

New Design Principle for High-Ratio Zoom Lenses

By K. MACHER

After a discussion of the requirements made of a zoom lens for color television, the author briefly deals with basic principles and then introduces a zoom system with a wide focal-length range.

1. Introduction and Requirements

Movie cameras designed for the amateur, or for shooting feature films, for newsreel coverage or for live television reporting make almost exclusive use of zoom lenses. Extremely high requirements are made of these lenses, above all, those for color television.^{1,1.1,1.2,1.3} In detail, these requirements are:

- (1) High speed in conjunction with high transmission in the spectral region between 380 and 700 nm and uniform illumination of the entire field, which calls for high residual illumination right up to the corners of the format.
- (2) A high zoom ratio — at least ten times — with the shortest focal length not exceeding the length of the format diagonal.
- (3) A focusing range from infinity down to less than 3 ft (91 cm).
- (4) Optimum performance and constant back focal distance in all color channels over the entire focal-length range and at any focus setting.
- (5) Optimum compactness.
- (6) Minimum weight.

The necessity for a long back focal distance to allow the picture to be divided into the three components, green, red and blue, in front of the focal plane complicates matters considerably.

The development of color television is still very much in flux. A growing number of applications can be expected with ever new requirements for the optical systems which are the first, and even decisive, links in the chain from the object to the television image. Outdoor work, with long camera-to-object distances, calls for considerably longer

focal lengths than are required in the studio; however, even in the case of live programs from large halls, the lack of very long focal lengths in studio lenses is frequently felt as a considerable handicap. This is why that, up to the present, special lens designs have been used for outdoor shooting with a zoom ratio of about 1:16 but whose shortest focal length corresponds to about 1.5 times the format diagonal. A system of this type with its relatively long initial focal length and a minimum working distance of about 10 ft (3 m) is, of course, of very little use in the studio; it has to be exchanged for a special studio lens of shorter initial focal length and shorter minimum focusing distance if the same camera is to be employed.

If studio lenses are to be converted for a longer maximum focal length, recourse is generally taken to tele-negative lenses, the so-called range extenders that are inserted behind the lens. These auxiliary systems shift the focal-length range by a certain factor but also reduce the lens aperture proportionally. To insert the auxiliary optical system it is necessary either to remove the lens from the camera or to mount it on a slide so that it can be shifted.

Another possibility for extending the focal-length range is to swing optical elements into the system. In this case, the overall length and the back focal distance of the lens remain unchanged.

However, whichever of these approaches is used, there will be a focal-length gap and also a sudden change in relative aperture. The focal-length gap makes an interruption of transmission unavoidable. It is, of course, possible to switch over to another camera for the duration of the interruption, but this is not only a cost factor but also very disturbing, particularly in live television broadcasting. And, finally, auxiliary optical systems have an adverse effect on image quality.

A more desirable optical system would thus have the following features: (1) large focal length range that can be covered continuously and short initial focal length, i.e., shorter than the format diagonal; (2) high relative aperture; (3) extremely short minimum focusing distance; (4) optimum performance in all color channels; (5) constant back focal distance at any focal length and distance setting; (6) high light transmission; (7) uniform illumination; (8) small size; (9) light weight; and (10) ease of operation. Since these requirements are partly incompatible, the creation of such a lens not only involves processes of optimization, but also many a compromise in which obviously contradicting parameters have to be carefully weighed to achieve a harmonious balance of overall features. It goes without saying that certain limits are set by basic optical laws.

2. Basic Principle of Zoom Lenses

For better understanding, one of the most widely used basic principles of variable-focal-length lenses will be briefly explained (see Fig. 1):

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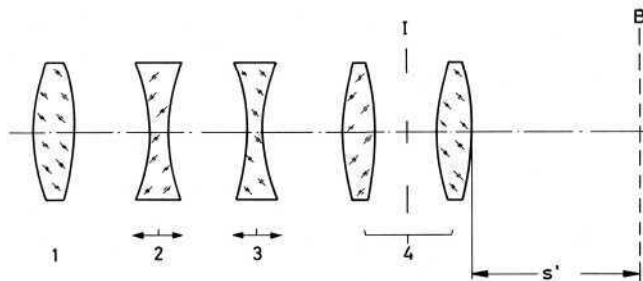


Fig. 1. A basic principle for an optical system of variable focal length.

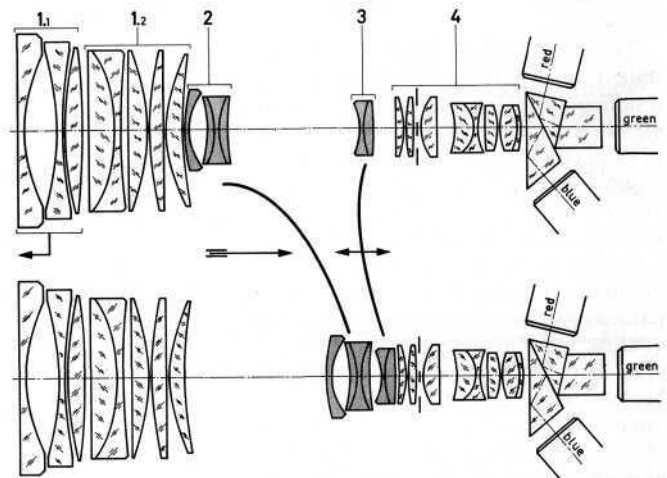


Fig. 2. Optical diagram of Schneider TV Variogon 18-200mm $f/2.14$ for infinity setting. Format: 12.85×17.12 mm (diagonal, 21.4 mm); length to front vertex when focused at infinity, 378 mm; clear diameter of front lens, 140 mm; back focal distance in air, 58.6 mm; glass path length in BK 7, 67 mm; and glass weight without beamsplitter, 4.6 kg.

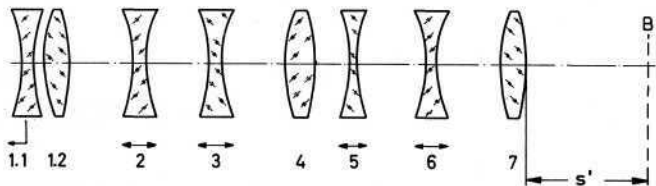


Fig. 3. New design principle of a high-ratio zoom optical system.

Fig. 4. Optical diagram of Schneider TV Variogon 20-600mm $f/2.1 \dots f/6.3$ focused at infinity. Format: 12.85 mm \times 17.12 mm (diagonal 21.4 mm); length to front vertex when focused at infinity, 403 mm; clear diameter of front lens, 130 mm; back focal distance in air, 63.5 mm; glass path length in BK 7, 67 mm; and glass weight without beamsplitter, 3.6 kg.

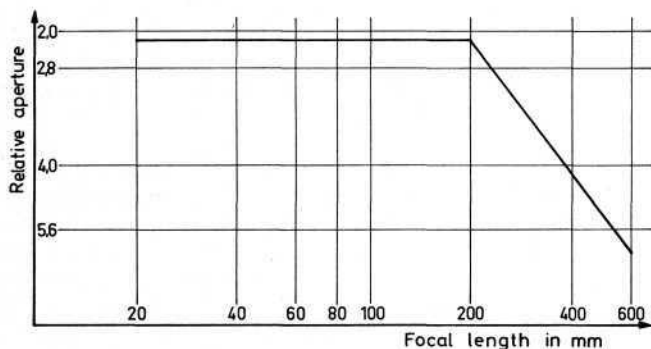
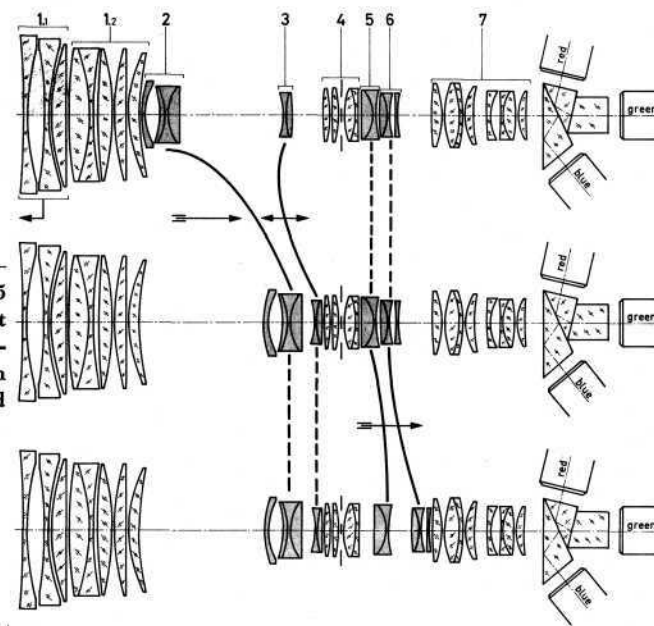


Fig. 5. Relative aperture and focal length of Schneider TV Variogon 20-600mm $f/2.1 \dots f/6.3$.



Between two fixed positive groups 1 and 4, two negative groups 2 and 3 are displaced axially to obtain a continuous variation of focal length. The positive group 4 contains the iris diaphragm (I).^{2,1,2,2} In this system, a suitable combination of the displacement of groups 2 and 3 leaves the back focal distance (s') unchanged over the entire focal-length range. As a result, the image plane (B) remains constant. Factors affecting the size of the system are not only its relative aperture but also the location of the entrance pupil and thus the distribution of the power of the different groups in the system.³

To focus on close objects, group 1 is shifted axially. In order to eliminate the resulting drop in image quality, above all when very long focal lengths are used to focus on very close objects, the positive group 1 has been split up into a negative and a positive portion. Aberrations have been so distributed over the entire group 1 that use of the object-side negative subgroup for focusing will not be accompanied by any noticeable loss in image quality, even at long focal lengths and very short focus settings. It is thus possible to attain relatively constant optical quality over a wide range of magnifications. This principle has been used in the optical system of the Schneider TV Variogon 18-200mm $f/2.1$ (Fig. 2).

3. New Design Principle for High-Ratio Zoom Systems

It is obvious that an extension of the focal-length range to, say 30:1 by the

design principle described above must give rise to considerable difficulty with dimensions and also with the correction of aberrations; therefore, a new solution had to be found. These considerations have resulted in a basic principle shown in Fig. 3. The new system consists of seven optical groups with a minimum of two variable groups. The first group 1.1 serves for focusing. Between the three fixed positive groups 1, 4, and 7, the negative groups 2 and 3 as well as 5 and 6 are shifted on the optical axis to achieve a variation of focal length. The variation range of the two variator groups V1 and V2 gives the total variation by multiplication of $V1 \times V2$

Different shifting modes seem possible for the four moving groups that are displaced in pairs. A variation of focal length can be obtained by shifting the zoom groups successively. In other words, only groups 2 and 3 would move at first. As their end position is reached, the shift is transmitted to groups 5 and 6. However, focal length could also be varied in the reverse order. Simultaneous shifting of the four moving groups would also be possible, either with different path lengths or, if the overall system is designed symmetrically, with identical but point-symmetric path lengths of groups 2 and 6 as well as 3 and 5.

If the motion of a pair of groups is linear, this pair may be mechanically linked. The type of shift employed for the variation of focal length will be chosen according to the purpose of the lens and the type of work to be performed.

By extending the motion to four shifting components, the actual travel for the same focal-length range is considerably less than in a system with only two moving groups. It is thus possible to cover continuously an extremely wide focal-length range with a constant focal plane and shift ranges that are well under control mechanically. Optical power can be distributed rather uniformly among the different groups; this has a favorable effect on the correction of aberrations and the life of the control cams.

The performance and outside dimensions of the system are a function of:

- (1) relative aperture;
- (2) the location of the entrance pupil in conjunction with the desired residual illumination;
- (3) the focal-length and shifting ranges;
- (4) the number and shape of the lens elements in the seven groups; and
- (5) the minimum focusing distance desired.

Once the relative aperture has been chosen, the location of the entrance pupil is determined by the position of the diaphragm and the distribution of optical power among the different groups. However, the distribution of optical power also affects the attainable focal-length and shifting ranges. In addition, optical power has a considerable effect on the number and curvature of lens elements. Shooting requirements also impose certain limits that should be taken into account. Thus, close-ups should give rise neither to distortion nor to a reduction of corner illumination.

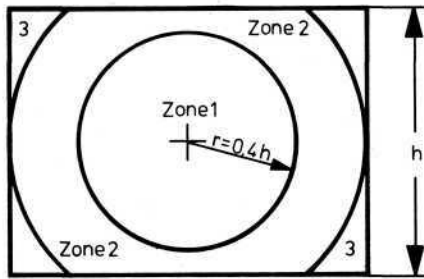


Fig. 6. Subdivision of field into zones ($h = \text{image height} = 12.85 \text{ mm}$).

4. The Schneider TV Variogon 20-600mm $f/2.1 \dots f/6.3$

The system shown in Fig. 4 has been designed along these lines and according to the principle described in Sec. 3. The initial focal length of 20 mm has been determined by the requirement "smaller than the format diagonal" (21.4 mm). Measured from one end of the diagonal to the other, 21.4 mm are equivalent to a field angle of 53° , 20 mm even to an angle of 56° . The longest focal length of 600 mm is then equivalent to an angular field of about 2° .

Apart from the distribution of optical power among the different groups, the desired optical performance is determined by the number and curvature of the lens elements, the selection of glass types being, above all, responsible for the correction of chromatic aberrations. In addition, the glass types have been selected to guarantee a high degree of effective transmission; therefore, close cooperation with the glass manufacturer (JENAer Glaswerk Schott & Gen., Mainz) was a supposition.

4.1. Shortest Focusing Distance

To facilitate illumination and to avoid distortion, the shortest focusing distance has been selected, so that objects about the size of the DIN A 10 to DIN A 1 paper formats can be continuously reproduced so that the entire frame is filled. The magnification varies between 0.018 X and 0.54x. Without an auxiliary optical system, focusing at any focal length is

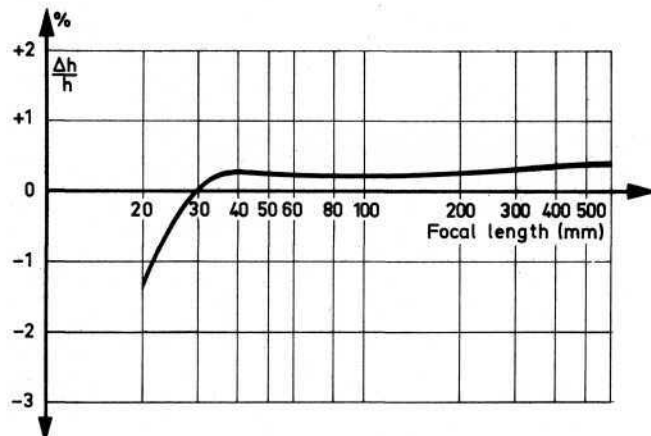


Fig. 7A. Geometric distortion over the entire focal-length range. It is practically independent of magnification.

Table I. Reproduction Scales (Image-to-Object Size) and Object Fields for Different Focal Lengths at the Shortest Focusing Distance E Without and With a Close-up Lens of 1.17 Diopters.

Focal length, mm	Reproduction scale	Without close-up lens, E = 0.85 m (33.46 in)		With 1.17 D close-up lens, E = 0.425 m (16.73 in)		
		Object field		Object field		
		(mm × mm)	(in × in)			
20	1:53	912 × 684	35.91 × 26.93	1:27	461 × 346	18.15 × 13.62
80	1:13	229 × 172	9.02 × 6.77	1:6.8	116 × 87	4.57 × 3.43
200	1:5.6	96 × 72	3.78 × 2.83	1:2.8	48 × 36	1.89 × 1.42
300	1:3.7	63 × 47	2.48 × 1.85	1:1.85	32 × 24	1.26 × 0.94
400	1:2.7	47 × 35	1.85 × 1.38	1:1.37	24 × 18	0.94 × 0.71
500	1:2.2	37 × 28	1.46 × 1.10	1:1.1	19 × 14	0.75 × 0.55
600	1:1.85	32 × 24	1.26 × 0.94	1:0.94	16 × 12	0.63 × 0.47

possible down to 0.85 m (2 ft 9½ in) from the front edge of the lens mount.

Table I gives the reproduction ratios and object fields for the full frame (12.85 mm X 17.12 mm) that are possible at seven different focal lengths, including the shortest and the longest, at the minimum focusing distance of 0.85 m.

If the lens is used in conjunction with a close-up lens of 1.17 diopters, the shortest focusing distance is reduced to 0.425 m (1 ft 5 in) from the close-up lens. The righthand part of Table I gives the reproduction ratios and object fields for this combination. The TV Variogon 20-600mm $f/2.1 \dots f/6.3$ allows even larger than life-size reproduction.

The object field of 32 X 24 mm (1.26 X 0.94 in) which, at the longest focal length of 600 and a focusing distance E = 0.85 m, can be reproduced so that it fills the frame, is attainable with one of the conventional systems with a maximum focal length of roughly 200 mm at the same working distance only if a 3X range extender is used or, at a correspondingly shorter working distance, with range extenders of 2.5x, 2x or 1.5x. Without a range extender, the focusing distance would have to be approximately 0.30 m (11.8 in). This means that the resulting drawbacks in shooting, i.e., interruption of transmission, unfavorable lighting conditions and, possibly, perspective distortion,

would have to be accepted as unavoidable. It should also be mentioned that extension of the focusing range to even shorter distances by front-lens adjustment would result in a larger diameter of the front component and greater weight of the entire system.

4.2. Relative Aperture

The specified relative aperture of $f/2.1$ is fully maintained up to 10x the shortest focal length, i.e., 200 mm, from where it decreases proportionally with increasing focal length to $f/6.3$ (Fig. 5). If the lens is stopped down to $f/6.3$ or even further, this aperture will remain unchanged over the entire focal-length range. Even at a common working aperture of $f/4$, a continuous reduction to $f/6.3$ will occur only from a focal length of 380 mm up to the longest focal length of 600 mm.

This solution has been chosen in order to keep the front-lens diameter small and the weight down. With a focal length of 600 mm and a relative aperture of $f/2.1$, the front-lens diameter would be $f/k = 286 \text{ mm}$ (where k is the lens-stop number), resulting in an increase in glass weight of about seven to eight times.

Also, from a practical point of view a wide aperture does not appear very promising for focal lengths of 500 mm and longer, since in this case the depth of field is so shallow that the lens has to be stopped down anyway. This is why lenses of fixed focal length of 500 mm generally have a relative aperture of

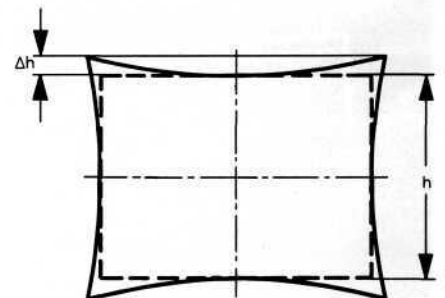


Fig. 7B. Definition of geometric distortion ($h = \text{image height} = 12.85 \text{ mm}$).

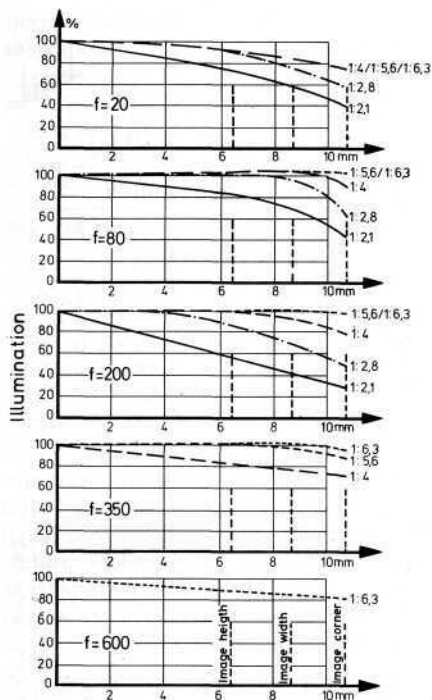


Fig. 8. Illumination of the field at infinity setting for various focal lengths and f-stops.

only $f/5.6$ or less. It is evident from Fig. 5 that at a focal length of 500 mm, the speed of the zoom lens described here is still higher than $f/5.6$.

In order to manipulate the location of

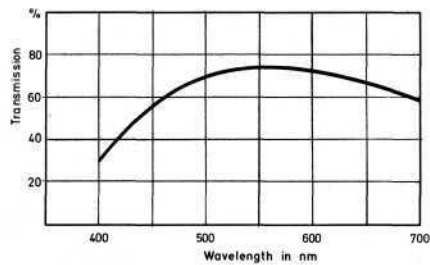


Fig. 9. Transmission as a function of wavelength.

the entrance pupil and thus to keep the diameter of the front element as small as possible in spite of the required high residual illumination, the iris diaphragm has not been inserted behind all the moving optical components, as is usual in zoom lenses, but between them, in group 4. During zoom with groups 2 and 3, the position of the exit pupil is unchanged and thus the relative aperture remains constant. During zooming with groups 5 and 6, the position of the exit pupil changes and thus also the relative aperture. Therefore, it is necessary to control the aperture diameter in this range in order to preserve the relative aperture over the entire partial focal-length range.

The design of groups 1 to 7 has been greatly influenced by the time-tried outside shape of the Schneider TV Variogon 18-200mm $f/2.1$ (see Fig. 2). Another

feature that has been taken over is focusing by means of the negative portion of the positive front component because this avoids any noticeable loss in performance over the entire focal-length range when focusing from infinity down to the shortest focusing distance. The shape and number of elements of groups 5 to 7 is a function of the optical power required in each case.

5. Performance of the Schneider TV Variogon 20-600mm $f/2.1 \dots f/6.3$

Modulation transfer is a suitable criterion for judging the performance of an optical system. Table II gives the mean modulation in percentages for 5 MHz (sinusoidal target, 15 line pairs per millimeter) for the axis and three distances off axis (Zone 1, Zone 2 and Zone 3) for several focal lengths at infinity setting and maximum aperture of $f/4$ for the green channel with a peak wavelength of 530 nm. Figure 6 shows the distribution of the field into zones, h representing the picture height of 12.85 mm.

Figure 7A shows the geometric distortion (the definition of which is given in Fig. 7B) over the entire focal-length range. It is practically independent of magnification. Up to a focal length of 30 mm, it is barrel-shaped; after that, it passes through zero and then becomes slightly cushion-shaped.

Figure 8 shows the illumination of the field at infinity setting for several focal lengths and f-stops. It is evident that the residual illumination leaves something to be desired only at full aperture and focal lengths below 200 mm.

Figure 9 shows transmission as a function of wavelength. Due to the large number of lens elements required to satisfy the requirements made of this lens, the antireflection coating normally applied to glass-air surfaces or ordinary lenses is not sufficient. Multilayer coating, which has been in use at Schneider ever since 1967, ensures that residual flare is reduced to a minimum, thus ensuring maximum transmission and, above all, minimum flare in the spectral region from 380 to 700 nm.

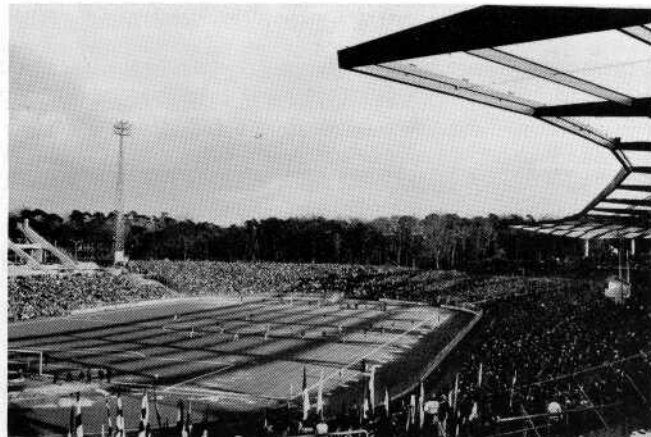


Fig. 10 (Top) General view. (Bottom left) 10 \times magnification. (Bottom right) 30 \times magnification.

Table II. Mean Modulation in Per Cent for 5 MHz (Sinusoidal Target, 15 Line Pairs/mm) for the Axis and Three Distances Off-axis for Several Focal Lengths at Infinity Setting and Maximum Aperture of $f/4$ for the Green Channel (Peak Wavelength: 530 nm).

Focal length, mm	Relative aperture $f/$	Axis	Zone 1	Zone 2	Zone 3
20	2.1	90	65	55	50
40	2.1	90	85	70	50
80	2.1	85	75	75	60
140	2.1	75	60	50	35
200	2.1	60	60	55	50
300	3.2	85	77	55	40
400	4.2	65	70	60	50
500	5.4	60	60	55	50
600	6.3	60	50	45	35
	stopped down to $f/4$				
20	4.0	95	85	75	55
40	4.0	95	90	70	50
80	4.0	90	90	90	75
140	4.0	90	90	75	50
200	4.0	90	90	75	65
300	4.0	85	70	50	40

Conclusion

In television, the optical image to be transmitted is of decisive importance. In other words, it is necessary to produce a perfect image before it can be broadcast. This is why television cameras

are equipped with optical systems of particularly high performance. However, these optical systems are not only expected to have high performance, but the lenses used in television cameras must be very flexible, i.e., their reproduction

scale should be continuously variable over a wide range. The Schneider TV Variogon 20-600mm $f/2.1$. . $f/6.3$ covers a 30 x zoom range without any gaps. It is thus ideally suited for television purposes. It is capable of offering television viewers a general view of the scene and a quick changeover without any interruption up to 30 x magnification of details (see Fig. 10).

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