two positive lenses and spaced from at least one of them, the said lenses all being movable axially and the positive lenses being constrained to maintain a constant axial distance between them during their axial movement, magnification varying means, in combination with said lenses, for continuously and simultaneously moving the two positive lenses and the negative lens along the optical axis relative to a stationary support according to a law such that the distance from a fixed point on the support at which the image of an object at a fixed distance from the said fixed point on the support is accurately focussed remains constant while the size of the said image is continuously varied during the operation of the magnification varying means, the distance between the image position for the rear one of the said positive lenses and the corresponding conjugate object position for the other of the said positive lenses being finite and not greater numerically than a small multiple of the focal length of one of the said positive lenses, and a stationary lens positioned optically in front of the said three movable lenses.

11. A variable magnification optical system as claimed in claim 10, in which the said stationary lens is a negative lens.

12. A variable magnification optical system as claimed in claim 11, in which the said stationary lens is adjustable along the axis to focus the system for objects at various distances from the support.

13. A variable magnification optical system as claimed in claim 12, in which the said stationary lens is of such focal length that when it is focussed for an infinite object distance said stationary lens is positioned to just permit the full range of movement of the movable positive lenses.

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Appendix D.2

Type 1

Feb. 23, 1965 **H. E. ROSENBERGER ETAL** 3,170,984

ZOOM OPTICAL SYSTEM

Filed May 29, 1961 2 Sheets-Sheet 1

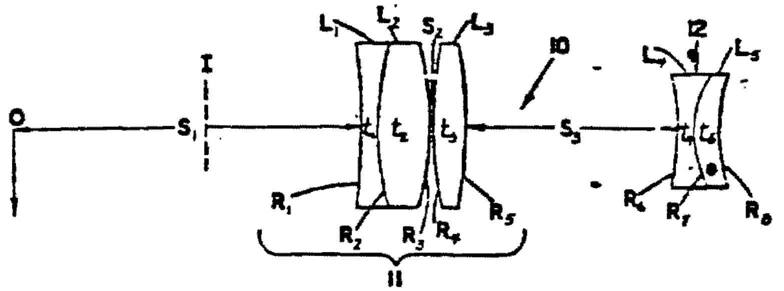

FIG. 1

Short object to lens spacing

Flat-crown-crown crown-flat

ZOOM SYSTEM MAGNIFICATION RANGE = 12 : 1					
LENS	RADIUS	THICKN'S	SPACINGS	n_D	✓
L_1	$R_1 = -177.01$ $R_2 = 37.67$	$t_1 = 2.5$	S_1 = 63.395 at 1.2 X	1.720	29.3
L_2	$R_3 = -37.67$	$t_2 = 7.8$	= 45.901 at 14.4 X	1.498	57.0
L_3	$R_4 = 53.45$ $R_5 = -65.46$	$t_3 = 4.5$	S_2 = 0.3	1.517	64.5
L_4	$R_6 = -50.58$ $R_7 = 16.14$	$t_4 = 2.6$	S_3 = 16.635 at 1.2 X	1.517	64.5
L_5	$R_8 = 27.04$	$t_5 = 3.2$	= 160.731 at 14.4 X	1.720	29.3

FIG. 2

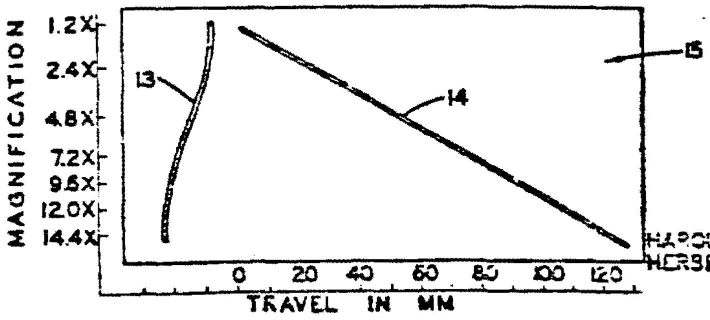

FIG. 3

HAROLD E. ROSENBERGER
HERBERT D. KORONES
INVENTORS

BY Frank C. Parker

ATTORNEY

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ZOOM OPTICAL SYSTEM

Filed May 29, 1961 2 Sheets-Sheet 2

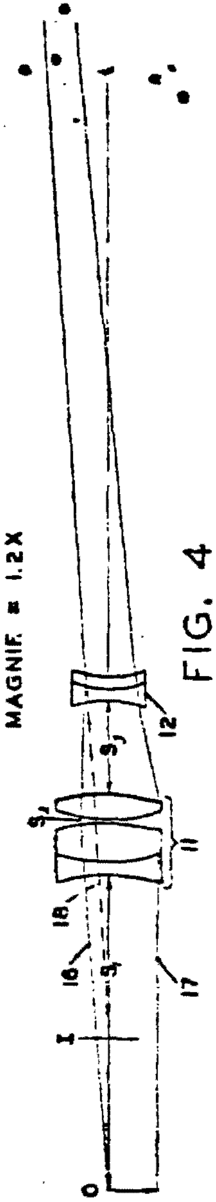


FIG. 4

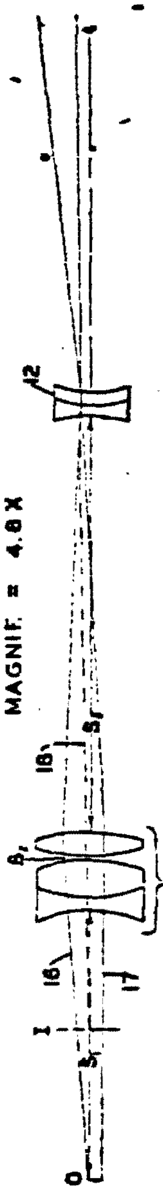


FIG. 5

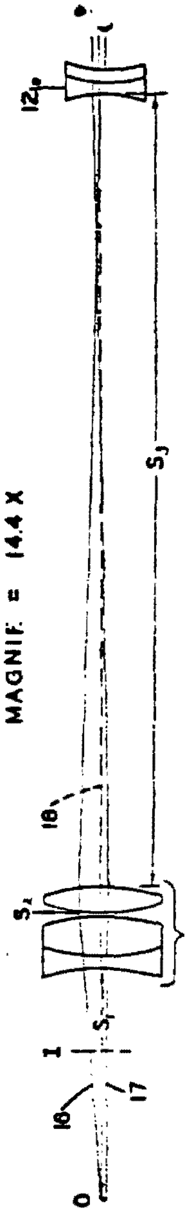


FIG. 6

INVENTORS
HAROLD E. ROSENBERGER
HERBERT D. KORONES
BY Frank C. Parker
ATTORNEY

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,170,984 February 23, 1965

Harold E. Rosenberger et al.

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 5, line 19, for "$.32F_1 < +F_7 < .39F_1$" read -- $.32F_1 < +R_7 < .39F_1$ --.

Signed and sealed this 17th day of August 1965.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents

United States Patent Office

3,170,984

Patented Feb. 23, 1965

3,170,984

ZOOM OPTICAL SYSTEM

Harold E. Rosenberger, Brighton, and Herbert D. Korones, Rochester, N.Y., assignors to Bausch & Lomb Incorporated, Rochester, N.Y., a corporation of New York

Filed May 29, 1961, Ser. No. 113,474
5 Claims. (Cl. 88—57)

The present invention relates to optical systems and more particularly relates to improvements in zoom type of pancratic optical systems.

In recent years, lens designers have developed a number of zoom type of pancratic optical systems for use on various kinds of optical apparatus and generally these systems are very complex in structure and high in cost whenever high grade imagery is achieved. For many purposes the magnification range is found to be too limited, particularly when superior imagery is demanded along with a large magnification range.

It is an object of the present invention to provide a novel zoom type of pancratic optical system which produces a virtual image of an object at a stationary position, said system being corrected in a superior manner for all chromatic and monochromatic image aberrations as well as distortion and flatness of field.

Another object of this invention is to provide such a device having an extraordinarily large magnification range of 12:1 or more without sacrificing any of the aforementioned desirable optical characteristics.

A still further object is to provide such a zoom optical system having utmost structural and optical simplicity consistent with superior optical performance and low cost.

Further objects and advantages of this invention will be found in the form and arrangement and in the details of structure of the parts thereof by reference to the specification herebelow when studied in connection with the accompanying drawings in which:

FIG. 1 is an optical diagram showing a preferred form of the present invention,

FIG. 2 is a table of constructional data which is related to the optical system in FIG. 1;

FIG. 3 is a chart which is explanatory of certain features of this invention,

FIG. 4 is an optical diagram of this invention showing one operative position thereof, and

FIGS. 5 and 6 are further optical diagram showing other operative positions thereof.

An optical system generally indicated by numeral 10 is shown in FIG. 1 of the drawing, according to a preferred form of the present invention.

According to this invention, said system 10 comprises a front lens member 11 of positive power and a rear lens member 12, of negative power which cooperatively produce a virtual image I of an object O, said image being formed in the space S_1 at a stationary position between the object O and the lens member 11. Mechanical means, not shown, are provided for mounting members 11 and 12, for axial motion, and for moving said members differentially and simultaneously as shown in FIG. 3 with respect to any fixed point on their optical axis so that the virtual image I may be continuously varied in size at said stationary position throughout a range of magnification of 12:1 or more.

The optical construction of the lens system 10, is especially designed for an extended range of magnification beyond 12:1 if desired and this useful property of the system is achieved along with other high grade features such as a superior correction for all chromatic and monochromatic image aberrations as well as coma, astigmatism, distortion and flatness of field. The front lens member 11 has a positive focal length F_1 and the rear lens member 12 has a negative focal length F_2 per se which is numerically expressed by the inequality,

$$.85F_1<-F_2<.95F_1$$

The variable space S_1 between the member 11 and the object changes throughout the zoom range and at the terminal ends of its travel it has the values given herebelow.

$$1.25F_1<S_1<1.55F_1 \text{ (at } 1.2\times)$$
$$.90F_1<S_1<1.20F_1 \text{ (at } 14.4\times)$$

Likewise, the space S_3 between the lens member 11 and member 12 changes throughout the zooming action, varying as shown diagrammatically in FIG. 3.

In the preferred form of the invention as shown in FIG. 1, the front lens member 11 comprises a compound meniscus lens consisting of a double concave element L_1 and a double convex element L_2 located in contact with its rear concave surface. The positive focal length of the meniscus lens (L_1, L_2) has a value between $5.0F_1$ and $6.0F_1$. Further comprised in said front lens member 11 is a double convex single lens L_3 located rearwardly of said meniscus lens and having a positive focal length which is between $1.2F_1$ and $1.4F_1$. Lens L_3 is spaced a fixed distance S_2 rearwardly of the meniscus lens (L_1, L_2), S_2 having a value between $.004F_1$ and $.11F_1$.

The aforesaid rear lens member 12 is preferably composed of a double concave lens element L_4 having contact rearwardly with a meniscus element L_5, the interface R_7 therebetween being convex toward the front.

Regarding the compound front lens (L_1, L_2), the radius of the first lens surface R_1 should have a value between 2.6× and 2.7× the sum of the radii of the next two lens surfaces R_2 and R_3. Furthermore the sum of the radii of the front and back lens surfaces R_4 and R_5 respectively of lens L_3 should be between 1.54× and 1.62× the sum of the radii R_2 and R_3. With regard to the rear lens member 12, the front surface R_6 thereof should have a radius equal to between 1.5× and 2.0× the radius of the rear surface R_8.

A more complete statement of constructional data for the optical system which satisfies the requirements of the present invention is given in the table herebelow, wherein R_1 to R_8 are the radii of the successive lens surfaces, t_1 to t_5 are the axial thicknesses of the successive lens elements L_1 to L_5, S_1 to S_3 are the spaces between the lenses and ND and ν are respectively the refractive index and the Abbe number respectively of the glasses in said elements.

$$3.80F_1<-R_1<4.06F_1$$
$$.73F_1<+R_2<.91F_1$$
$$.73F_1<-R_3<.91F_1$$
$$1.0F_1<+R_4<1.28F_1$$
$$1.3F_1<-R_5<1.57F_1$$
$$1.0F_1<-R_6<1.2F_1$$
$$.32F_1<+R_7<.39F_1$$
$$.53F_1<+R_8<.67F_1$$
$$.050F_1<t_1<.061F_1$$
$$.155F_1<t_2<.190F_1$$
$$.089F_1<t_3<.110F_1$$
$$.051F_1<t_4<.067F_1$$
$$.065F_1<t_5<.078F_1$$
$$1.25F_1<S_1<1.55F_1 \text{ (least } m)$$
$$.90F_1<S_1<1.20F_1 \text{ (highest } m)$$
$$.004F_1<S_2<.11F_1$$
$$.37F_1<S_3<.47F_1 \text{ (least } m)$$
$$3.50F_1<S_3<3.64F_1 \text{ (highest } m)$$
$$1.717<N_D(1)<1.723$$
$$1.496<N_D(2)<1.500$$
$$1.515<N_D(3)<1.519$$

$1.515<N_D(4)<1.519$
$1.717<N_D(5)<1.723$
$28.9<\nu(1)<29.7$
$66.0<\nu(2)<68.0$
$63.5<\nu(3)<65.5$
$63.5<\nu(4)<65.5$
$28.9<\nu(5)<29.7$

wherein F_1 denotes the focal length of the first lens member 11, and *m* denotes the magnification of the object cooperatively produced by the two lens members 11 and 12.

The constructional data for one successful form of the present invention is given specifically in the table herebelow and as shown in FIG. 2 of the drawing wherein the symbols R, *t*, S, etc. are the same as specified in the foregoing table, and F.L. designates the focal lengths of the lenses L_1 to L_5.

Zoom system

[Magnification range=12:1]

Lens	Radius	F.L.	Thickness	Spaces	n_D	ν
				$S_1\begin{cases}=63.395 \text{ at } 1.2\times\\=46.901 \text{ at } 14.4\times\end{cases}$		
	$R_1=-177.91$					
L_1		-42.9	$t_1=2.5$		1.720	29.3
	$R_2=37.67$					
L_2		$+39.2$	$t_2=7.8$		1.498	67.0
	$R_3=-37.67$					
				$S_2=0.3$		
	$R_4=53.45$					
L_3		$+57.7$	$t_3=4.5$		1.517	64.5
	$R_5=-63.46$					
				$S_3\begin{cases}=18.535 \text{ at } 1.2\times\\=160.731 \text{ at } 14.4\times\end{cases}$		
	$R_6=-50.55$					
L_4		-23.4	$t_4=2.6$		1.517	64.5
	$R_7=16.14$					
L_5		$+49.6$	$t_5=3.2$		1.720	29.3
	$R_8=27.04$					

The operation of a zoom optical system constructed according to the above specified optical data is best understood by reference to FIGS. 4, 5 and 6 of the drawing wherein ray traces are shown for two typical rays, 16 and 17. As here shown, the axial positions of the movable lens members 11 and 12 are shown for three image magnifications which are 1.2× (FIG. 4), 4.8× (FIG. 5) and 14.4× (FIG. 6) corresponding to the motions indicated in the curves 13 and 14 of FIG. 3. Similarly to FIG. 1, the object O is shown at the left of the optical diagram and as indicated by the dotted lines 18, the lens members 11 and 12 form a virtual image I, shown in dotted lines also, at an axially fixed position. As the lens members are simultaneously moved through their excursions, the virtual image remains fixed in position at I while the magnification of said image goes through the range of 12:1. The sizes and positions of the lens members 11 and 12 are chosen so that the image I remains of constant size throughout the zoom range, the observed area of the object O decreasing as the magnification of the system is increased. The system thus presents an image of constant size which may be projected or visually observed through the use of suitable auxiliary optical systems (not shown).

Given herebelow is a table wherein the spaces S_1 and S_3 are specified for the aforementioned magnification range of 12:1 as related to the optical system 10.

Zoom Power	S_1	S_3
1.2	63.395	18.535
2.4	61.970	46.217
3.6	57.746	66.102
4.8	54.963	83.678
6.0	53.027	96.519
7.2	51.554	108.365
8.4	50.323	119.769
9.6	49.449	128.349
10.8	48.600	137.164
12.0	47.959	145.462
13.2	47.409	153.204
14.4	46.901	160.731

It should be emphasized at this point that the zoom optical system 10 as above described is not limited to a zoom range of 12:1 as mentioned in connection with one form of this invention, but the range may be extended considerably without structural changes in the optical parts and without sacrificing any of the superior optical performance stated in the objects of this invention.

Although only a preferred form of this invention has been shown and described in detail, changes may be made in the details of construction and form of the parts and substitutions may be made therein without departing from the spirit of the invention as claimed in the appended claims.

We claim:

1. A zoom type of pancratic optical system corrected for chromatic and monochromatic image aberrations and having a substantially flat field, said system comprising a front lens member which consists of a compound meniscus lens which is concave on the object side and has a positive focal length of between $5.0F_1$ and $6.0F_1$ where F_1 is the focal length of the front member and is composed of a front double concave element having its surface of strongest curvature in contact with a rear double convex element and further includes a double convex lens spaced a fixed distance rearwardly thereof and having a positive focal length of between $1.2F_1$ and $1.4F_1$, said system comprising a double concave compound rear lens member which is optically aligned rearwardly of the front member and has a negative focal length which is substantially $.91F_1$ and which is composed of a front double concave element having its surface of strongest curvature forming an interface with a rear convex-concavo element wherein the concavo surface is rearmost and has weaker curvature than the interface, said members being movable with respect to a fixed point on their common optical axis simultaneously and continuously at different rates so as to form a virtual image of continuously variable size of an object at a stationary position on said axis through a magnification range of greater than 4:1, and said members being spaced apart a distance between $.37F_1$ and $.47F_1$ when the system produces least magnification and being spaced apart a distance between $3.5F_1$ and $3.64F_1$ when the system produces highest magnification, the space between the object and the front member being correspondingly between $1.25F_1$ and $1.55F_1$ when the system produces least magnification and between $.90F_1$ and $1.20F_1$ when the system produces the greatest magnification.

2. A zoom type of pancratic optical system as set forth in claim 1 wherein said meniscus lens is formed of a double concave front element and a double convex rear element and further characterized by lens radii which have numerical values as given hereinbelow:

$$2.0(R_2+R_3)<R_1<2.7(R_2+R_3)$$
$$1.54(R_2+R_3)<R_4+R_5<1.62(R_2+R_3)$$

the radius of the front surface of said negative member being between 1.5 and 2.0 times the radius of the rear surface of said negative member, wherein R_1 to R_8 designate the radius of the lens surfaces named in order in the front lens member.

3. A zoom type of pancratic optical system as set forth in claim 1 wherein said meniscus lens is formed of a double concave front element and a double convex rear element, and said rear member is formed of a front double concave element and a rear meniscus element, the constructional data for said system being given in the table of inequalities herebelow:

$$3.80F_1<-R_1<4.06F_1$$
$$.73F_1<+R_2<.91F_1$$
$$.73F_1<-R_3<.91F_1$$
$$1.0F_1<+R_4<1.28F_1$$
$$1.3F_1<-R_5<1.57F_1$$
$$1.0F_1<-R_6<1.2F_1$$
$$.32F_1<+R_7<.39F_1$$
$$.53F_1<+R_8<.67F_1$$
$$.050F_1<t_1<.061F_1$$
$$.155F_1<t_2<.190F_1$$
$$.089F_1<t_3<.110F_1$$
$$.051F_1<t_4<.067F_1$$
$$.065F_1<t_5<.078F_1$$
$$1.25F_1<S_1<1.55F_1 \text{ (least } m\text{)}$$
$$.90F_1<S_1<1.20F_1 \text{ (highest } m\text{)}$$
$$.004F_1<S_2<.11F_1$$
$$.37F_1<S_3<.47F_1 \text{ (least } m\text{)}$$
$$3.5F_1<S_3<3.64F_1 \text{ (highest } m\text{)}$$

$$1.717<n_D(1)<1.723$$
$$1.496<n_D(2)<1.500$$
$$1.515<n_D(3)<1.519$$
$$1.515<n_D(4)<1.519$$
$$1.717<n_D(5)<1.723$$
$$28.9<\nu(1)<29.7$$
$$66.0<\nu(2)<68.0$$
$$63.5<\nu(3)<65.5$$
$$63.5<\nu(4)<65.5$$
$$28.9<\nu(5)<29.7$$

the numerals 1 to 5 designating the successive component lens elements named in order from the front of the system, R_1 to R_8 denote the radii of the respective lenses, the radius R_2 being related to a cemented lens interface t_1 to t_5 denote the thicknesses of the successive lens elements, S_1 represents the axial space between the object and the first lens, and S_2 and S_3 represent the successive spaces between the lenses, n_D represents the refractive index and ν represents the Abbe number of the glass in the respective lens elements, and m signifies the magnification of the image.

4. A zoom type of pancratic optical system comprising a front lens member of positive power and a rear lens member of negative power optically aligned therewith, the front member consisting of three lens elements and the rear member consisting of two elements, said members being movable axially simultaneously and continuously relative to a fixed point on the axis so as to form a virtual image of variable size at a stationary position along the axis of an object, the constructional data therefor being given in the table herebelow wherein L_1 to L_5 designate the successive lens elements in order from the front, R_1 to R_8 denote the radii of the lens surfaces, F.L. designates the focal length, t_1 to t_5 denote the thicknesses of the lens elements, S_1 represents the axial space between the object and the first lens, and S_2 and S_3 represent the successive axial spaces between the lenses, and n_D and ν represent the refractive index and Abbe number respectively of the glass from which said elements are made,

Zoom system

[Magnification range=12:1]

Lens	Radius	F.L.	Thickness	Spaces	n_D	ν
				S_1 =[illegible] at 1.2X =46.90[illegible] at 14.4X		
	R_1=−[illegible]					
L_1		−42.9	t_1=2.5		1.720	29.3
	R_2=[illegible]					
L_2		+[illegible].2	t_2=7.8		1.498	67.0
	R_3=−[illegible]					
				S_2=0.3		
	R_4=53.65					
L_3		+[illegible]	t_3=4.5		1.517	64.5
	R_5=−[illegible]					
				S_3 =[illegible] at 1.2X =160.[illegible] at 14.4X		
	R_6=−58.56					
L_4		−23.4	t_4=2.6		1.517	64.5
	R_7=16.14					
L_5		+40.6	t_5=3.2		1.720	29.3
	R_8=[illegible]					

5. A zoom optical system according to claim 3 wherein the rear surface of the front double concave element, and the front and rear surfaces of the double convex element all have the same radius.

References Cited in the file of this patent

UNITED STATES PATENTS

2,844,996	Klemt	July 29, 1958

Appendix D 3

Type 3

July 23, 1968 EIICHI TAKANO 3,393,958

COMPACT ZOOM LENS CORRECTED OVER A LARGE RANGE OF MAGNIFICATION

Filed April 15, 1964 2 Sheets-Sheet 1

FIG. 1

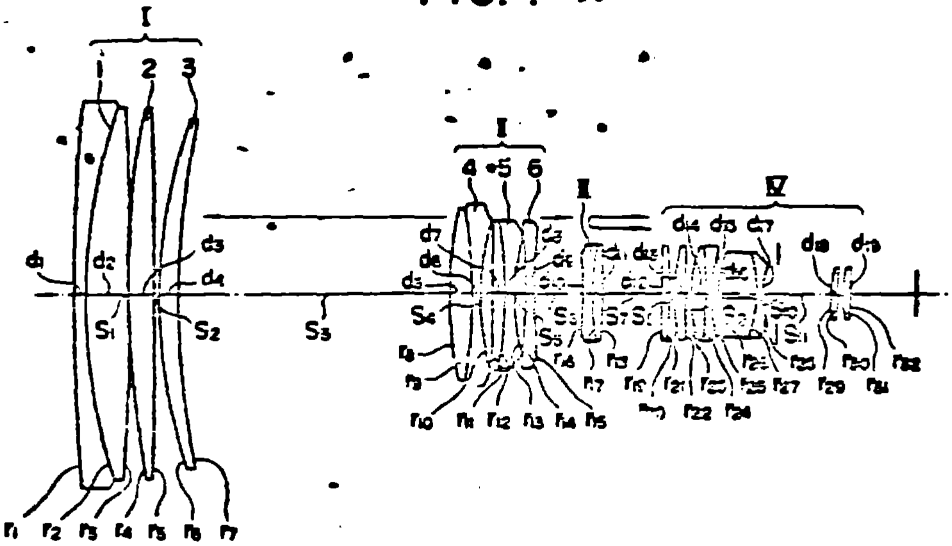
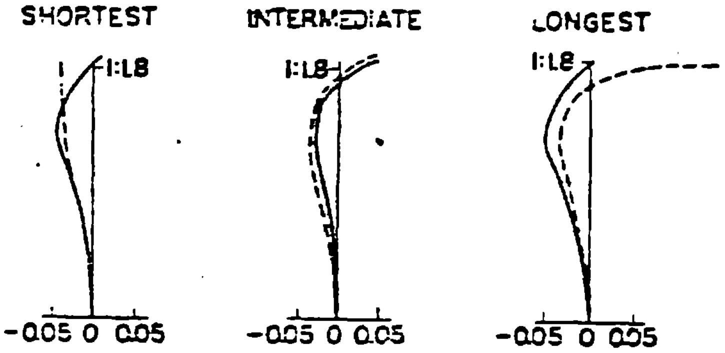


FIG. 2



SPHERICAL ABERRATION & SINUSOIDAL CONDITION (mm)

INVENTOR
EIICHI TAKANO
BY
ATTORNEY

July 23, 1968 EIICHI TAKANO 3,393,958

COMPACT ZOOM LENS CORRECTED OVER A LARGE RANGE OF MAGNIFICATION

Filed April 15, 1964 2 Sheets-Sheet 2

FIG. 3

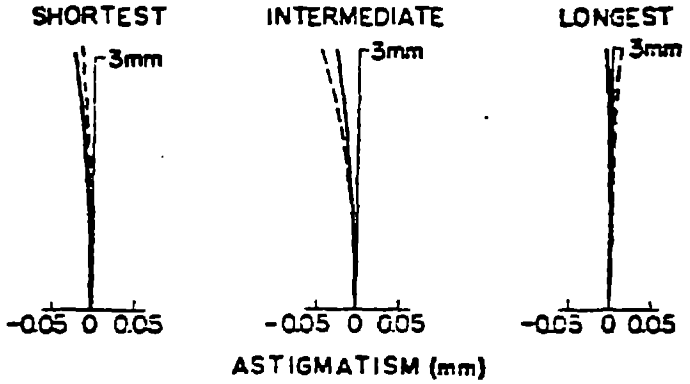


FIG. 4

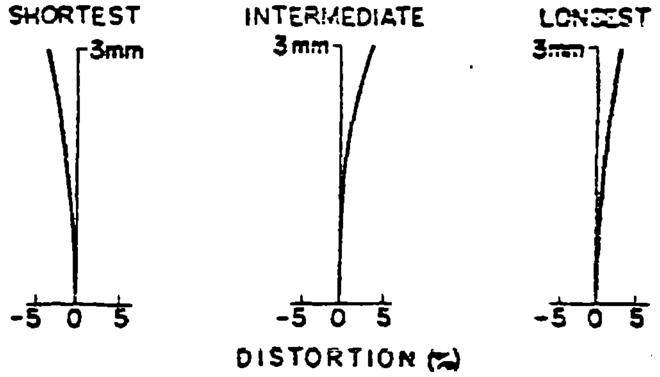
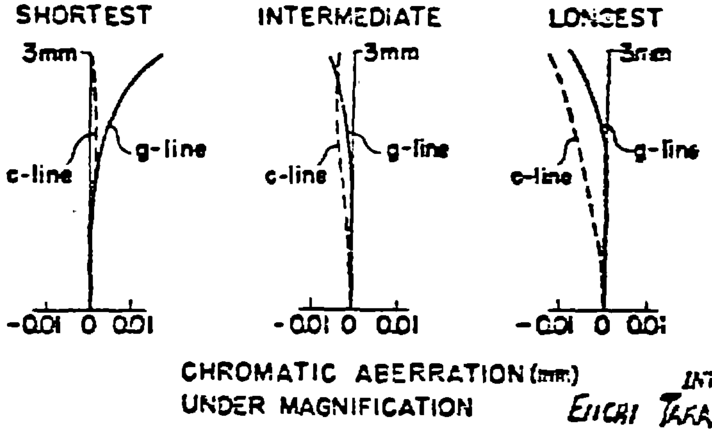


FIG. 5



INVENTOR
Eiichi Takano
BY
ATTY

United States Patent Office

3,393,958

Patented July 23, 1968

3,393,958

COMPACT ZOOM LENS CORRECTED OVER A LARGE RANGE OF MAGNIFICATION

Eiichi Takano, Tokyo, Japan, assignor to Canon Camera Kabushiki Kaisha, Tokyo, Japan, a corporation of Japan

Filed Apr. 15, 1964, Ser. No. 360,323
Claims priority, application Japan, Apr. 17, 1963, 38/19,678
1 Claim. (Cl. 350—176)

ABSTRACT OF THE DISCLOSURE

Compact zoom lens having a zooming ratio as large as 12 and a relative aperture as great as $f/1.8$, the lens being highly corrected over a large range of magnification with little variation in aberration upon zooming operation; the lens comprising four components, a first fixed convergent lens group, a second axially movable divergent zooming lens group, a third lens group moving axially corresponding to the axial movement of the second lens group to avoid movement of the paraxial image point and a fourth fixed and image forming lens group.

This invention relates to a zoom lens, and more particularly to a zoom lens highly corrected over a large range of magnification. An object of the invention is to provide miniaturized zoom lens highly corrected over a large range of magnification.

Another object of the invention is to provide a compact inexpensive zoom lens highly corrected over a magnification of at least ten to one.

Another object of the invention is to provide such a zoom lens which is of simple form and of a construction suitable for economical manufacture and which is capable of superior performance when used with photographic objectives having a relative aperture as great as $f/1.8$.

Further objects and advantages will be apparent in the details of construction and arrangement of parts as described in the specification hereafter taken together with the drawing, in which:

FIG. 1 is an optical diagram of one illustrative form of zoom lens constructed according to the invention;

FIG. 2 depicts the graphs representing the correction for spherical aberrations and the deviation in the sine condition of the zoom lens shown in FIG. 1 at the wide, mean and telephoto positions;

FIG. 3 depicts the graphs representing the correction for astigmatism and image curvature of the zoom lens at the wide, mean and telephoto positions;

FIG. 4 depicts the graphs representing the correction for distortion of the zoom lens at the wide, mean and telephoto position; and

FIG. 5 depicts the graphs representing the correction for transverse chromatic aberrations at the wide, mean and telephoto positions.

It is to be understood that the terms "front" and "rear" as used hereinafter refer to the ends of the zoom lens respectively nearer the longer and shorter conjugates thereof.

The miniaturized zoom lens system in accordance with the present invention consists of four components: a fixed convergent component (I), an axially movable divergent zooming component (II), a component moving axially corresponding to the axial movement of said second component to avoid movement of the paraxial image point, and a fixed and image forming component (IV). The instant system satisfies the following two conditions:

(1) The first component composed of three positive members includes a cemented doublet of a negative and a positive lens, in which all the single positive lenses have Abbe numbers more than 55, and all the single negative lenses less than 30, satisfying the following conditions:

$$|\varphi_1-\Phi_{1/3}|<0.25|\Phi_1|$$
$$|\varphi_2-\Phi_{1/3}|<0.25|\Phi_1|$$
$$|\varphi_3-\Phi_{1/3}|<0.25|\Phi_1|$$

and

$$0<X_1<X_2<X_3<0.5$$

wherein, the refractive power φ and shape factor X of the three positive members are numbered, respectively, by subscripts in order from the front to rear, and the refractive power of the whole first component is designated by Φ_1.

The shape factor X is defined as

$$X=\frac{1/r_a+1/r_b}{1/r_a-1/r_b}$$

where r_a and r_b denote respectively the radii of curvature of the rear and front surfaces of the lens member. The definition and the meaning of the shape factor is disclosed in "Wave Theory of Abberation" by H. H. Hopkin, published by Oxford at the Clarendon Press, 1950, pages 119 through 121.

(2) The second component composed of three negative members including a cemented doublet of negative and positive lenses, in which all the negative lenses have Abbe numbers of more than 50, and all the positive lenses of less than 30, satisfies the following conditions:

$$|\varphi_4-\Phi_{2/3}|<0.1|\Phi_2|$$
$$|\varphi_5-\Phi_{2/3}|<0.1|\Phi_2|$$
$$|\varphi_6-\Phi_{2/3}|<0.1|\Phi_2|$$

and

$$-1.5<X_4<X_5<X_6<0$$

wherein, the refractive power φ and shape factor X of the three members are numbered, respectively, by subscripts in order from front to rear, and the refractive power of the whole second component is denoted by Φ_2.

FIG. 1 shows one embodiment according to the present invention, wherein (I), (II), (III) and (IV) denote the components comprising the whole system, 1, 2, and 3 the members comprising the component (I), and 4, 5 and 6 those comprising component (II).

If a zoom lens system is miniaturized while maintaining its large zooming ratio, the focal lengths of every component would necessarily have to be shortened, whereby some deterioration in the correction of the aberrations would be caused. As a countermeasure against this, therefore, it is necessary to keep these focal lengths longer by widening the moving space of the movable component with the axial thicknesses of both said movable components, with those at the front and at the back of the same as thin as possible. On the other hand, to minimize variation in chromatic aberrations, each component should separately be achromatized, which accompanies a short radius of curvature of the cemented surface and an increase in said axial thicknesses of the components. Though this increase of the axial thickness contradicts the above mentioned countermeasure, observance of the Abbe numbers mentioned in the above conditions successfully eliminates these inconveniences and sufficiently improves the aberration correction.

Aberration variations during zooming operation are mostly caused by the first and second components, and to defeat such variations, the residual aberrations of both components must constantly be kept nearly equal but of the opposite sign, and, moreover, to decrease variation in higher order aberrations, which is caused by the combination of the third order aberrations caused by the third and fourth components as also by the first and second components, each of the first and second components should be separately well corrected. In such a zooming system having not only a zooming ratio as large as 12 but also a large aperture ratio the incident point of the refractive surfaces of the marginal ray and the principal ray is greatly changed during zooming operation, and therefore the above mentioned expedients are particularly important for such a system. For such a zoom lens system having a large zooming ratio it is generally desired that when it is set at wide position, distortion and astigmatism, which are conspicuous in the edge of the image field, and when it is set at telephoto position, spherical and chromatic aberrations, which are significant in the center of the image field, are substantially highly corrected: the present inventive system having the first and second components respectively composed of three members, each of which has power and shape factors as defined in the above conditions, satisfactorily fulfils such essential and general requirements.

A preferred example of the zoom lens forming a specific embodiment of the invention, and having a magnification range of about twelve to one, is constructed in conformity with the following table wherein dimensions are in terms of millimeters, and the refractive indices for the sodium D-line and the Abbe dispersion numbers are respectively designated at *n* and *ν*, the radii *r*, thicknesses *d*, spaces *s*, effective focal length F, and aperture ratio *f*, are numbered, respectively, by subscripts in order from front to rear.

F 6.5-75 *f* 1-1.8

$r_1=356.99$		
$d_1=1.2$	$n_1=1.7552$	$\nu_1=27.5$
$r_2=61.66$		
$d_2=6.7$	$n_2=1.713$	$\nu_2=53.9$
$r_3=-602.28$		
$s_1=0.1$		
$r_4=152.45$		
$d_3=3.0$	$n_3=1.62041$	$\nu_3=60.3$
$r_5=\infty$		
$s_2=0.1$		
$r_6=66.54$		
$d_4=3.4$	$n_4=1.62041$	$\nu_4=60.3$
$r_7=178.931$		
$s_3=1.152-36.364-49.553$		
$r_8=42.95$		
$d_5=2.9$	$n_5=1.80518$	$\nu_5=25.5$
$r_9=-46.07$		
$d_6=0.6$	$n_6=1.76595$	$\nu_6=50.6$
$r_{10}=30.0$		
$s_4=1.7$		
$r_{11}=\infty$		
$d_7=2.0$	$n_7=1.80518$	$\nu_7=25.5$
$r_{12}=-43.8$		
$d_8=0.6$	$n_8=1.76595$	$\nu_8=50.6$
$r_{13}=36.73$		
$s_5=2.5$		
$r_{14}=-36.73$		
$d_9=0.6$	$n_9=1.62041$	$\nu_9=60.3$
$r_{15}=142.853$		
$s_6=51.597-7.001-3.196$		
$r_{16}=-24.48$		
$d_{10}=0.6$	$n_{10}=1.51633$	$\nu_{10}=64.1$
$r_{17}=15.69$		
$d_{11}=1.8$	$n_{11}=1.53256$	$\nu_{11}=46.0$
$r_{18}=-2436.889$		
$s_7=1.0-8.294-1.8$		
$r_{19}=-411.24$		
$d_{12}=1.3$	$n_{12}=1.53461$	$\nu_{12}=42.9$
$r_{20}=-35.33$		
$s_8=0.1$		
$r_{21}=35.33$		
$d_{13}=1.4$	$n_{13}=1.882$	$\nu_{13}=41.0$
$r_{22}=-450.37$		
$s_9=0.1$		
$r_{23}=17.21$		
$d_{14}=2.5$	$n_{14}=1.58313$	$\nu_{14}=59.3$
$r_{24}=-54.57$		
$d_{15}=0.6$	$n_{15}=1.78472$	$\nu_{15}=25.7$
$r_{25}=41.09$		
$s_{10}=0.1$		
$r_{26}=10.4$		
$d_{16}=8.65$	$n_{16}=1.6393$	$\nu_{16}=45.0$
$r_{27}=-25.05$		
$d_{17}=0.5$	$n_{17}=1.69895$	$\nu_{17}=30.0$
$r_{28}=6.91$		
$s_{11}=9.6$		
$r_{29}=20.89$		
$d_{18}=1.8$	$n_{18}=1.62041$	$\nu_{18}=60.3$
$r_{30}=-99.62$		
$s_{12}=0.1$		
$r_{31}=23.94$		
$d_{19}=1.9$	$n_{19}=1.62041$	$\nu_{19}=60.3$
$r_{32}=\infty$		
Back focus=9.239		

FIGS. 2, 3, 4, and 5 show respectively the aberration curves for the spherical aberrations, astigmatism, distortion, and chromatic aberrations at the shortest (6.5 mm.), intermediate (30 mm.), and longest (75 mm.) focal lengths in the above mentioned embodiment, which provides an excellent quality of zoom lens system according to this invention.

While the invention is thus described, it is not limited to the precise values given, any change may be readily made without departing from the spirit of the invention.

What I claim is:

1. A zoom lens comprising four components: a first convergent component, a second axially movable divergent zooming component, a third component moving axially corresponding to the axial movement of the second component to avoid movement of the paraxial image point and a fourth fixed and image forming component, the lens being constructed in substantial compliance with the following table where the dimensions are given in millimeters, and proceeding from the front to the rear r_1 to r_{32} designate the radii of curvature of the surface, d_1 to d_{19} the axial thicknesses, s_1 to s_{12} the axial separations, n_1 to n_{19} the indices of the indices of refraction for the sodium D-line and V_1 to V_{19} the Abbe dispersion numbers; the numerical values of S_3, S_6, and S_7, represent, respectively, the spacings between the first, second, third, and fourth components for three positions of the movable components as they are moved to provide at least minimum, intermediate, and maximum magnifications.

F 6.5-75 *f* 1:1.8

$r_1=356.99$			
$d_1=1.2$	$n_1=1.7552$	$\nu_1=27.5$	SF4
$r_2=61.66$			
$d_2=6.7$	$n_2=1.713$	$\nu_2=53.9$	LaK 8
$r_3=-602.28$			
$s_1=0.1$			
$r_4=152.45$			
$d_3=3.0$	$n_3=1.62041$	$\nu_3=60.3$	SK16
$r_5=\infty$			
$s_2=0.1$			
$r_6=66.54$			
$d_4=3.4$	$n_4=1.62041$	$\nu_4=60.3$	[illegible]
$r_7=178.531$			
$s_3=1.152-36.364-46.553$			
$r_8=42.95$			
$d_5=2.9$	$n_5=1.80518$	$\nu_5=25.5$	SF6
$r_9=-46.07$			
$d_6=0.6$	$n_6=1.76595$	$\nu_6=50.6$	~ LaKN7, LaFN28
$r_{10}=30.0$			
$s_4=1.7$			
$r_{11}=\infty$			
$d_7=2.0$	$n_7=1.80518$	$\nu_7=25.5$	SF6
$r_{12}=-43.8$			
$d_8=0.6$	$n_8=1.76595$	$\nu_8=50.6$	~ LaFN28
$r_{13}=36.73$			
$s_5=2.5$			
$r_{14}=-36.73$			
$d_9=0.6$	$n_9=1.62041$	$\nu_9=60.3$	[illegible]
$r_{15}=142.853$			
$s_6=51.597-7.881-3.196$			
$r_{16}=-24.48$			
$d_{10}=0.6$	$n_{10}=1.51633$	$\nu_{10}=64.1$	[illegible]
$r_{17}=15.59$			
$d_{11}=1.8$	$n_{11}=1.53256$	$\nu_{11}=46.0$	[illegible]
$r_{18}=-2456.869$			
$s_7=1.0-8.294-1.8$			
$r_{19}=-411.24$			
$d_{12}=1.3$	$n_{12}=1.53461$	$\nu_{12}=42.9$	[illegible]
$r_{20}=-35.33$			
$s_8=0.1$			
$r_{21}=35.33$			
$d_{13}=1.4$	$n_{13}=1.882$	$\nu_{13}=41.0$	[illegible]
$r_{22}=-450.57$			
$s_9=0.1$			
$r_{23}=17.21$			
$d_{14}=2.5$	$n_{14}=1.58313$	$\nu_{14}=59.3$	SK12
$r_{24}=-54.57$			
$d_{15}=0.6$	$n_{15}=1.78472$	$\nu_{15}=25.7$	SF11
$r_{25}=41.09$			
$s_{10}=0.1$			
$r_{26}=10.4$			
$d_{16}=8.65$	$n_{16}=1.6393$	$\nu_{16}=45.0$	BaF12
$r_{27}=-25.05$			
$d_{17}=0.5$	$n_{17}=1.69895$	$\nu_{17}=30.0$	SF15
$r_{28}=6.91$			
$s_{11}=9.6$			
$r_{29}=20.89$			
$d_{18}=1.8$	$n_{18}=1.62041$	$\nu_{18}=60.3$	SK16
$r_{30}=-94.62$			
$s_{12}=0.1$			
$r_{31}=23.94$			
$d_{19}=1.9$	$n_{19}=1.62041$	$\nu_{19}=60.3$	SK16
$r_{32}=\infty$			
Back focus=9.239			

(References on following page)

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FOREIGN PATENTS

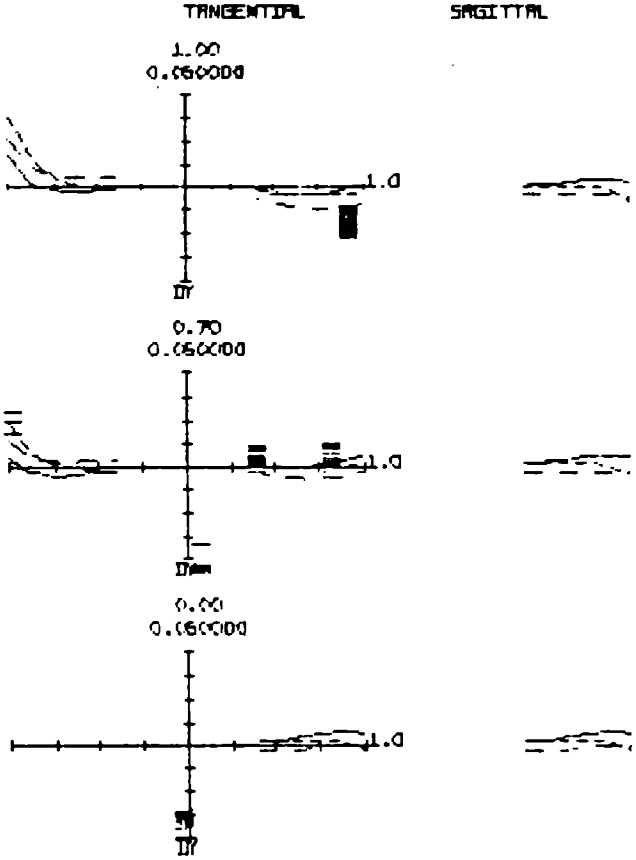
1,325,487	3/1963	France.

DAVID H. RUBIN, *Primary Examiner.*

J. K. CORBIN, *Assistant Examiner.*

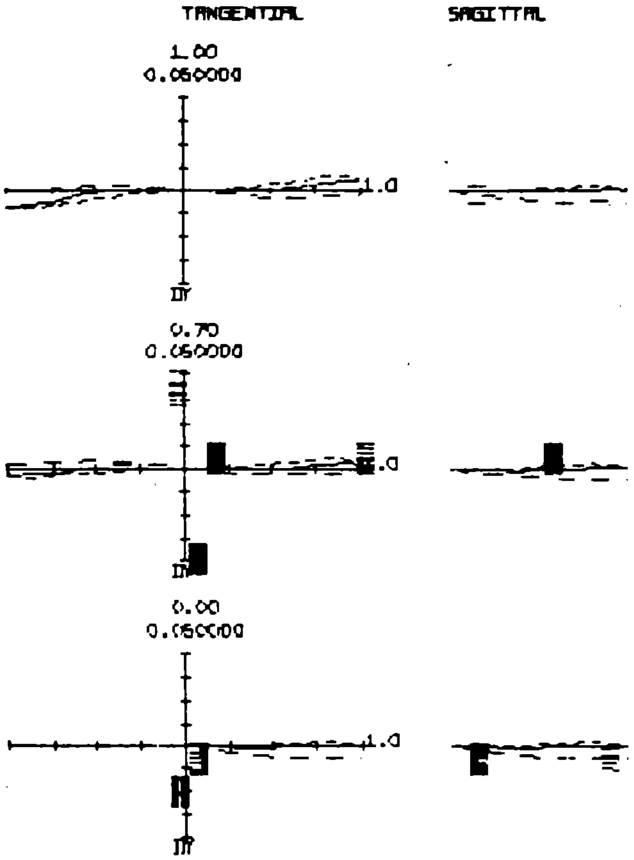
APPENDIX B

RAY FAN PLOTS



MIRROR ZOOM WITH RELAY AND FIELD FLATNER

31 JULY. CFG.1.



MIRROR ZOOM WITH RELAY AND FIELD FLATNER

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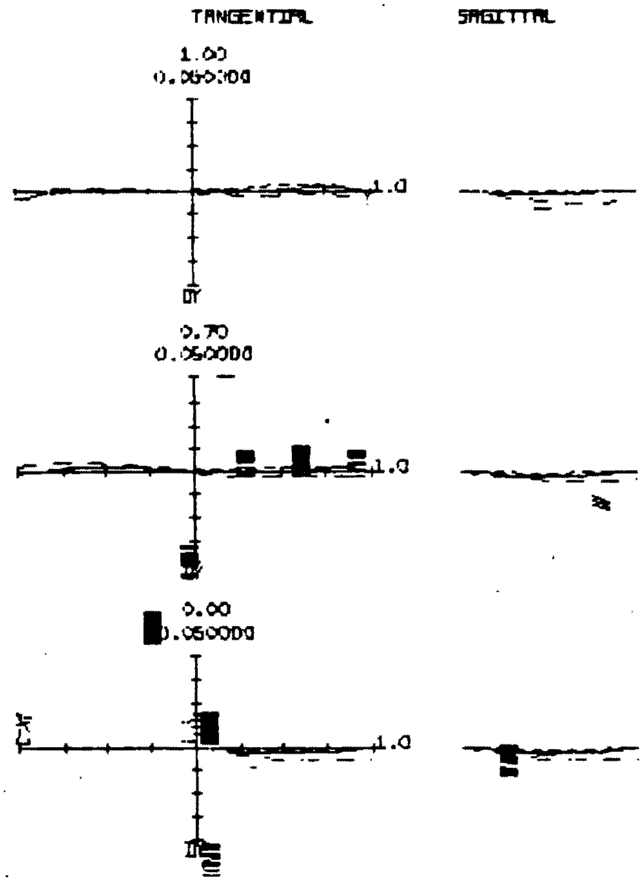
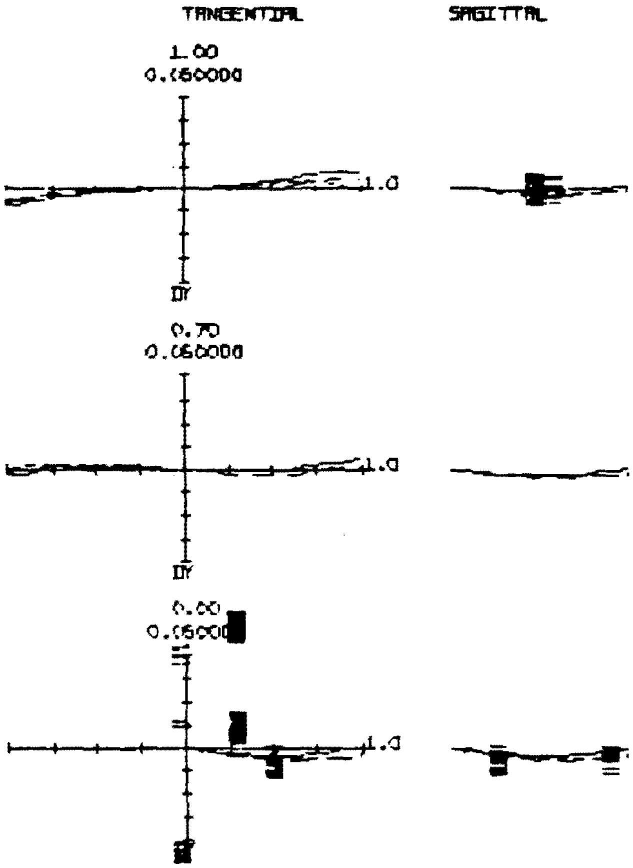


MIRROR ZOOM WITH RELAY AND FIELD FLATNER

JULY,31. CFG,3.



MIRROR ZOOM WITH RELAY AND FIELD FLATNER

JULY 31. CFG,4.

APPENDIX C

COMPANY INFORMATION

Information was requested from the following companies:

1. Rank Precision Industries, Inc.
   411 East Jarvis Avenue
   Des Planes, Illinois 60018

2. Celestron International
   2835 Columbia Street
   Torrance, California 90503

3. Fuji Optical Systems Inc.
   4855 Atherton Avenue
   San Jose, California 95130

4. Arriflex
   25-20 Brooklyn-Queens
   Expressway West
   Woodside, New York 11377

5. Angenieux
   7700 N. Kendall Drive
   Miami, Florida 33156

6. Canon U. S. A.
   One Canon Plaza
   Lake Success, New York 11042

7. Zoomar Optical Systems
   55 Sea Clift Ave.
   Glen Cove, New York 11542

TYPICAL LETTER

Angenieux
7700 N. Kendall Drive
Miami, Florida 33156

Dear Sirs,

I am looking for what is available, or modifiable, for a zoom lens to be used in a space mission. Could you please send any information, including optical system layout if possible, on any system which would come close to meeting the following specifications:

Variable focal length	20 to 200 cm
Image size (on vidicon)	18.6×18.6 mm
F/number	F/8
Spectral range	400 to 1000 nm
Volume	30×30×70 cm
Back focal length	9 cm or more
Front focal distance	10 m to infinity

Thank you.

Sincerely,

Douglas W. Ricks

angenieux

ANGENIEUX INC.
120 Derry Road, P.O. Box 7
Hudson, New Hampshire 03051
Telephone: (603) 889-2116
Telex: 94-3469

16 July 1984

UNIVERSITY OF ARIZONA
Attn: Mr. Douglas W. Ricks
Optical Sciences Center
Tucson, Arizona 85721

Dear Mr. Ricks:

Mr. Juergen Schwinzer of Arriflex has forwarded your request for information on a zoom lens to be used in a space mission to my attention.

Angenieux quality lens systems can very well meet your optical requirements. Enclosed please find dossier techniques and literature on the Angenieux 42X zoom lens for 1" and 1¼" tube formats.

If additional information is required, please do not hesitate to contact us. We welcome your continued interest in Angenieux products.

Sincerely,

Henry A. Peterson

ANGENIEUX, INC.
Henry A. Peterson
EO Technical Sales

HAP/ps

Enc.

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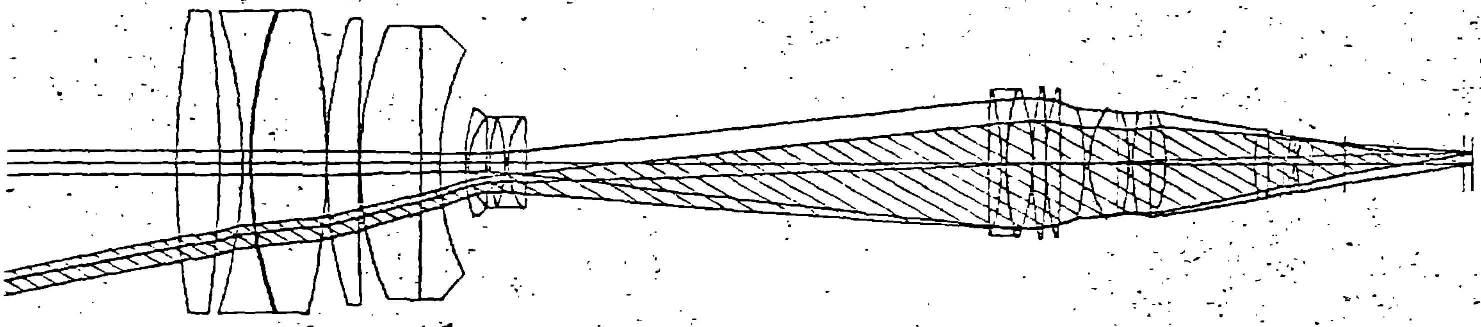
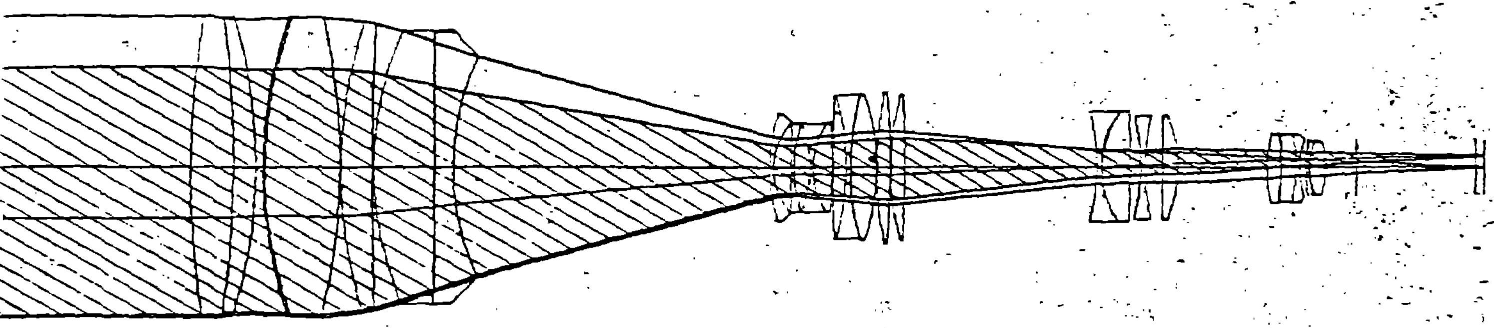
DOSSIER TECHNIQUE

ZOOM 42 x 32 E 11

SCHEMAS OPTIQUES DU ZOOM
42 X 32 E11



POSITION COURTE FOCALE



POSITION LONGUE FOCALE

ANGENIEUX ZOOM

42 x 32 E 11

RENSEIGNEMENTS TECHNIQUES (suite)
TECHNISCHE DATEN (Folge)
TECHNICAL DATA (Continuation)

Diamètre de la lentille avant Freier Durchmesser der ersten linse Clear aperture front glass	180 x 160 mm
Diamètre de la lentille arrière Freier Durchmesser der letzen linse Clear aperture rear glass	28 mm
Diamètre extérieur maximal Grösster Aussendurchmesser Maximum overall diameter	220 x 190 mm
Rotation des bagues de commande Stell ring Total angular rotation 1) Mise au point - Schärfe - Focus 2) Zoom 3) Iris - Blende - Iris	Déplacement : 24 mm 188° 95°
Couple maximal : axe horizontal Maximaldrehmoment Maximum torque 1) Mise au point - Schärfe - Focus 2) Zoom (prise de mouvement) 3) Iris - Blende - Iris	0,7 cm kg 0,9 cm kg 0,5 cm kg
Poids Gewicht Weight	35 kg en version manuelle avec capot, avec platine sans pare - soleil
Monture neutre Neutral fassung Neutral mount	
Centre de gravité par rapport au plan image dans l'air	450 mm environ

N° 102283 A

ANGENIEUX ZOOM

RENSEIGNEMENTS TECHNIQUES - TECHNISCHE DATEN - TECHNICAL DATA

42 x 32 E 11

TV PUMBICON 1 " 1/4

Distances Focales Brennweiten Focal lengths	32 - 1344 mm 1,26" - 53 "
Ouverture Offnung Aperture	f/2,3 -7,6 - f/26
Diamètre du champ image Bildfeld Durchmesser Image field diameter	21,4 mm 0,845 "
Tirage optique (dans l'air) Schnittweite (in luft) Back focal length (in air)	64,7 mm 2,55 "
Facteur photométrique Photometrischer faktor Photometric factor	1,31
Champ angulaire objet Bildfeld winket Object angular field	Diagonal 35° à 56' Horizontal 28°52 à 46' Vertical 22° à 34'
Mise au point minimale Nahpunkt Shortest focusing distance	4 m. 13 ft
Avec bonnettes n° 1 Mit vorsatzlinsen n° 2 With close-up lenses n° 3	
Plus petit champ objet Kleinstes bildfeld Smallest object field	37,4 x 49,6 mm 1,47" x 1,95 "
Avec bonnettes n° 1 Mit vorsatzlinsen n° 2 With close-up lenses n° 3	

P. ANGENIEUX

N° 102274 A

COURBE DE DISTORSION (NORME EIA)

ZOOM 42 X 32 E11

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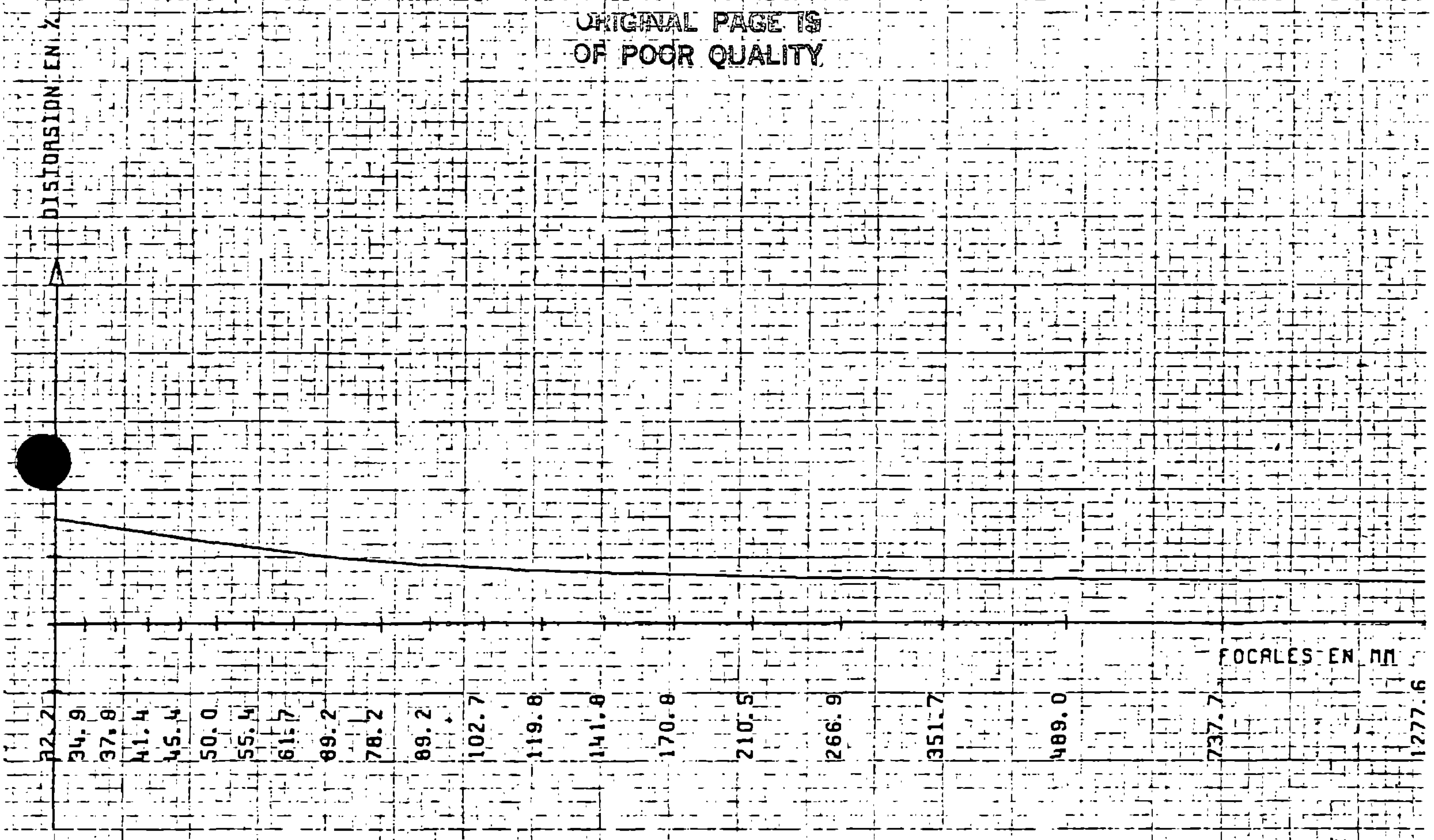


MISE AU POINT A L'INFINI

DIMENSIONS IMAGE

PETIT COTE= 12.84 MM

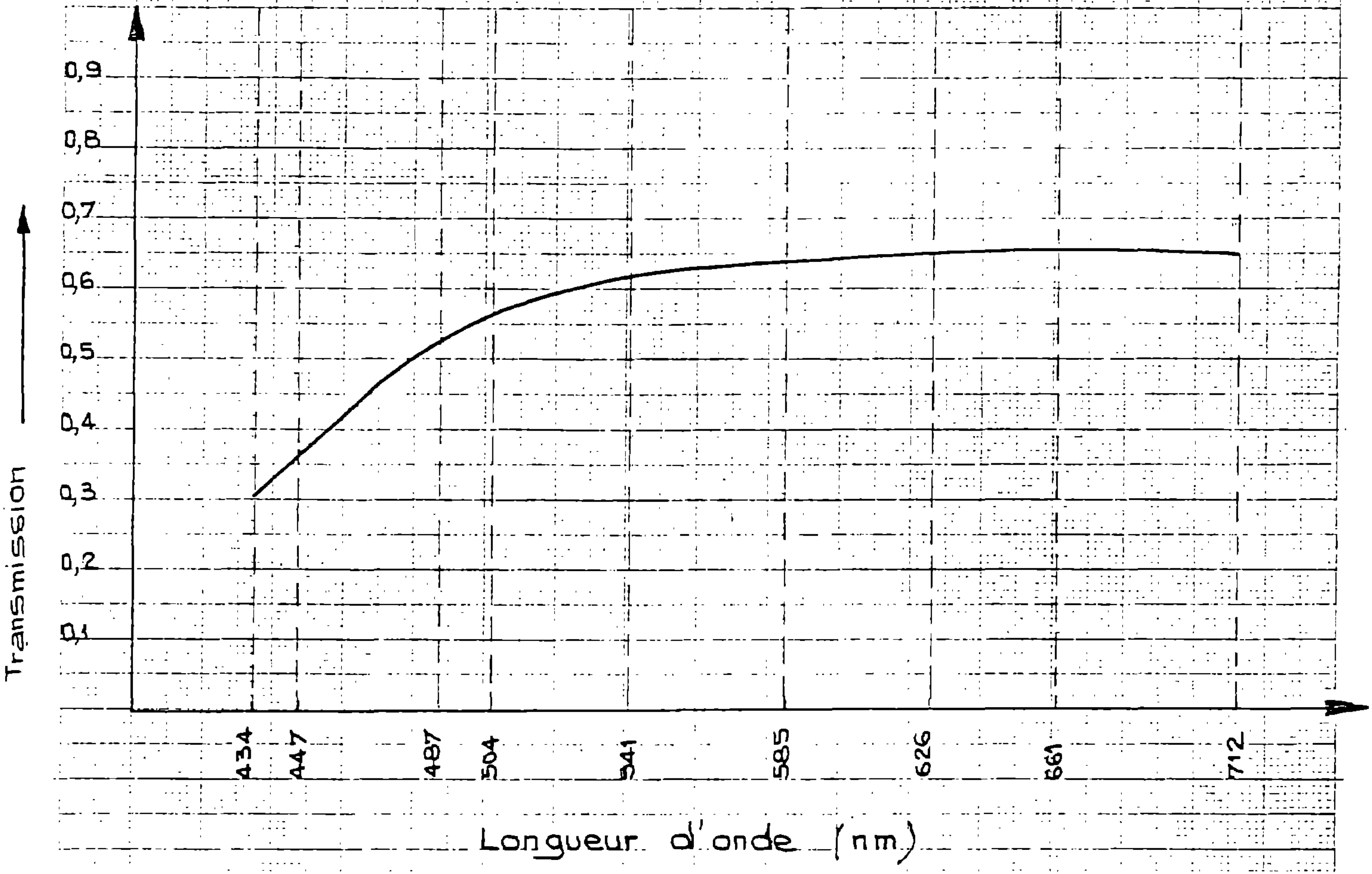
DIAGONALE = 21.40 MM

LE 23/9 /76

P. ANGENIEUX Nº 102273 A

COURBE DE TRANSMISSION SPECTRALE

ZOOM 42 × 32 E 11



Infra rouge
800 nm ft = 0,45
1000 nm. ft = 0,22

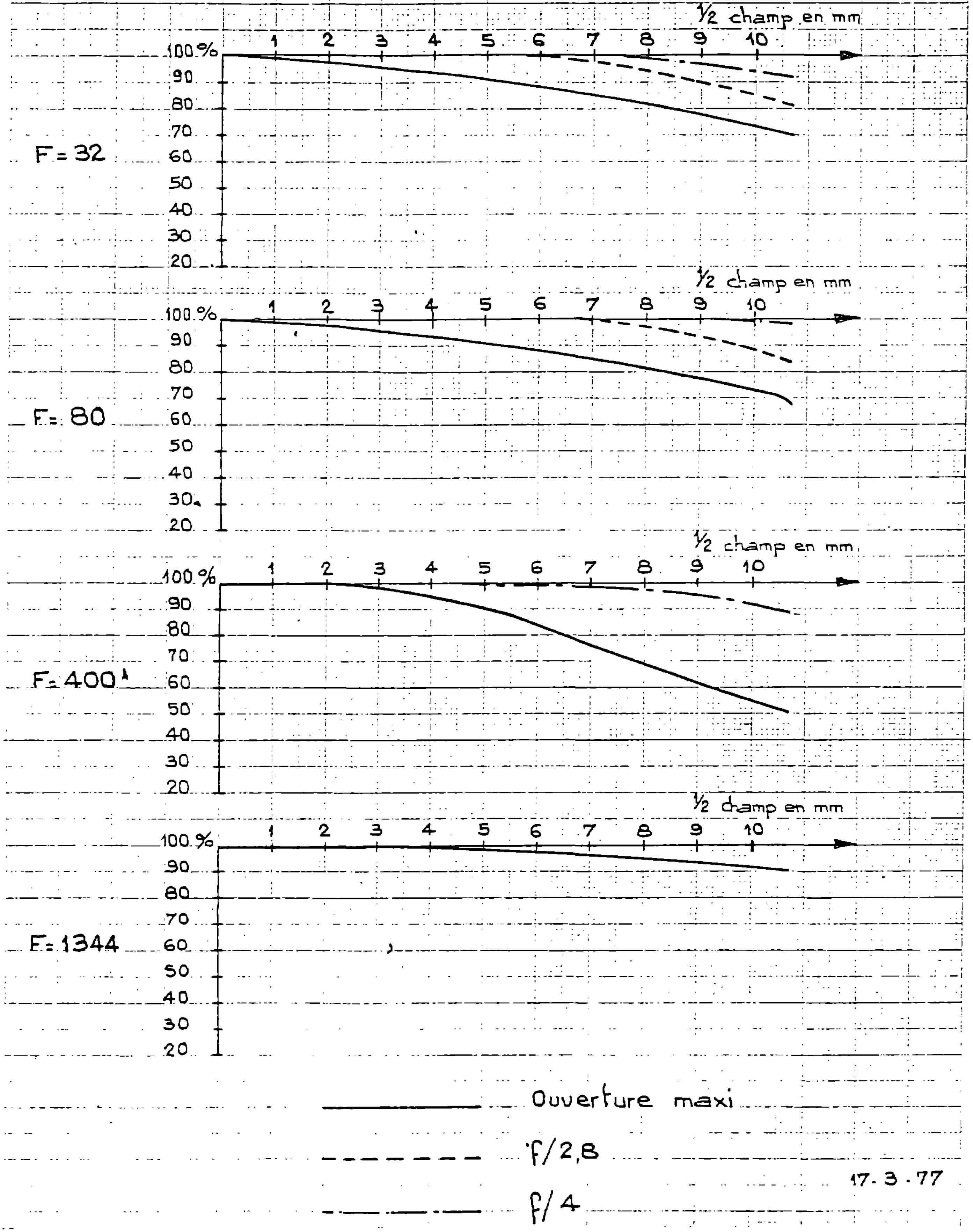
Lumière blanche (Illuminant "A") ft = 0,58 T = 1,31

17 - 3 - 77

P. ANGENIEUX N° 102271 A

COURBES DE REPARTITION D'ECLAIREMENT

DANS LE CHAMP
Zoom 42 x 32 E11



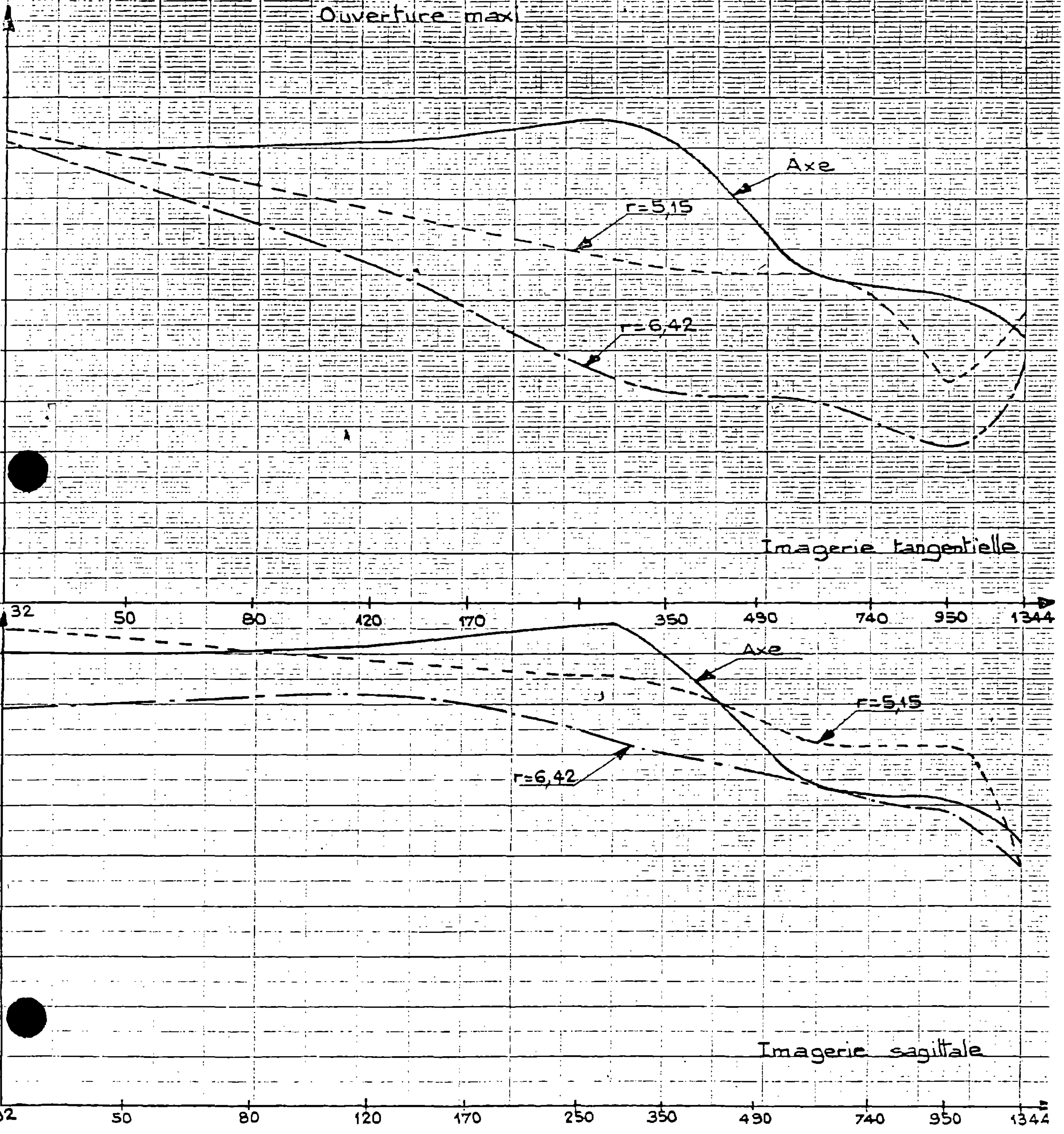
17.3.77

P-ANGENIEUX N° 102272 A

COURBES DES TRANSFERTS DE MODULATION

Zoom 42 x 32 E 11

Fréquence 15 cycles/mm -
λ - 546 mm
Ouverture maxi



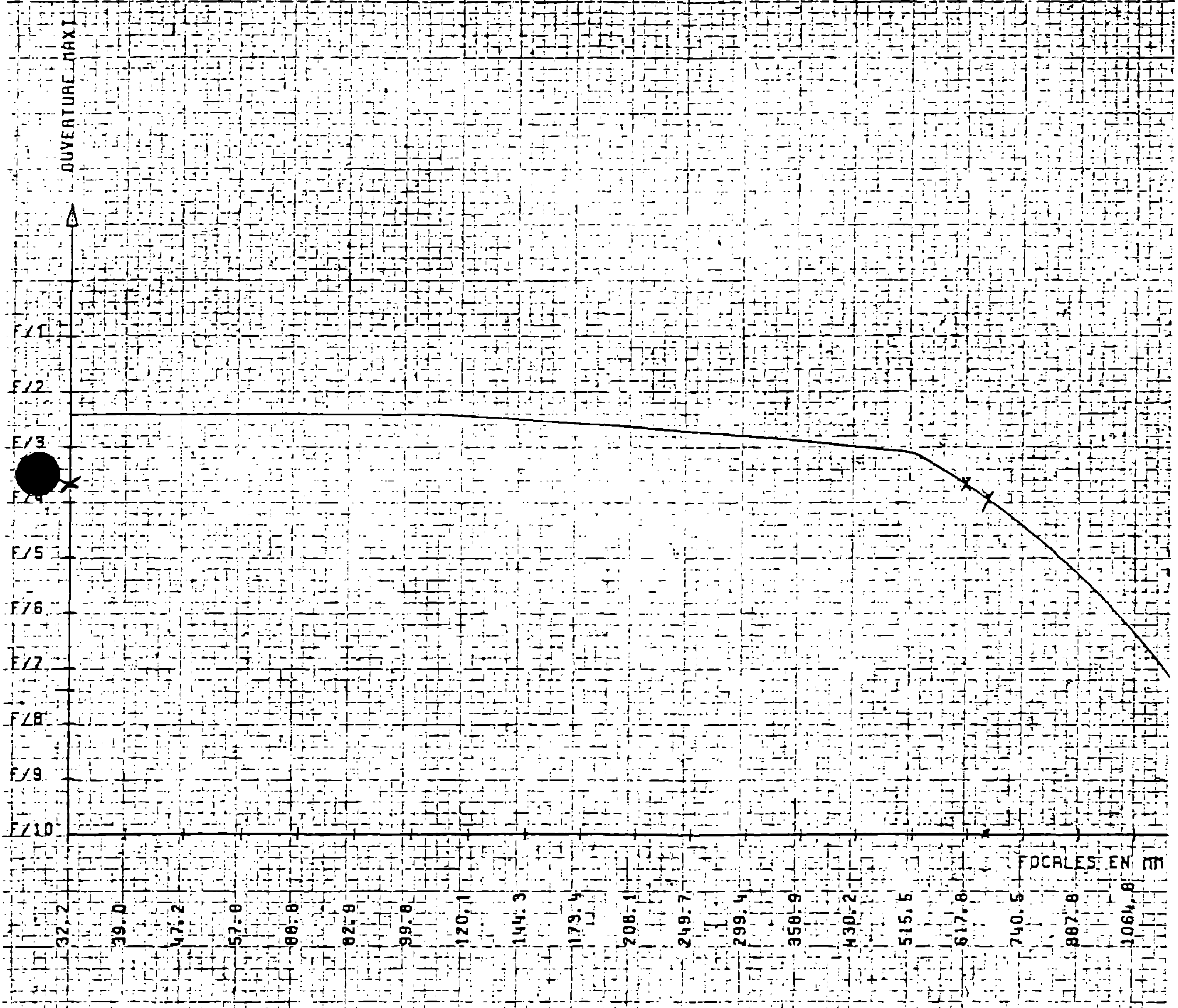
Le 17.3.77

P. ANGENIEUX

N° 100 534 A

OUVERTURE EN FONCTION DE LA FOCALE

ZOOM 42 X 32 E11 plumbicon 1" 1/4



LE 18/10/76

ngenieux
CORPORATION OF AMERICA
7700 N. Kendall Drive - Suite 303
Miami, Florida 33156
Telephone: (305) 595-1144
Telex: 80-8425

ORIGINAL PAGE IS
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ne 5th, 1984

e University of Arizona
tical Sciences Center
cson, Arizona 85721

tn: Mr. Douglas W. Ricks
: Zoom Lens for Space Mission

ar Sir:

ter consulting with our factory in France in regards to your letter
May 22nd, we would like to propose the following lens.

om 10x18 T2 lens which would cover the 21.4 mm format but back
cal length will be 50 mm. To reach 90 mm back focal length, we
be using a 10x40 T1 Zoom F/1.5. In this condition, the exact
focal distance would be 87.7 mm and the format 40 mm. Is this
ceptable?

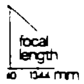
find that 18.6 x 18.6 mm is excessive in vidicon tubes.

ease advise us with reference to the above. Thank you for your
terest in Angenieux optics.

ncerely,

oseph A. Martinez
ice President

AM:drl



FAD 377 - Imp Le Henaff

APPENDIX D

PRELIMINARY REFRACTIVE DESIGN

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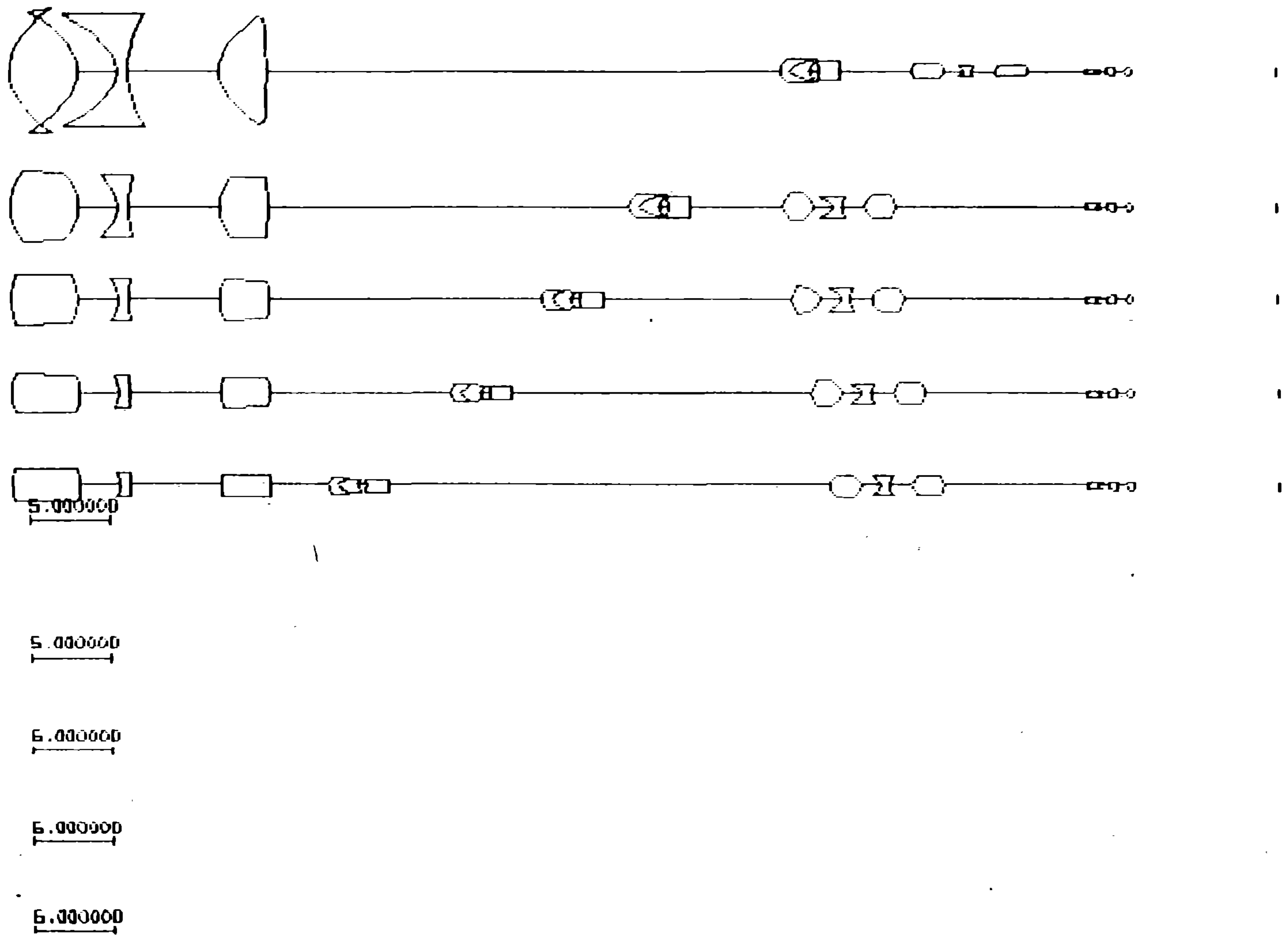
```
ZOOM TYPE 2

BASIC LENS DATA
SURF        RD              TH        MEDIUM                RN        DF
  0      0.000000  0.100000E 12      AIR

  1     45.140284       4.283954     SCHOTT SK16       1.620411   -0.057
  2    -37.669434       2.460121     AIR

  3    -29.271120       0.673914     SCHOTT SF2        1.647689    0.870
  4     84.446700       5.678698     AIR

  5     36.291188       3.032369     SCHOTT SK16       1.620411   -0.057
  6   -360.673864      31.987545     AIR

  7     11.473710       0.632647     SCHOTT SK16       1.620411   -0.057
  8      3.262479       0.008024     AIR

  9      3.337721       1.150909     SCHOTT SF2        1.647689    0.870
 10      5.672495       0.673208     AIR

 11    -12.209494       1.331681     SCHOTT SK16       1.620411   -0.057
 12    207.674109       4.474065     AIR

 13     10.424758       1.973770     SCHOTT SK16       1.620411   -0.057
 14     -6.923343       1.245396     AIR

 15     -4.515431       0.500000     SCHOTT SF2        1.647689    0.870
 16     13.814128       1.408239     AIR

 17      8.034839       2.000000     SCHOTT SK16       1.620411   -0.057
 18    -13.730680       3.715300     AIR

 19     -3.269180       0.500289     SCHOTT SK16       1.620411   -0.057
```

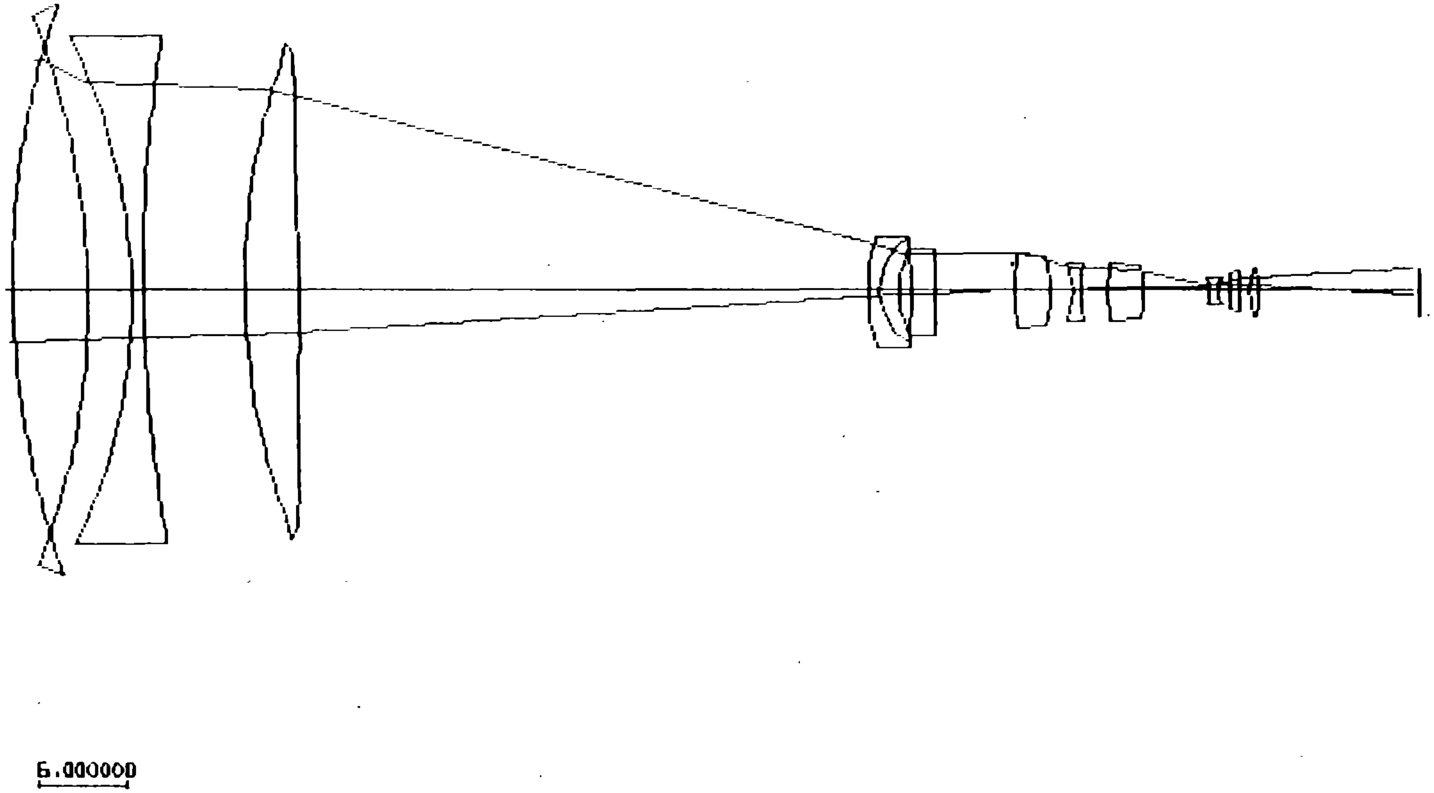
```
 19      -3.269180       0.500289   SCHOTT SF16       1.620411  -0.057
 20       1.685510       0.689543   AIR

 21     -21.562267       0.546426   SCHOTT SF2        1.647689   0.870
 22     -11.652065       0.533502   AIR

 23       4.398860       0.500000   SCHOTT SF16       1.620411  -0.057
 24      -9.339125       9.000000   AIR

 25       0.000000       0.000000   AIR


REFRACTIVE INDICES

SURF        N1          N2          N3          N4          N5
  1     1.620411    1.638527    1.608929    1.000000    1.000000
  3     1.647689    1.684065    1.628939    1.000000    1.000000
  5     1.620411    1.638527    1.608929    1.000000    1.000000
  7     1.620411    1.638527    1.608929    1.000000    1.000000
  9     1.647689    1.684065    1.628939    1.000000    1.000000
 11     1.620411    1.638527    1.608929    1.000000    1.000000
 13     1.620411    1.638527    1.608929    1.000000    1.000000
 15     1.647689    1.684065    1.628939    1.000000    1.000000
 17     1.620411    1.638527    1.608929    1.000000    1.000000
 19     1.620411    1.638527    1.608929    1.000000    1.000000
 21     1.647689    1.684065    1.628939    1.000000    1.000000
 23     1.620411    1.638527    1.608929    1.000000    1.000000

CC AND ASPHERIC DATA

SURF       CC               AD             AE             AF             AG
  2    2.95328E-01
  8   -6.73870E-02
 13   -3.50468E-01
```

```
 19  -1.03876E 01

 REF OBJ HT                          REF AP HT   OBJ SURF   REF SURF   IMG SURF
-0.657999E 09 (    0.38 DG)          2.03541        0          13         25

    EFL             BF         F/NBR       LENGTH          GIH
  199.0144        9.0000       7.96       69.9996        1.3124

LENS IS CURRENTLY IN CFG 1


ALTERNATE CONFIGURATIONS

         PARAMETER   SURF   CURRENT VALUE

CFG 2:
             SAY        1      7.000000
             PUCY       0      0.011743
             PCY        1      0.000000
             TH        12      5.696891
             TH        18     11.874881
             TH         6     22.585569

CFG 3:
             SAY        1      3.937500
             PUCY       0      0.020876
             PCY        1      0.000000
             TH        12     11.661789
             TH        18     11.396253
             TH         6     17.100021

CFG 4:
             SAY        1      2.250000
             PUCY       0      0.036533
```

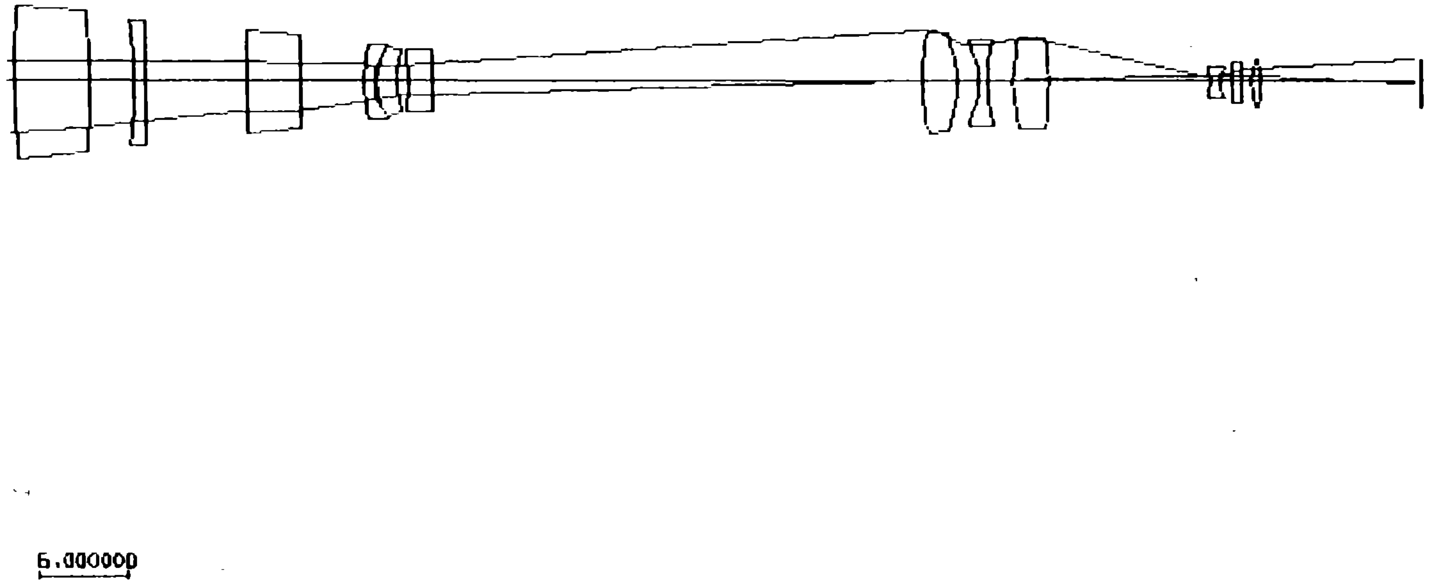
```
CFG 4:
          SAY          1       2.250000
          PUCY         0       0.036533
          PCY          1       0.000000
          TH          12      18.610517
          TH          18      10.179426
          TH           6      11.368399

CFG 5:
          SAY          1       1.250000
          PUCY         0       0.065894
          PCY          1       0.000000
          TH          12      27.467300
          TH          18       9.024772
          TH           6       3.666300

WAVL NBR            1          2          3          4          5
WAVELENGTH       0.58756    0.40000    1.00000    0.00000    0.00000
SPECTRAL WT       1.0000     1.0000     1.0000     1.0000     1.0000

APERTURE STOP AT SURF 13

LENS UNITS ARE CM

EVALUATION MODE IS FOCAL

CONTROL WAVELENGTH IS 1

PRIMARY CHROMATIC WAVELENGTHS ARE 2 - 3

SECONDARY CHROMATIC WAVELENGTHS ARE 2 - 1
```



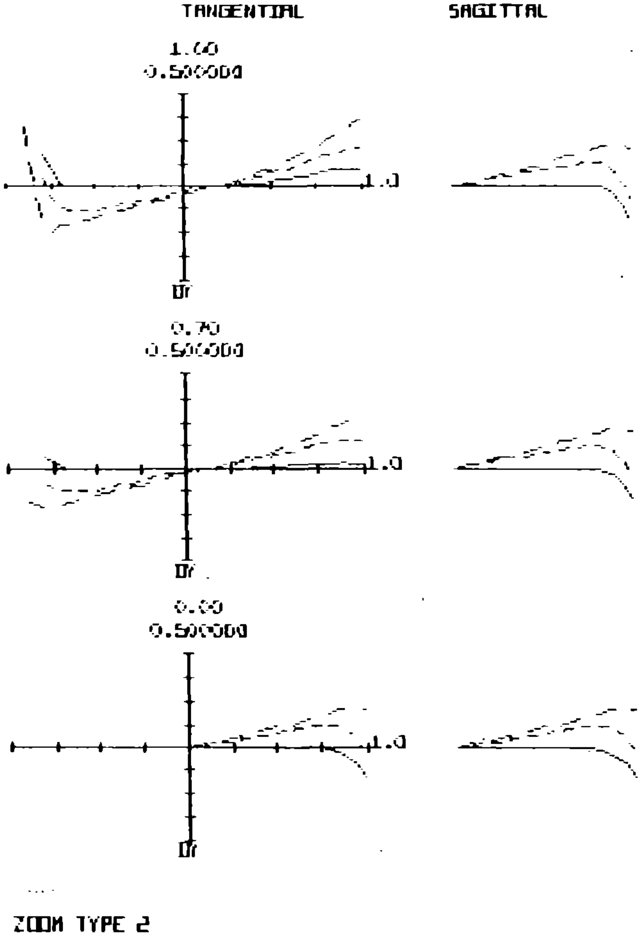
REFRACTIVE OPTICS. LONGEST FOCAL LENGTH (2000 MM) CONFIGURATION AT TOP.



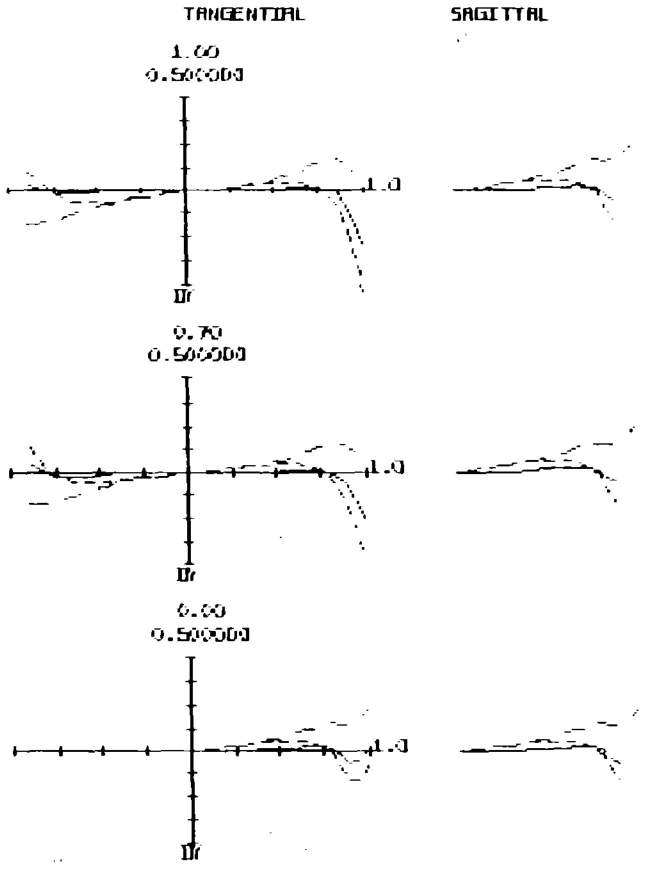
LONGEST FOCAL LENGTH.



SHORTEST FOCAL LENGTH CONFIGURATION (200 MM).

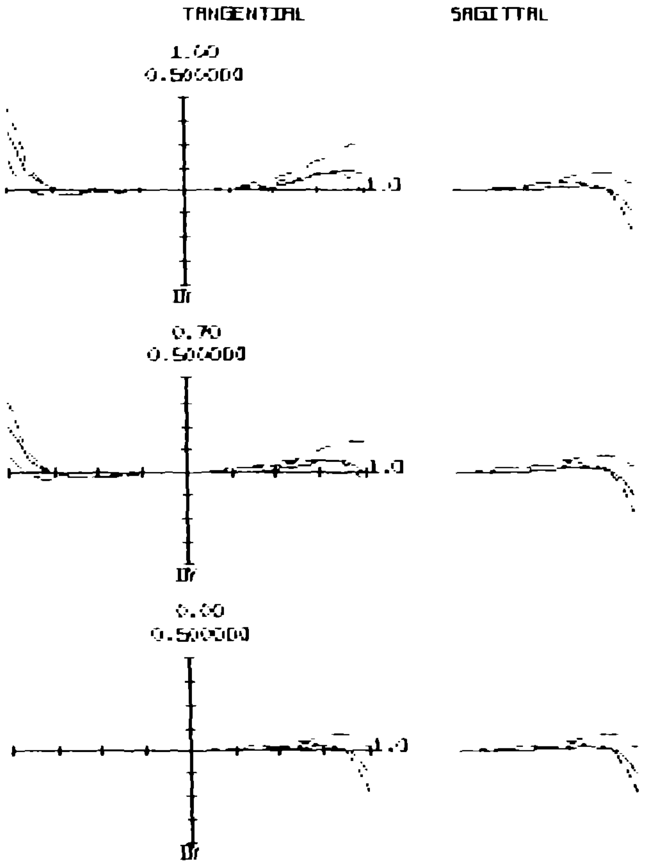


RAY FAN PLOTS. REFRACTIVE OPTICS 2000 MM FOCAL LENGTH. 400 - 1000 NM WAVELENGTH



ZOOM TYPE 2

REFRACTIVE OPTICS, FOCAL LENGTH 1120MM. PLOT SCALE IS .5 CM.



ZOOM TYPE 2

REFRACTIVE OPTICS. 200 MM FOCAL LENGTH.   SCALE .5 CM.

Refractive Optics 'CFE, 1 ; FOB 0.

```
GEOMETRIC OTF:     FOCUS =    1.586000
   TARGET:           90 DG
    FREQ          MOD        PHA
     0.0         1.000        0.0
     1.0         0.042        0.0
     2.0         0.331      180.0
     3.0         0.027       -0.0
     4.0         0.011       -0.0
     5.0         0.278      180.0
     6.0         0.162      180.0
     7.0         0.037       -0.0
     8.0         0.325       -0.0
     9.0         0.017      180.0
    10.0         0.044       -0.0
    11.0         0.082      180.0
    12.0         0.051      180.0
    13.0         0.131       -0.0
    14.0         0.030        0.0
    15.0         0.105     -180.0
    16.0         0.160       -0.0
    17.0         0.115       -0.0
    18.0         0.080     -180.0
    19.0         0.274      180.0
    20.0         0.098       -0.0
    21.0         0.168       -0.0
    22.0         0.041      180.0
    23.0         0.052     -180.0
    24.0         0.104       -0.0
    25.0         0.120       -0.0
    26.0         0.029       -0.0
    27.0         0.257      180.0
    28.0         0.004       -0.0
    29.0         0.072      180.0
    30.0         0.078       -0.0
```

APPENDIX E

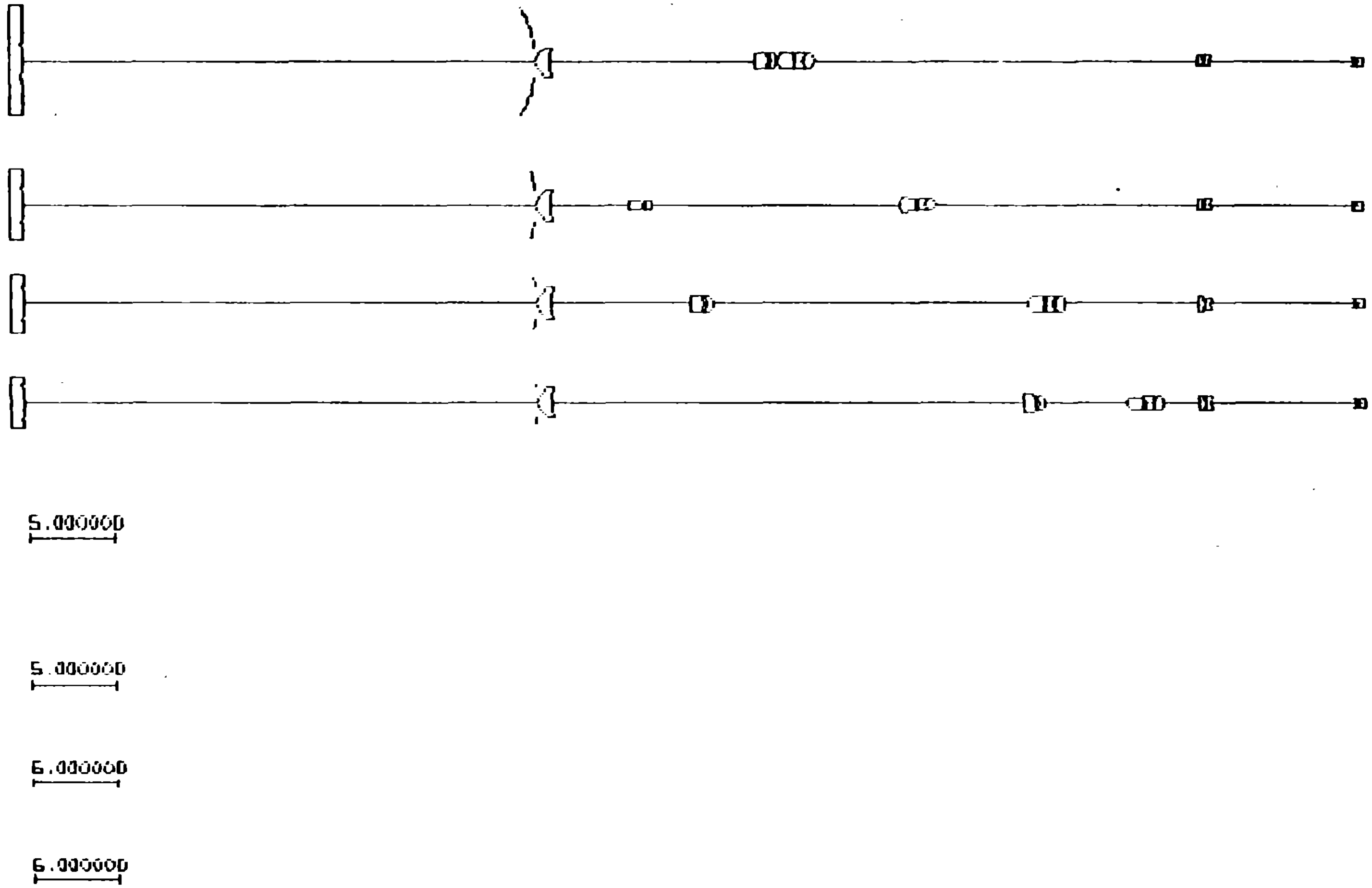
PRELIMINARY CATADIOPTRIC DESIGN

```
MIRROR ZOOM WITH FIELD FLATTENER

BASIC LENS DATA
SURF        RD             TH          MEDIUM                  RN        DF
  0      0.000000   0.100000E 12   AIR

  1    9919.116000       0.840201   SCHOTT BK7         1.516800    0.311
  2  -3929.602694      29.979709   AIR

  3     -90.411566     -29.979709   REFL

  4     -57.690562      29.979709   REFL

  5      10.669782       0.799447   SCHOTT LAK8        1.713003   -0.006
  6      47.410182      12.039217   AIR

  7     136.672961       0.735270   SCHOTT SK16        1.620411   -0.025
  8     -14.010775       0.200286   AIR

  9      -7.931797       0.335593   SCHOTT SF4         1.755201    0.981
 10     -11.157716       0.000000   AIR

 11       9.910903       0.947291   SCHOTT LAK9        1.691003   -0.000
 12     -80.350031       0.123377   AIR

 13      -9.022872       0.337031   SCHOTT F2          1.620041    0.935
 14       6.972849       0.100838   AIR

 15       8.382768       0.605227   SCHOTT LAK8        1.713003   -0.006
 16      -9.188521      22.225798   AIR

 17      12.414584       0.416382   SCHOTT LAK8        1.713003   -0.006
 18     -12.376881       0.057877   AIR
```

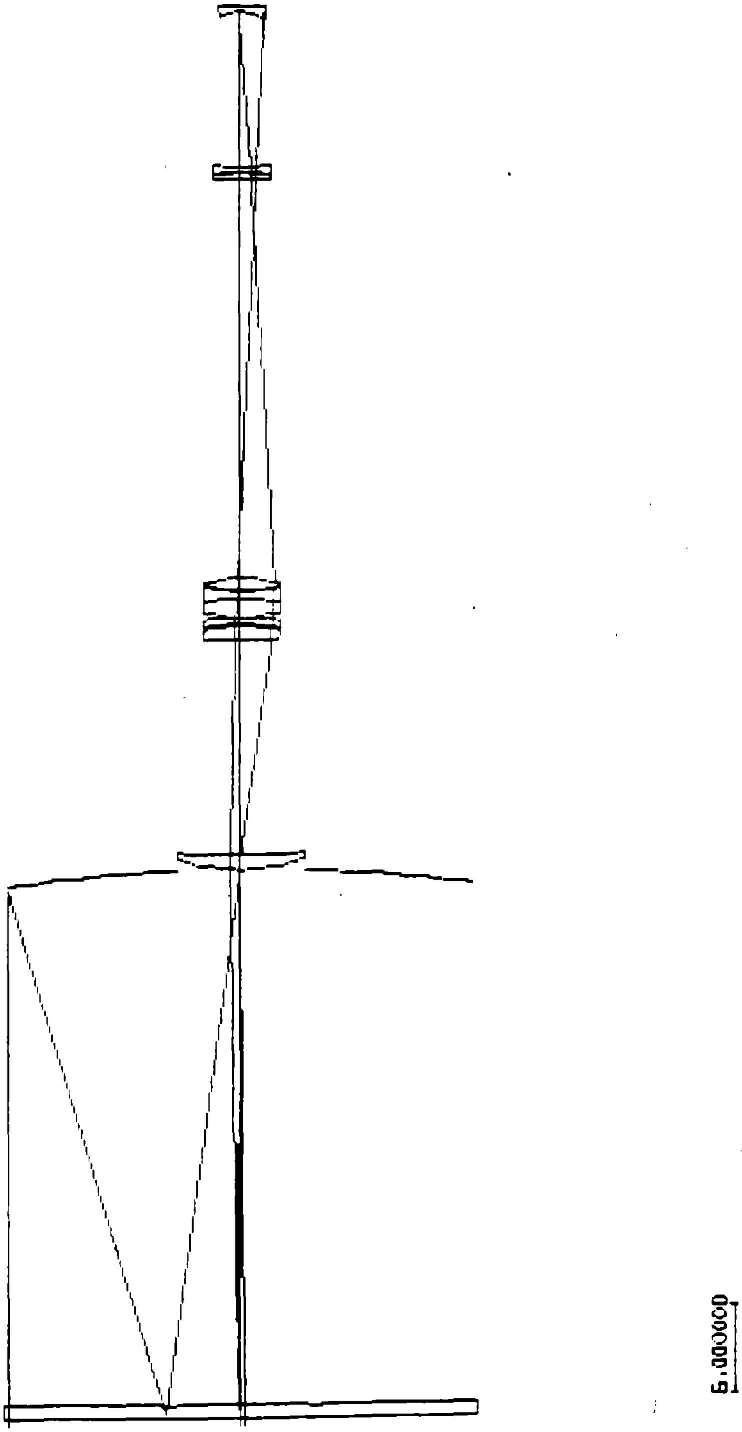
```
 19    -13.318980       0.256452   SCHOTT LLF1      1.548141   0.973
 20      8.888944       8.700000   AIR

 21     -2.895609       0.300000   SCHOTT LLF1      1.548141   0.973
 22      0.000000       0.000000   AIR

 23      0.000000       0.000000   AIR


REFRACTIVE INDICES

SURF       N1          N2          N3          N4          N5
  1     1.516800    1.526685    1.512894    1.522377    1.514323
  5     1.713003    1.729437    1.706678    1.722220    1.708975
  7     1.620411    1.633122    1.615479    1.627558    1.617273
  9     1.755201    1.791202    1.742997    1.774680    1.747297
 11     1.691003    1.706673    1.684977    1.699794    1.687163
 13     1.620041    1.642015    1.612268    1.632083    1.615033
 15     1.713003    1.729437    1.706678    1.722220    1.708975
 17     1.713003    1.729437    1.706678    1.722220    1.708975
 19     1.548141    1.563323    1.542563    1.556546    1.544566
 21     1.548141    1.563323    1.542563    1.556546    1.544566
CC AND ASPHERIC DATA

SURF       CC              AD              AE              AF              AG
  2   -6.35041E 04
  3   -5.16264E-01
  4    1.51502E 00
 17   -1.18594E 00

CLEAR APERTURES AND OBSTRUCTIONS

 -
```

```
SURF         TYPE         CAY          CAX
  2 (OB)    CIRCLE       4.3500
  3 (OB)    CIRCLE       3.4500
  4         CIRCLE       4.3500
  5         CIRCLE       3.4500
  6         CIRCLE       3.4500

PICKUPS

SURF    TYPE     J     A           B
  3     TH       2   -1.0000     0.000000
  4     TH       2    1.0000     0.000000

 REF OBJ HT                    REF AP HT   OBJ SURF   REF SURF   IMG SURF
-0.657597E 09 (   0.38 DG)     12.43083       0          3          23

   EFL            BF          F/NBR       LENGTH        GIH
 -196.1110       0.0000      -7.84       79.0000      -1.3152

LENS IS CURRENTLY IN CFG 1


ALTERNATE CONFIGURATIONS

       PARAMETER   SURF   CURRENT VALUE

CFG 2:
          SAY         1     7.880000
          PUCY        0     0.011743
          PCY         1     0.000000
          TH          6     4.726286
          TH         10    14.380409
          TH         16    15.158346
-
```

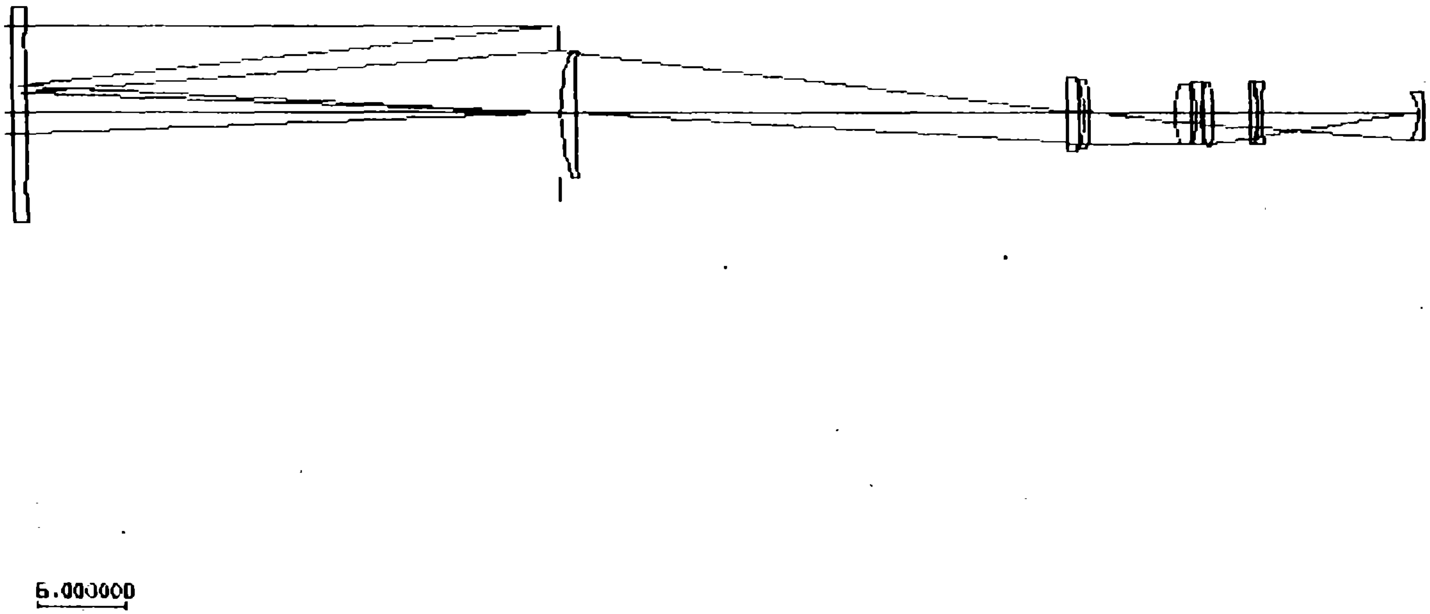
```
CFG 3:
              SAY         1      5.680000
              PUCY        0      0.020876
              PCY         1      0.000000
              TH          6      8.249708
              TH         10     18.300768
              TH         16      7.714525

CFG 4:
              SAY         1      4.780000
              PUCY        0      0.036533
              PCY         1      0.000000
              TH          6     27.499407
              TH         10      4.767607
              TH         16      1.998033

WAVL NBR             1          2          3          4          5
WAVELENGTH       0.58756    0.43584    0.70652    0.48613    0.65627
SPECTRAL WT       1.0000     1.0000     1.0000     1.0000     1.0000

APERTURE STOP AT SURF  3

LENS UNITS ARE CM

EVALUATION MODE IS FOCAL

CONTROL WAVELENGTH IS 1

PRIMARY CHROMATIC WAVELENGTHS ARE 2 - 3

SECONDARY CHROMATIC WAVELENGTHS ARE 2 - 1
```



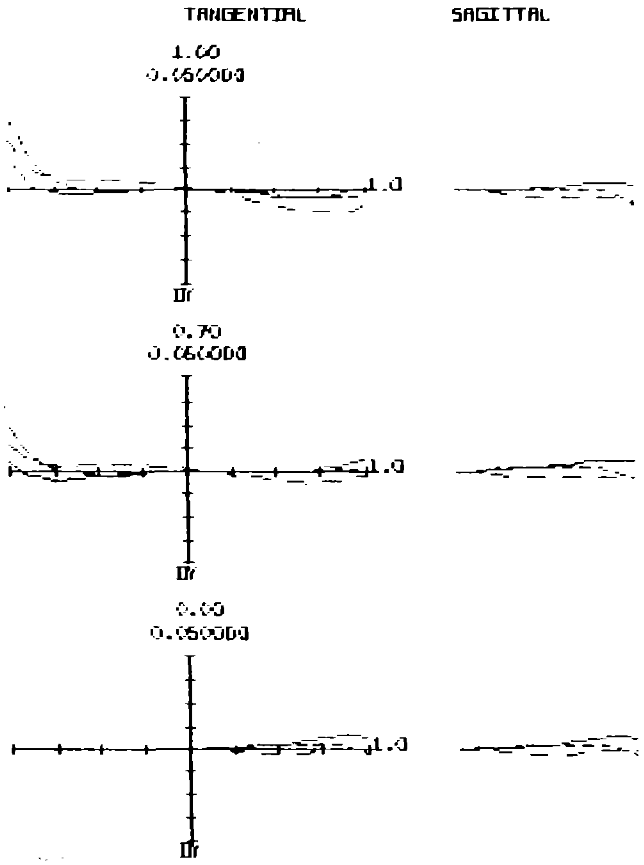
CATADIOPTRIC ZOOM. 2000 MM FOCAL LENGTH CONFIGURATION AT TOP.



CATADIOPTRIC ZOOM. 2000 MM FOCAL LENGTH.

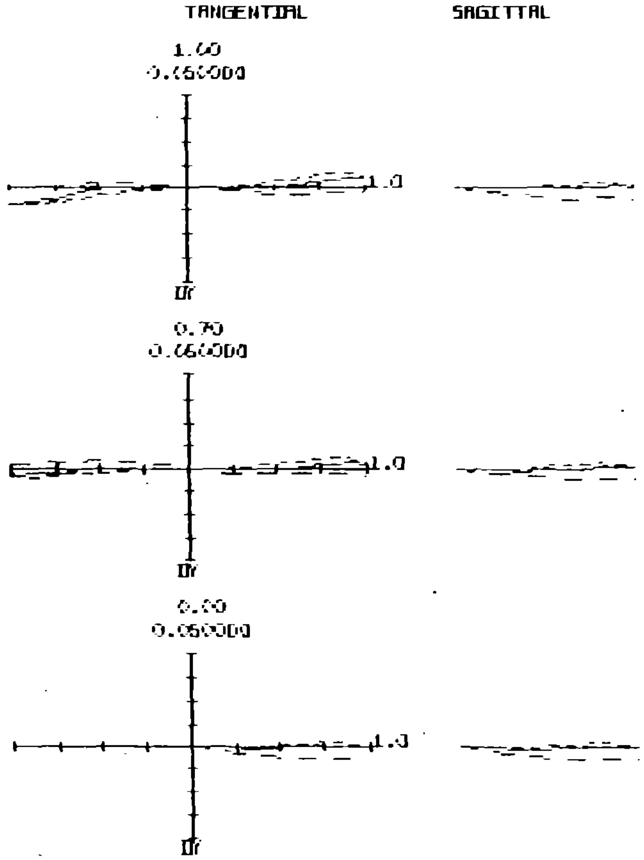


SHORTEST FOCAL LENGTH (367 MM) CONFIGURATION.



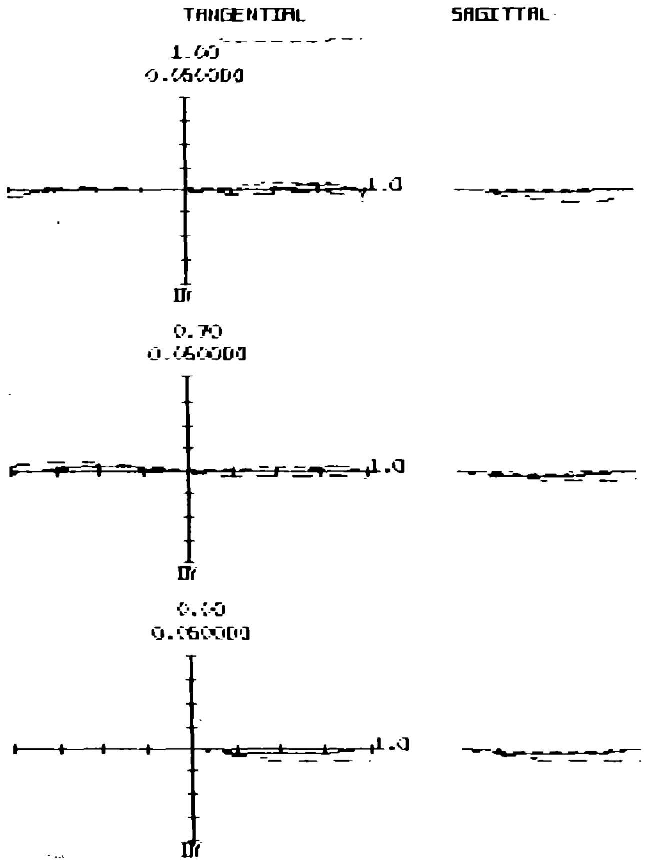
MIRROR ZOOM WITH FIELD FLATTENER

2000 MM CONFIGURATION.   PLOT SCALE .05 CM.



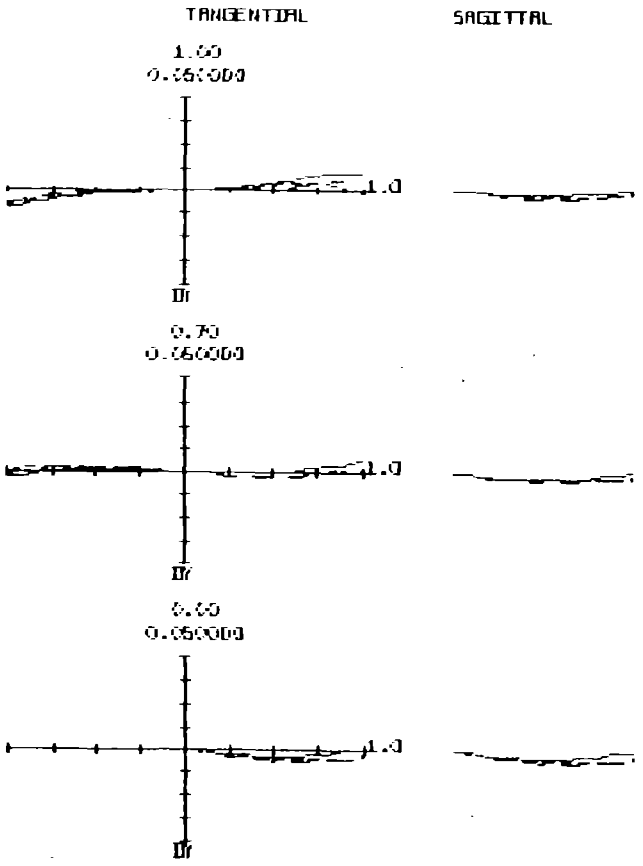
MIRROR ZOOM WITH FIELD FLATTENER

1120 MM FOCAL LENGTH CONFIGURATION. PLOT SCALE .05 CM.



MIRROR ZOOM WITH FIELD FLATTENER

645 MM FOCAL LENGTH CONFIGURATION. PLOT SCALE .05 CM.



MIRROR ZOOM WITH FIELD FLATTENER

568 MM FOCAL LENGTH CONFIGURATION. PLOT SCALE .05 CM.

Catadioptric System
2000 mm configuration
on axis

```
GEOMETRIC OTF:     FOCUS =   -0.054000
   TARGET:             30 DG
    FREQ          MOD        PHA
     0.0         1.000        0.0
     1.0         0.991        0.0
     2.0         0.964        0.0
     3.0         0.920        0.0
     4.0         0.861        0.0
     5.0         0.791        0.0
     6.0         0.712        0.0
     7.0         0.628        0.0
     8.0         0.543        0.0
     9.0         0.461        0.0
    10.0         0.383        0.0
    11.0         0.314        0.0
    12.0         0.255       -0.0
    13.0         0.208       -0.0
    14.0         0.174       -0.0
    15.0         0.151       -0.0
    16.0         0.140       -0.0
    17.0         0.139       -0.0
    18.0         0.145       -0.0
    19.0         0.157        0.0
    20.0         0.172        0.0
    21.0         0.188        0.0
    22.0         0.201        0.0
    23.0         0.210        0.0
    24.0         0.214        0.0
    25.0         0.211        0.0
    26.0         0.200        0.0
    27.0         0.182        0.0
    28.0         0.157        0.0
    29.0         0.126        0.0
    30.0         0.091        0.0
```

Catadioptric system

2000 nm configuration

edge

```
GEOMETRIC OTF:     FOCUS =  -0.054000
   TARGET:            0 DG                 45 DG                90 DG
   FREQ          MOD        PHA       MOD        PHA       MOD        PHA
    0.0         1.000       0.0      1.000       0.0      1.000       0.0
    1.0         0.987      -0.0      0.981      -0.6      0.975      -0.8
    2.0         0.950      -0.0      0.928      -1.3      0.906      -1.8
    3.0         0.891      -0.0      0.849      -2.3      0.806      -3.3
    4.0         0.816      -0.0      0.756      -3.6      0.694      -5.4
    5.0         0.728      -0.0      0.661      -5.2      0.589      -8.3
    6.0         0.635      -0.0      0.574      -6.9      0.503     -11.9
    7.0         0.544      -0.0      0.501      -8.6      0.444     -16.0
    8.0         0.459      -0.0      0.445     -10.1      0.410     -20.2
    9.0         0.386      -0.0      0.403     -11.4      0.394     -24.4
   10.0         0.330      -0.0      0.374     -13.0      0.392     -29.2
   11.0         0.291      -0.0      0.353     -15.5      0.396     -34.9
   12.0         0.270      -0.0      0.339     -19.5      0.405     -41.5
   13.0         0.266      -0.0      0.331     -24.9      0.420     -48.5
   14.0         0.276      -0.0      0.328     -31.4      0.437     -54.9
   15.0         0.296      -0.0      0.329     -38.0      0.451     -60.0
   16.0         0.322      -0.0      0.330     -44.0      0.457     -63.5
   17.0         0.348      -0.0      0.327     -49.0      0.449     -65.7
   18.0         0.370      -0.0      0.318     -52.8      0.426     -67.3
   19.0         0.384      -0.0      0.303     -55.5      0.389     -68.9
   20.0         0.387      -0.0      0.284     -56.9      0.345     -71.6
   21.0         0.379      -0.0      0.265     -57.0      0.300     -76.3
   22.0         0.359      -0.0      0.249     -55.4      0.262     -83.4
   23.0         0.329      -0.0      0.238     -52.1      0.233     -92.1
   24.0         0.291      -0.0      0.232     -47.3      0.213    -100.4
   25.0         0.248      -0.0      0.230     -41.8      0.195    -106.9
   26.0         0.205      -0.0      0.227     -36.3      0.173    -111.3
   27.0         0.165      -0.0      0.220     -31.3      0.147    -114.5
   28.0         0.131      -0.0      0.204     -27.3      0.119    -118.0
   29.0         0.107      -0.0      0.180     -24.8      0.099    -124.3
   30.0         0.093      -0.0      0.151     -24.7      0.093    -133.5
```

```
GEOMETRIC OTF:     FOCUS =  -0.054000
  TARGET:             0 DG                     45 DG                     90 DG
   FREQ          MOD        PHA         MOD        PHA         MOD        PHA
    0.0         1.000        0.0       1.000        0.0       1.000        0.0
    1.0         0.978       -0.0       0.949       -0.9       0.920       -1.3
    2.0         0.915       -0.0       0.818       -3.0       0.727       -5.2
    3.0         0.822       -0.0       0.660       -7.4       0.526      -14.1
    4.0         0.712       -0.0       0.523      -13.8       0.397      -26.9
    5.0         0.602       -0.0       0.425      -20.5       0.336      -36.5
    6.0         0.506       -0.0       0.362      -26.5       0.299      -41.5
    7.0         0.434       -0.0       0.326      -32.7       0.269      -46.7
    8.0         0.392       -0.0       0.314      -39.3       0.241      -53.2
    9.0         0.378       -0.0       0.312      -45.0       0.206      -57.4
   10.0         0.386       -0.0       0.296      -49.4       0.152      -57.1
   11.0         0.406       -0.0       0.258      -53.7       0.095      -54.4
   12.0         0.426       -0.0       0.206      -58.5       0.066      -59.4
   13.0         0.439       -0.0       0.156      -60.8       0.084      -67.3
   14.0         0.436       -0.0       0.116      -51.6       0.120      -63.6
   15.0         0.415       -0.0       0.096      -23.9       0.131      -54.6
   16.0         0.378       -0.0       0.103        5.2       0.100      -42.2
   17.0         0.329       -0.0       0.106       19.7       0.052      -23.8
   18.0         0.274       -0.0       0.091       18.1       0.025       -5.7
   19.0         0.219       -0.0       0.082       -1.9       0.035      -21.6
   20.0         0.170       -0.0       0.102      -17.0       0.065      -22.2
   21.0         0.131       -0.0       0.128      -14.8       0.071      -14.9
   22.0         0.104       -0.0       0.143       -6.2       0.034      -13.1
   23.0         0.089       -0.0       0.141       -0.4       0.032     -140.6
   24.0         0.085       -0.0       0.127       -3.8       0.086     -134.6
   25.0         0.089       -0.0       0.117      -18.3       0.115     -115.5
   26.0         0.099       -0.0       0.119      -35.5       0.116      -96.5
   27.0         0.111       -0.0       0.123      -48.3       0.094      -84.5
   28.0         0.124       -0.0       0.122      -56.9       0.060      -86.2
   29.0         0.133       -0.0       0.120      -58.9       0.039      -94.4
   30.0         0.137       -0.0       0.120      -50.2       0.033      -61.5
```

Catadioptric System
2000 mm focal length
corner

```
GEOMETRIC OTF:     FOCUS =    0.047900
   TARGET:            90 DG
    FREQ         MOD       PHA
     0.0        1.000       0.0
     1.0        0.995       0.0
     2.0        0.979       0.0
     3.0        0.954       0.0
     4.0        0.919       0.0
     5.0        0.876       0.0
     6.0        0.827       0.0
     7.0        0.772       0.0
     8.0        0.712       0.0
     9.0        0.651       0.0
    10.0        0.588       0.0
    11.0        0.526       0.0
    12.0        0.466       0.0
    13.0        0.409       0.0
    14.0        0.356       0.0
    15.0        0.309       0.0
    16.0        0.267       0.0
    17.0        0.232       0.0
    18.0        0.203       0.0
    19.0        0.180       0.0
    20.0        0.163       0.0
    21.0        0.152       0.0
    22.0        0.145       0.0
    23.0        0.142       0.0
    24.0        0.142       0.0
    25.0        0.145       0.0
    26.0        0.149       0.0
    27.0        0.154      -0.0
    28.0        0.158      -0.0
    29.0        0.162      -0.0
    30.0        0.164      -0.0
```

Catadioptric

645 mm focal length

on axis

```
GEOMETRIC OTF:     FOCUS =   0.047900
  TARGET:              0 DG                 45 DG                  90 DG
   FREQ        MOD        PHA      MOD        PHA      MOD        PHA
    0.0       1.000       0.0     1.000       0.0     1.000       0.0
    1.0       0.995      -0.0     0.992       1.2     0.989       1.7
    2.0       0.979      -0.0     0.967       2.4     0.955       3.3
    3.0       0.954      -0.0     0.927       3.6     0.902       4.9
    4.0       0.919      -0.0     0.874       4.8     0.832       6.4
    5.0       0.876      -0.0     0.809       6.1     0.751       7.7
    6.0       0.826      -0.0     0.736       7.3     0.664       8.7
    7.0       0.771      -0.0     0.657       8.6     0.575       9.2
    8.0       0.711      -0.0     0.575       9.8     0.491       8.8
    9.0       0.649      -0.0     0.494      11.0     0.415       7.4
   10.0       0.586      -0.0     0.415      12.0     0.353       4.4
   11.0       0.523      -0.0     0.342      12.8     0.308      -0.3
   12.0       0.462      -0.0     0.276      13.1     0.281      -6.1
   13.0       0.404      -0.0     0.218      12.5     0.271     -11.9
   14.0       0.351      -0.0     0.170      10.7     0.274     -16.5
   15.0       0.303      -0.0     0.133       6.9     0.285     -19.3
   16.0       0.261      -0.0     0.106       0.8     0.300     -20.5
   17.0       0.226      -0.0     0.089      -7.0     0.314     -20.4
   18.0       0.196      -0.0     0.082     -14.8     0.322     -19.6
   19.0       0.174      -0.0     0.080     -20.1     0.324     -18.3
   20.0       0.157      -0.0     0.082     -22.1     0.317     -16.7
   21.0       0.147      -0.0     0.085     -21.1     0.301     -15.2
   22.0       0.141      -0.0     0.087     -18.0     0.277     -13.7
   23.0       0.139      -0.0     0.089     -13.2     0.245     -12.4
   24.0       0.141      -0.0     0.089      -7.2     0.208     -11.4
   25.0       0.145      -0.0     0.088      -0.2     0.170     -10.9
   26.0       0.150      -0.0     0.086       7.7     0.132     -11.4
   27.0       0.155      -0.0     0.082      16.3     0.099     -13.5
   28.0       0.160      -0.0     0.078      25.9     0.072     -18.2
   29.0       0.164      -0.0     0.073      36.2     0.055     -25.7
   30.0       0.165      -0.0     0.068      47.2     0.047     -33.6
```

Catadioptric
645 mm focal length
edge.

```
GEOMETRIC OTF:     FOCUS =    0.047900
   TARGET:                0 DG                   45 DG                  90 DG
    FREQ          MOD        PHA        MOD        PHA        MOD        PHA
     0.0         1.000        0.0      1.000        0.0      1.000        0.0
     1.0         0.995       -0.0      0.986        0.7      0.977        1.0
     2.0         0.979       -0.0      0.944        1.4      0.911        2.0
     3.0         0.953       -0.0      0.878        2.3      0.811        3.0
     4.0         0.918       -0.0      0.793        3.2      0.689        4.0
     5.0         0.874       -0.0      0.694        4.2      0.560        4.7
     6.0         0.824       -0.0      0.588        5.4      0.438        4.6
     7.0         0.768       -0.0      0.482        6.6      0.335        2.6
     8.0         0.708       -0.0      0.381        7.8      0.259       -3.0
     9.0         0.646       -0.0      0.290        8.6      0.218      -12.9
    10.0         0.583       -0.0      0.212        8.1      0.211      -24.4
    11.0         0.522       -0.0      0.149        4.9      0.230      -32.8
    12.0         0.462       -0.0      0.103       -4.0      0.258      -37.2
    13.0         0.406       -0.0      0.077      -21.4      0.285      -38.7
    14.0         0.355       -0.0      0.072      -42.0      0.300      -38.5
    15.0         0.308       -0.0      0.080      -55.5      0.301      -37.0
    16.0         0.268       -0.0      0.089      -61.1      0.287      -34.4
    17.0         0.234       -0.0      0.095      -62.1      0.261      -30.4
    18.0         0.206       -0.0      0.094      -60.5      0.229      -25.0
    19.0         0.184       -0.0      0.087      -57.0      0.199      -18.0
    20.0         0.167       -0.0      0.073      -51.3      0.176      -10.3
    21.0         0.155       -0.0      0.054      -41.3      0.162       -4.2
    22.0         0.148       -0.0      0.034      -18.4      0.154       -1.8
    23.0         0.143       -0.0      0.026       36.8      0.149       -4.0
    24.0         0.142       -0.0      0.042       80.3      0.147      -10.5
    25.0         0.142       -0.0      0.065       97.2      0.148      -19.9
    26.0         0.142       -0.0      0.087      105.9      0.150      -30.4
    27.0         0.144       -0.0      0.105      111.8      0.152      -40.5
    28.0         0.144       -0.0      0.118      116.3      0.152      -49.4
    29.0         0.144       -0.0      0.125      120.2      0.147      -56.4
    30.0         0.142       -0.0      0.127      123.6      0.136      -61.1
```

```
GEOMETRIC OTF:     FOCUS =    0.042500
  TARGET:            90 DG
   FREQ           MOD       PHA
    0.0          1.000       0.0
    1.0          0.995      -0.0
    2.0          0.982      -0.0
    3.0          0.960      -0.0
    4.0          0.930      -0.0
    5.0          0.893      -0.0
    6.0          0.851      -0.0
    7.0          0.804      -0.0
    8.0          0.754      -0.0
    9.0          0.703      -0.0
   10.0          0.651      -0.0
   11.0          0.600      -0.0
   12.0          0.550      -0.0
   13.0          0.502      -0.0
   14.0          0.457      -0.0
   15.0          0.415      -0.0
   16.0          0.377      -0.0
   17.0          0.341      -0.0
   18.0          0.308      -0.0
   19.0          0.278      -0.0
   20.0          0.250      -0.0
   21.0          0.224      -0.0
   22.0          0.200      -0.0
   23.0          0.178      -0.0
   24.0          0.158      -0.0
   25.0          0.139      -0.0
   26.0          0.122      -0.0
   27.0          0.107      -0.0
   28.0          0.094      -0.0
   29.0          0.083       0.0
   30.0          0.074       0.0
```

Cal. dioptric
368 mm focal length
on axis

```
GEOMETRIC OTF:     FOCUS =    0.042500
   TARGET:               0 DG                 45 DG                 90 DG
    FREQ          MOD        PHA        MOD        PHA        MOD        PHA
     0.0         1.000       0.0       1.000       0.0       1.000       0.0
     1.0         0.996      -0.0       0.988       1.0       0.981       1.4
     2.0         0.983      -0.0       0.954       2.0       0.927       2.8
     3.0         0.963      -0.0       0.901       2.9       0.844       4.0
     4.0         0.935      -0.0       0.833       3.8       0.744       4.9
     5.0         0.903      -0.0       0.756       4.4       0.638       5.4
     6.0         0.866      -0.0       0.675       5.0       0.537       5.4
     7.0         0.827      -0.0       0.595       5.3       0.449       4.6
     8.0         0.786      -0.0       0.521       5.4       0.378       3.2
     9.0         0.746      -0.0       0.453       5.4       0.325       1.0
    10.0         0.706      -0.0       0.394       5.1       0.288      -1.5
    11.0         0.669      -0.0       0.343       4.7       0.263      -4.3
    12.0         0.633      -0.0       0.298       4.1       0.246      -7.3
    13.0         0.599      -0.0       0.258       3.3       0.234     -10.3
    14.0         0.567      -0.0       0.222       2.1       0.227     -13.3
    15.0         0.537      -0.0       0.188       0.3       0.224     -15.9
    16.0         0.507      -0.0       0.157      -2.5       0.225     -17.5
    17.0         0.478      -0.0       0.128      -6.6       0.228     -17.8
    18.0         0.449      -0.0       0.103     -12.6       0.233     -16.7
    19.0         0.420      -0.0       0.082     -20.6       0.238     -14.4
    20.0         0.390      -0.0       0.066     -30.2       0.242     -11.3
    21.0         0.360      -0.0       0.054     -40.3       0.243      -8.1
    22.0         0.331      -0.0       0.044     -49.7       0.239      -5.2
    23.0         0.302      -0.0       0.034     -57.9       0.231      -3.1
    24.0         0.275      -0.0       0.023     -66.8       0.218      -2.0
    25.0         0.250      -0.0       0.012     -86.6       0.203      -2.1
    26.0         0.227      -0.0       0.008    -170.1       0.188      -3.3
    27.0         0.207      -0.0       0.020     152.3       0.175      -5.3
    28.0         0.191      -0.0       0.034     145.3       0.167      -7.5
    29.0         0.177      -0.0       0.047     143.6       0.163      -9.4
    30.0         0.167      -0.0       0.059     143.7       0.163     -10.7
```

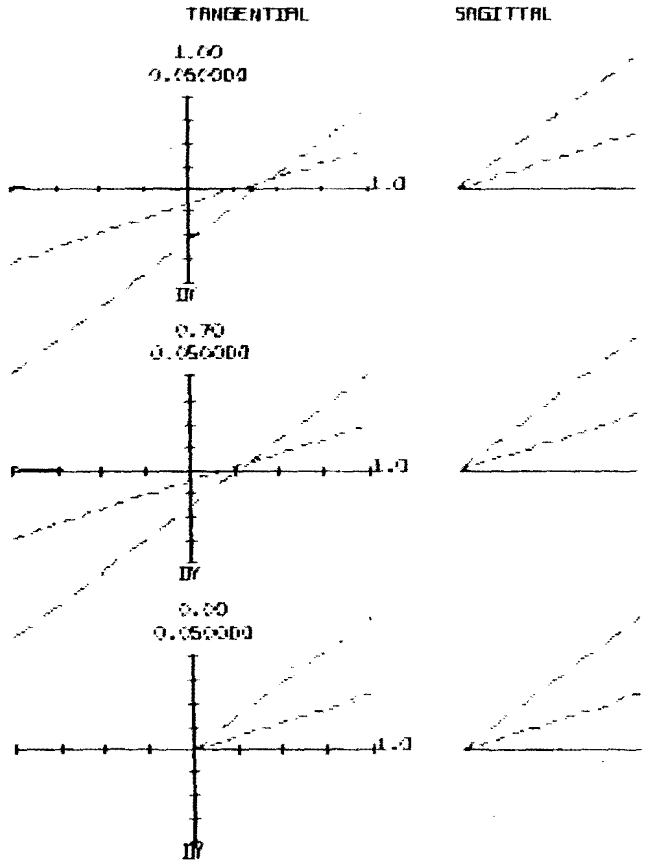
Catadioptric
368 mm focal length
edge

```
GEOMETRIC OTF:    FOCUS =   0.042500
 TARGET:               0 DG               45 DG               90 DG
  FREQ         MOD       PHA       MOD       PHA       MOD       PHA
   0.0       1.000       0.0     1.000       0.0     1.000       0.0
   1.0       0.995      -0.0     0.958       0.5     0.922       0.7
   2.0       0.980      -0.0     0.840       0.8     0.714       1.2
   3.0       0.956      -0.0     0.668       0.8     0.442       0.8
   4.0       0.925      -0.0     0.472       0.1     0.185      -2.4
   5.0       0.890      -0.0     0.284      -2.0     0.021     -86.1
   6.0       0.852      -0.0     0.129      -8.6     0.094    -163.8
   7.0       0.815      -0.0     0.027     -58.2     0.108    -165.7
   8.0       0.778      -0.0     0.057    -158.7     0.080    -159.3
   9.0       0.745      -0.0     0.084    -170.0     0.050    -130.7
  10.0       0.714      -0.0     0.087    -174.0     0.056     -84.8
  11.0       0.687      -0.0     0.075    -173.2     0.081     -65.5
  12.0       0.663      -0.0     0.057    -163.6     0.095     -56.7
  13.0       0.641      -0.0     0.045    -137.0     0.089     -47.9
  14.0       0.619      -0.0     0.048    -100.6     0.062     -33.3
  15.0       0.596      -0.0     0.063     -76.7     0.028      12.3
  16.0       0.572      -0.0     0.076     -62.5     0.039      98.6
  17.0       0.547      -0.0     0.080     -51.6     0.063     122.3
  18.0       0.520      -0.0     0.073     -40.9     0.064     132.1
  19.0       0.492      -0.0     0.055     -27.2     0.041     136.6
  20.0       0.464      -0.0     0.033      -0.8     0.005     108.4
  21.0       0.436      -0.0     0.025      61.1     0.028     -27.8
  22.0       0.409      -0.0     0.040     102.4     0.040     -30.5
  23.0       0.384      -0.0     0.054     115.0     0.029     -36.6
  24.0       0.362      -0.0     0.059     117.3     0.008     -87.3
  25.0       0.342      -0.0     0.054     112.5     0.021     169.9
  26.0       0.324      -0.0     0.042      99.2     0.032     154.1
  27.0       0.308      -0.0     0.031      72.2     0.030     141.2
  28.0       0.292      -0.0     0.025      27.9     0.020     131.8
  29.0       0.276      -0.0     0.030     -16.8     0.011     170.8
  30.0       0.260      -0.0     0.041     -47.9     0.029    -135.5
```

catadioptric

368 mm focal length

corner



ZOOM TYPE 3 (TAKANO)

RAY FAN PLOT. FROM PATENT 3,393,958. PLOT SCALE .05 CM. LENGTH OF LENS 2978 MM.