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New Generation Lens Systems for the Wild Aviophot Aerial Camera System

The new objectives and their image quality are compared with earlier types of lenses.

INTRODUCTION

THE NEED for the further development of lens systems for aerial cameras arises directly out of increasing demands made from time to time by their users. So, in recent years, the increasing importance of analytical methods in photogrammetry and the trend towards larger image scales have produced a reassessment of lens quality as one of the characteristic values in the complex system extending from the photograph to restitution.

ABSTRACT: *This contribution reports on some of the criteria which have to be met in the further development of aerial-camera lens systems. The quality criteria that were constantly observed in the development work are described in detail, among which integrals on the* MTF *and their area-weighted average proved particularly useful. Details are given of the metric characteristics and of the image quality of the new lens systems in the visible and near infrared range, and these are compared with the comparable performance data of the older lens types.*

It is demonstrated that the lens systems of this new generation have a substantially greater information-transmission capacity, a more homogeneous image quality, and lower residual distortion.

One possibility for the continual further development is given by the circumstance that the extremely large information-transfer capacity of modern aerial-camera lens systems calls for a relatively complex optical construction which, in turn, causes the imaging characteristics to depend to a considerable extent on the optical data of the various types of glass used. Thus, adaptation calculations are required for each series of camera objectives, and a quasi-permanent further development can in this way be carried out within the framework of these computations, albeit only in small steps at a time. However, this method used to be of much greater importance than it is now. Today it is customary to use sophisticated computer programs through which far greater optimization is possible from the very beginning. These allow a better convergence to be achieved to the optimum that is in fact attainable with a given type than was possible by the optimization methods used in the past. Even so, even in the past it had been possible by this means to improve noticeably, if gradually, the metric characteristics and image quality of a number of types of objectives manufactured in relatively large quantities over the period during which they remained in production.

Once these possibilities have been fully exploited, or if substantially higher requirements are set for new lens systems with regard to image quality, metric accuracy, and/or light-gathering power, a new approach will to a large extent be necessary in order to produce a satisfactory solution. If, as a result, solutions are produced that are substantially different from the construction and performance of earlier systems, one may properly regard them as a new generation of lenses.

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The conditions for such substantial improvements may be provided by a more profound understanding of image structure and by ideas as to the technical means to be used to translate this into fact. But the requisite conditions may also be provided by improved optimization algorithms, and by progress in the manufacture of different types of optical glass, of reducing reflection, and of mechanical lens components.

All these prerequisites have played an important part in the newly developed objectives presented below. In particular, based on detailed numerical studies concerned with the origin and effect of transverse chromatic aberration in spectrums of the second and higher orders and on a consideration of the results of the diapoint theory, Herzberger and Pulvermacher (1968) produced new data and thus provided a favorable point of departure for new developments. The optimization program developed by the author and his colleagues (Hildebrand, 1976) has been further expanded in recent years, though it still retains its basic principles. A number of improvements suggested by critical monitoring in running the program in its day-to-day applications have led to the effectiveness of the algorithm being increased, for example by speeding up its convergence.

The new objectives now available could not have been designed as they were without progress in the manufacture of new types of optical glass. For lenses used in aerial cameras, which are to be used without refocusing both in the visible and in the infrared portions of the spectrum, mainly apochromatic correction is a basic requirement. Thus, it has been possible to improve the correction of chromatic aberration to a large extent only because of the development of newer types of glass, produced by Schott (Mainz) with partial dispersion deviating from the normal case. The improved durability of certain types of glass compared with earlier versions has also proved invaluable.

Progress in the technique of antireflection coatings has permitted a more even distribution of the thin-layer systems on strongly curved surfaces and thus, in certain cases, has for the first time made it possible to use complex broad-band coatings of high efficiency both in the visible and the infrared spectral range. The development work done by Balzers Ltd. (Balzers, Liechtenstein) has resulted in considerable improvement in color fidelity compared with older types of lenses.

The use of improved measuring equipment is often also an important prerequisite for the more economical manufacture of improved products. This is true also in the case of these new aerial camera lenses. Measuring instruments developed during the last few years by Wild Heerbrugg provide new possibilities for checking the quality of objectives and for doing so far more accurately and more quickly. An example of these is the EVG Electronic Goniometer (Mathieu, 1980) (Figure 1) which makes it possible to measure distortion rapidly, objectively, and extremely accurately in any spectral range from 400 nm to 900 nm.

Quality Criteria

In new developments, an evolutionary strategy is regularly used which assumes the existence of a criterion of choice that allows the best of a number of alternative solutions to be found. As the central part of such a criterion, we have used an area-weighted mean of the integral of the modulation transfer function (MTF), which takes into account the threshold values of the film emulsion. The MTF represents the real part of the complex optical transfer function (OTF) and can be computed or measured for any image point. It is a function of the spatial frequency in line pairs per mm (lp/mm), but it is also dependent on the spectral range, aperture size, choice of image plane, and azimuth under which a periodic object is presented.

Let $\text{MTF}_{\sqrt{RT}}\ (\nu)$ represent the geometric mean MTF for radial and tangential objects and $\Theta\ (\nu)$ the threshold contrast of a given film emulsion, i.e., the contrast below which the emulsion is no longer able to store information. Then, the integral

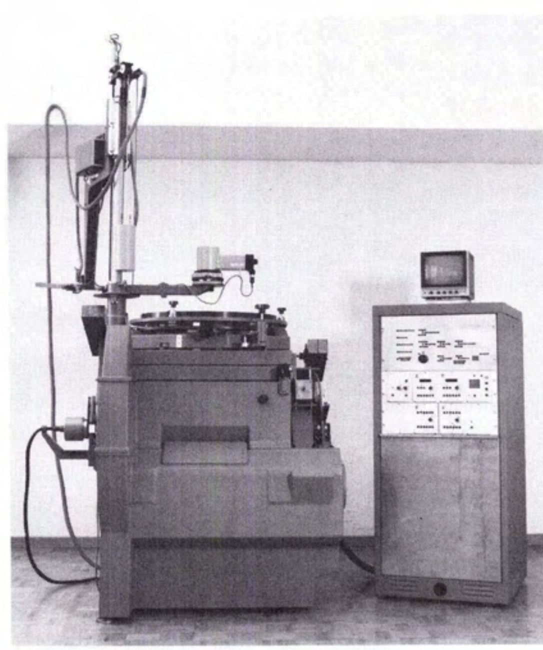

Fig. 1. EVG Electronic Vertical Goniometer.

$$q_{\sqrt{RT}}(\alpha_i) = \int_0^{\mathrm{MIN}\,[\nu_{\mathrm{MAX}}\ ,64]} \{\mathrm{MTF}_{\sqrt{RT}}(\alpha_i,\ \nu) - \Theta(\nu)\}\ d\nu \tag{1}$$

is a measure of the image quality which can be obtained with the film selected, for an image point assigned to the field angle α_i. By laying down the upper integration limit, spatial frequencies exceeding 64 lp/mm are disregarded; in view of the conditions encountered in the use of aerial cameras (atmosphere, image motion, vibration), this seems appropriate. If the point of coincidence of MTF and threshold function, defined by

$$\mathrm{MTF}_{\sqrt{RT}}(\alpha_i, \nu_{\mathrm{MAX}}) = \Theta(\nu_{\mathrm{MAX}}) \tag{2}$$

lies below this limiting value, integration is carried out only as far as ν_{MAX}.

Let $p\ (\alpha_i)$ be the area weighting assigned to every field angle α_i and let their sum be unity (these weightings are the same as those used in computing the area-weighted average resolution, or AWAR). The area-weighted mean value from Equation 1 will then be

$$\bar{q} = \sum_i p(\alpha_i) \cdot q_{\sqrt{RT}}(\alpha_i), \tag{3}$$

a measure of the information-transmission capacity of an optical system in the spatial frequency range below 64 lp/mm when an emulsion is used that is described by its spectral sensitivity and its threshold-value function $\Theta(\nu)$.

It is of interest to compare $\bar{q}$ with the corresponding value q_{MAX} of an ideal (aberration-free) system having the same aperture, whose transfer capacity is limited only by diffraction and the characteristics of the emulsion. The image-quality coefficient

$$Q = \frac{\bar{q}}{q_{\mathrm{MAX}}} \tag{4}$$

indicates which part of the theoretically attainable transfer capacity (in the sense of definitions of Equations 1 and 3) is available.

In practice, during the course of development work, Q values were computed for the apertures f:4, f:5.6, and f:8, in each case for the same image plane, and each time for panchromatic, color, false-color, and infrared black-and-white emulsions. However, it is possible to compute the geometrical approximation for MTF considerably more quickly, and this proved generally adequate for comparative purposes.

Where there were similar sets of Q values for different objectives, homogeneity of image quality was also taken into account in the evaluation. In particular, the quality of the worst image point relative to an object oriented in any direction was again compared with the quality of the ideal image, using the following:

$$q_{\mathrm{MIN}} = \frac{\mathrm{MIN}\ [q_{\mathrm{Rad}},\ q_{\mathrm{Tang}}]}{q_{\mathrm{MAX}}}. \tag{5}$$

The minimum value in this term has been taken by using all possible field angles.

Q and q_{MIN} can attain a value of 1 only in the case of an ideal (diffraction-limited) image, but for aerial-camera objectives at full aperture they are noticeably less. The widely used existing types of lenses have thoroughly proved their worth in practice. However, the values given in Tables 1 to 4 for these show that imaging quality limited only by the effect of diffraction should not be regarded as indispensable for aerial-camera objectives whose apertures have not been stopped down to a greater extent.

The metric qualities, i.e., the distortion graph and its dependence on wavelength, also form an important component of the set of assessment criteria.

Further, a number of other characteristics also need to be included in the evaluation. These still cannot be accurately quantified at reasonable cost before prototypes are built, despite far-reaching automation in computing tolerances. These considerations include the relative ease of manufacture and production costs. It is also worth noting that the considerable advances made in computer technology have raised the selection criteria used routinely to a remarkable level. Nevertheless, these advances do not make the optical designer's experience less indispensable than before.

The New Objectives and Their Image Quality

The objectives of this generation are introduced in detail below. Their performance data are compared with those of the older types of lenses. The quality standards provided by the existing range of Wild lenses are an absolute criterion for numerous photogrammetrists. The performance data will give these specialists a clearer idea of the characteristics of these new objectives. All the lenses described here are designed for the 9 by 9 inch standard format used in aerial photogrammetry.

SUPER AVIOGON 8.8/4SAG (f:4)

The new 120° super-wide-angle objective (F = 88 mm, Figure 2) differs very substantially from its predecessor, the 8.8SAGII. This applies not only with regard to the initial aperture, which has been increased from f:5.6 to f:4. This objective consists of 12 lenses forming 6 elements, compared with its predecessor which consisted of 11 lenses, also forming 6 elements. Particularly striking in the new system is the extremely small image-side back-focus distance.

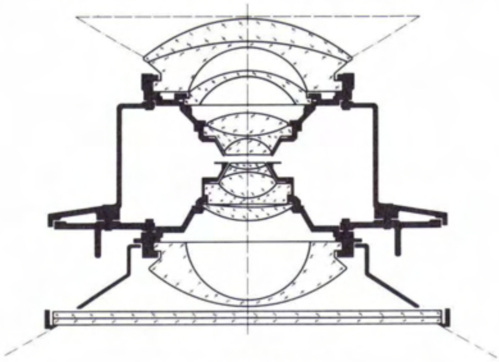

FIG. 2. 8.8/4SAG.

Table 1* provides a summary of data on image quality at full aperture and stopped down to f:5.6. Table 1 also gives the corresponding data at full aperture for the SAG II as available since 1970.

Table 1 shows that the image quality of the 8.8/4SAG at f:4 is already slightly better than that of the previous model at its maximum aperture of f:5.6. A substantial improvement has been achieved for the worst image point, and this influences both the quality coefficient q_{MIN} and the value obtained for resolution. When the aperture is stopped down to 5.6, the Q values both in the visible and in the infrared spectral ranges show the new objective to be greatly superior. This is also confirmed by the increase in the low-contrast AWAR which is extremely significant for the functional value of the objective. On the other hand, there is only a small increase in the high-contrast AWAR. This shows that the improvement mainly affects the spatial frequency spectrum utilized in photogrammetry.

Figure 3† shows the MTF for the 8.8/4SAG lens.

Figure 4** shows that it has been possible to reduce the residual distortion by a factor of about two compared with the earlier model. The number of zero points in the distortion graph is also worth noting.

UNIVERSAL AVIOGON 15/4UAG (f:4)

The new 90° wide-angle objective (F = 152 mm, Figure 5) is of similar construction to the 8.8/4SAG and like it consists of 12 lenses forming 6 elements. Its predecessor, 15UAG II, supplied from 1972 to 1980, also consisted of 12

* *Notes to Tables 1 to 4*

The mean and minimum image-quality coefficients Q and q_{MIN} are computed values. The values given for resolution are measured mean values obtained with serially produced objectives, except in the case of the new objectives where they have been measured on prototypes.

PAN: Agfapan 25 professional film, for Q and q_{MIN} without filter, for resolution with 444-nm cut-off filter

IR: Kodak Infra-red Aerographic 2424 film with 705-nm cut-off filter

High-contrast: $J_{MAX}:J_{MIN} = 10^2 = 100$

Low-contrast: $J_{MAX}:J_{MIN} = 10^{0.2} = 1.58$

The worst image point in all cases is the outermost corner of the 9 by 9 inch format.

† *Note to Figure 3, 6, 9, and 12:*

These show the geometrical mean of the contrast-transfer functions for the radial and tangential orientation of the object for the spatial frequencies of 12 lp/mm and 24 lp/mm as a function of the field angle, in each case for the apertures f:4 and f:5.6. The divisions of the abscissa axis have been chosen in such a way that identical lengths correspond with identical relative areas (with respect to the square picture format of nominally 9 by 9 inches); this greatly facilitates evaluation of the effects of field angle on image quality.

The MTF values were determined by measurement, generally on prototypes. For these, white light was used (halogen lamp + 420-nm yellow filter).

** *Note to Figures 4, 7, 10, and 13:*

Distortion, Vz, is shown as a function of the image radius, R. The values given are mean values obtained from serially manufactured objectives or values measured on prototypes (white light + 450 nm yellow filter). Further, the mean deviation from zero for distortion is also given.

TABLE 1. IMAGE-QUALITY DATA FOR 8.8/4SAG AND SAG II

		8.8/4 SAG f:4	8.8/4 SAG f:5.6	SAG II f:5.6	
Image-quality coefficient Q	PAN	0.28	0.38	0.27	
Worst image point q_{MIN}	PAN	0.09	0.13	0.06	
High-contrast AWAR	PAN	47	51	45	lp/mm
Low-contrast AWAR	PAN	28	32	22	lp/mm
High-contrast resolution for worst image point	PAN	23	26	17	lp/mm
Image-quality coefficient Q	IR	0.20	0.27	0.18	
High-contrast AWAR	IR	22	23	20	lp/mm

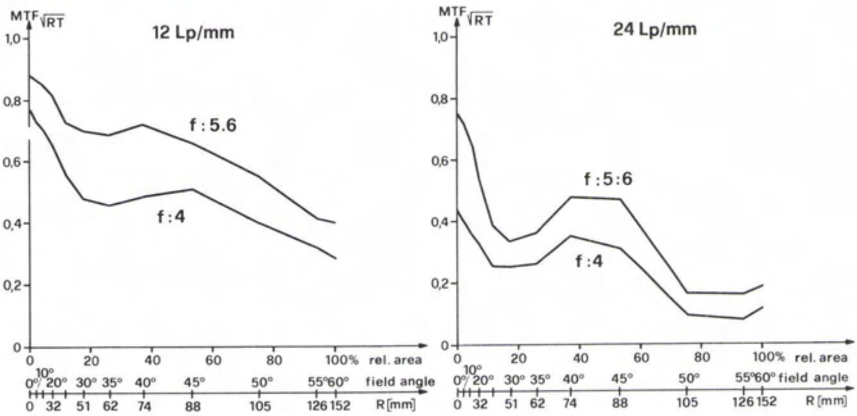

FIG. 3. 8.8/4SAG: contrast-transfer functions.

lenses, but these were arranged in 7 elements. Both the rearmost negative element and, especially, the positive central system are substantially different from the corresponding parts of the UAG II.

The new design not only enabled image quality to be greatly improved, but by avoiding strongly curved air meniscuses in the central system it also made possible more favorable assembly tolerances.

Table 2 and Figure 6 provide quantitative information on the image quality of the new objective, compared with the corresponding data for its predecessor (see also Hakkarainen, 1981). In the visible part of the spectrum, the entire information-transfer capacity has been increased by more than 60 percent. Particularly impressive are the improvements in the low-contrast AWAR and the worst image point; in the outermost corner of the image, the new objective has a high-contrast resolution of at least 38 lp/mm. At maximum aperture, it has also been possible to increase the overall quality in the infrared range. This improvement, however, is not of advantage to the resolution but to the imaging contrast.

Figure 7 shows that it has also been possible to reduce distortion. The mean deviation from zero for this is now less than 1 μm.

NORMAL AVIOGON 21NAG II (f:4)

This objective (F = 213 mm, Figure 8) has now been in serial production since 1976. Although it dates back to 1973, it has been included in this report, because it is the first of the series of aerial-camera objectives designed by the author and belongs more properly to the new generation of objectives. Its imaging quality is in every respect comparable with the remainder of the objectives presented here.

The image angle of the 21NAG II is slightly greater than 70°. This objective, like the other two described above, can be regarded as an Aviogon in the wider sense (L. Bertele, e.g., Swiss patents, 1951).

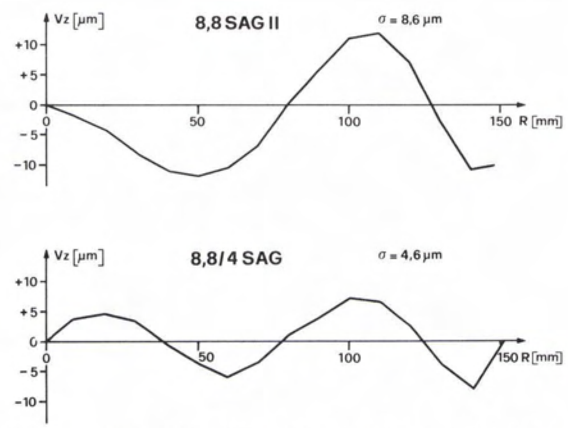

FIG. 4. 8.8SAG II (old) and 8.8/4SAG (new): distortion.

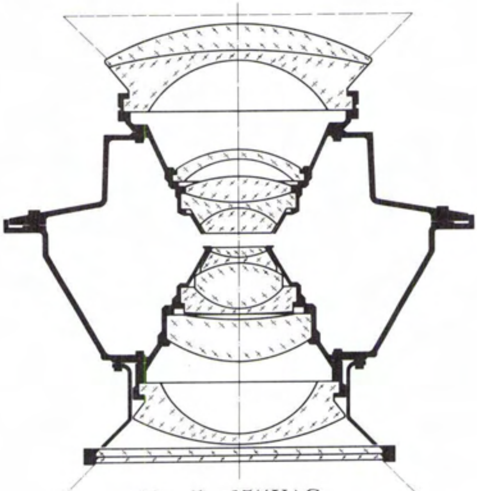

FIG. 5. 15/4UAG.

TABLE 2. IMAGE-QUALITY DATA FOR 15/4 UAG AND UAG II

		15/4 UAG		UAG II		
		f:4	f:5.6	f:4	f:5.6	
Image-quality coefficient Q	PAN	0.35	0.55	0.21	0.34	
Worst image point q_{MIN}	PAN	0.15	0.25	0.08	0.10	
High-contrast AWAR	PAN	67	75	54	58	lp/mm
Low-contrast AWAR	PAN	32	40	21	25	lp/mm
High-contrast resolution for worst image point	PAN	38	40	12	12	lp/mm
Image-quality coefficient Q	IR	0.23	0.27	0.17	0.30	
High-contrast AWAR	IR	21	24	26	27	lp/mm

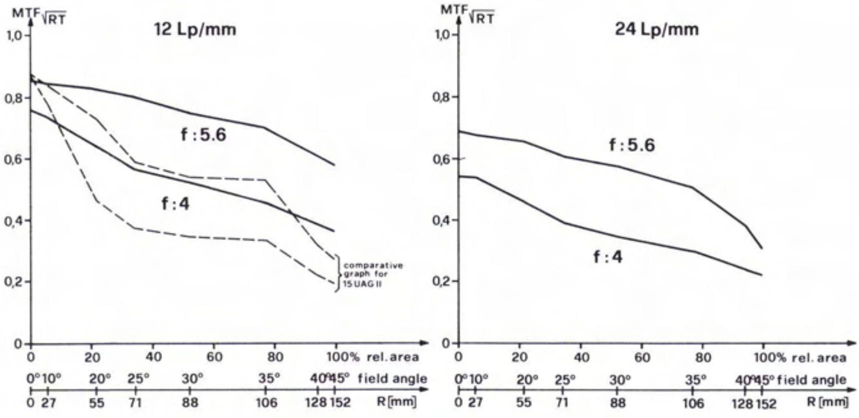

FIG. 6. 15/4UAG: contrast-transfer functions.

Table 3 and Figures 9 and 10 provide information on image quality and distortion. It is worth noting that very similar image qualities, Q, are achieved in the infrared and visible parts of the spectrum, although different AWAR values result on account of the difference in the threshold-value functions of the two types of film.

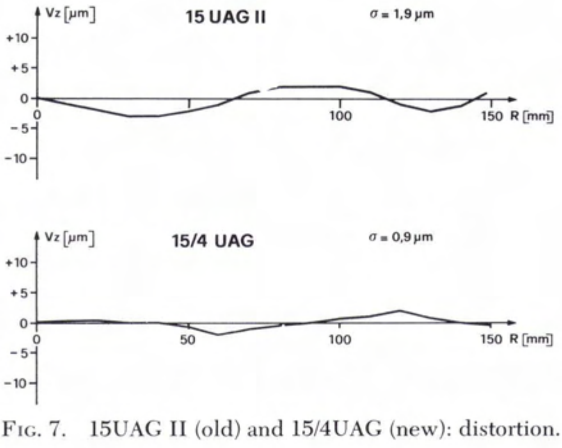

FIG. 7. 15UAG II (old) and 15/4UAG (new): distortion.

NORMAL AVIOTAR 30/4NAT (f:4)

The 30/4NAT (F = 300 mm, Figure 11) is a modified double-Gauss objective consisting of 10 lenses in 7 elements. The composite element next

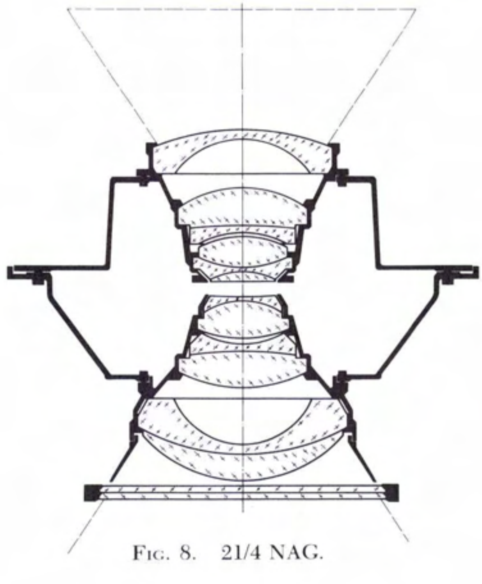

FIG. 8. 21/4 NAG.

TABLE 3. IMAGE-QUALITY DATA FOR 21 NAG II

		21 NAG II f:4	21 NAG II f:5.6	
Image-quality coefficient Q	PAN	0.32	0.49	
Worst image point q_{MIN}	PAN	0.17	0.28	
High-contrast AWAR	PAN	54	64	lp/mm
Low-contrast AWAR	PAN	26	31	lp/mm
High-contrast resolution for worst image point	PAN	35	36	lp/mm
Image-quality coefficient Q	IR	0.28	0.48	
High-contrast AWAR	IR	32	37	lp/mm

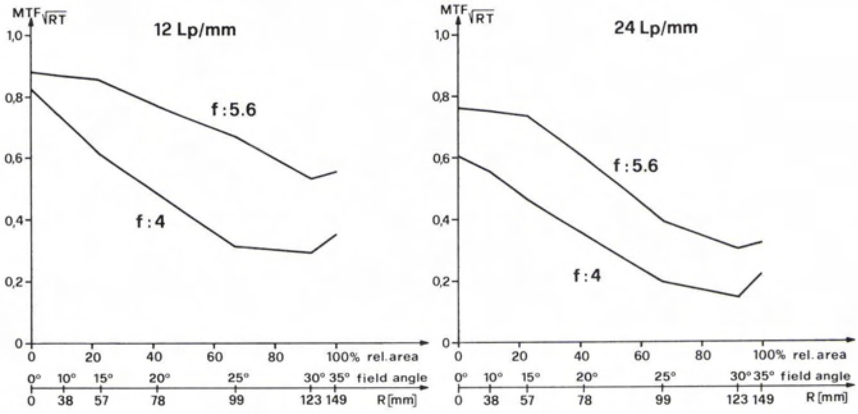

FIG. 9. 21NAG II: contrast-transfer functions.

to the diaphragm produces the apochromatic correction of longitudinal chromatic aberration. The residual distortion and residual field curvature of the basic objective are corrected by the negative lens on the image side; this lens has a weak anti-vignetting filter to compensate for light loss. The image angle is about 54°.

Table 4 and Figure 12 provide information on image quality. Compared with the earlier model available since 1973, the 30AT II, substantial improvements have been achieved. Image contrast and homogeneity of image quality over the entire field are the main beneficiaries of these. The improvement achieved for the characteristics in the infrared range are particularly impressive; here, it has been possible to increase the image-quality coefficient, Q, at full aperture by more than two-fold.

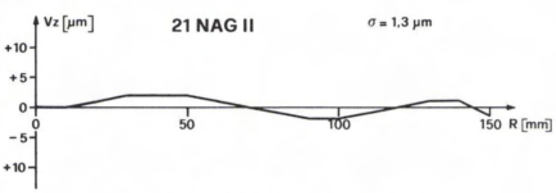

FIG. 10. 21NAG II: distortion.

By comparison with its predecessor, it has also been possible to reduce residual distortion (Figure 13).

CONCLUSIONS

The behavior of the new objectives as regards light loss towards the corners of the image is very

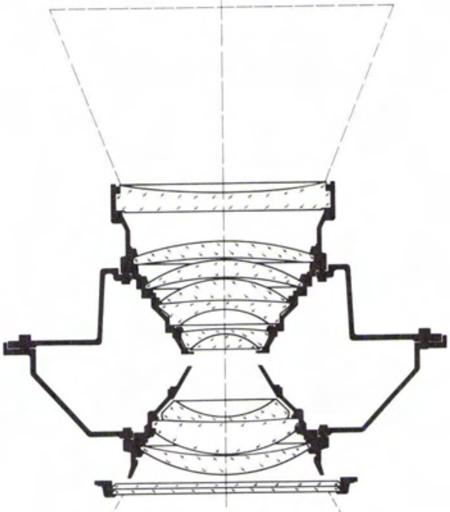

FIG. 11. 30/4NAT.

TABLE 4. IMAGE-QUALITY DATA FOR 30/4 NAT AND AT II

		30/4 NAT		AT II		
		f:4	f:5.6	f:4	f:5.6	
Image-quality coefficient Q	PAN	0.39	0.45	0.26	0.36	
Worst image point q_{MIN}	PAN	0.19	0.20	0.09	0.13	
High-contrast AWAR	PAN	50	51	44	47	lp/mm
Low-contrast AWAR	PAN	30	32	22	26	lp/mm
High-contrast resolution for worst image point	PAN	33	36	27	28	lp/mm
Image-quality coefficient Q	IR	0.45	0.53	0.20	0.33	
High-contrast AWAR	IR	36	36	26	28	lp/mm

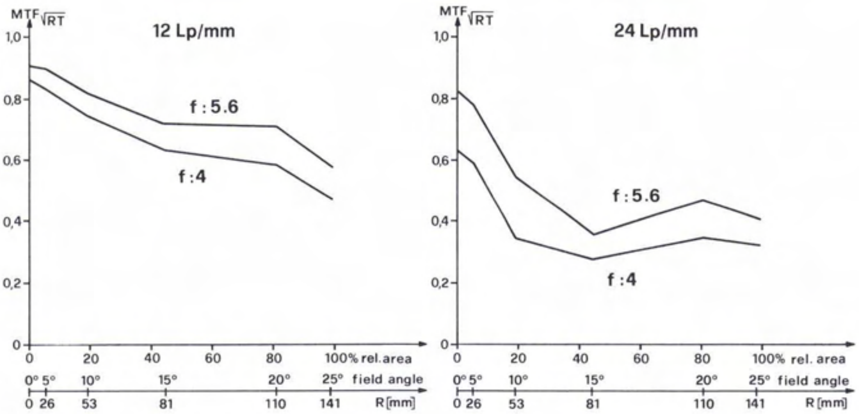

FIG. 12. 30/4NAT: contrast-transfer functions.

similar to that of their predecessors. In the 8.8/4SAG, 15/4UAG, and 21NAT II, the light loss is corrected by graded antivignetting filters deposited by vacuum evaporation on glass filter plates, whose transmissivity is adapted to the intended uses to which the lens will be put. A weak antivignetting filter is already integrated in the 30/4NAT.

Technological progress in the field of antireflection coatings has made it possible to achieve substantial improvements in these new-generation objectives, with regard to freedom from reflection in all spectral ranges and far-reaching independence from the field angle of the color character of the image. At the same time it has been possible to reduce very substantially the effects of stray light by using a new approach in the design of beam-limiting components such as the edges of lenses and mounts.

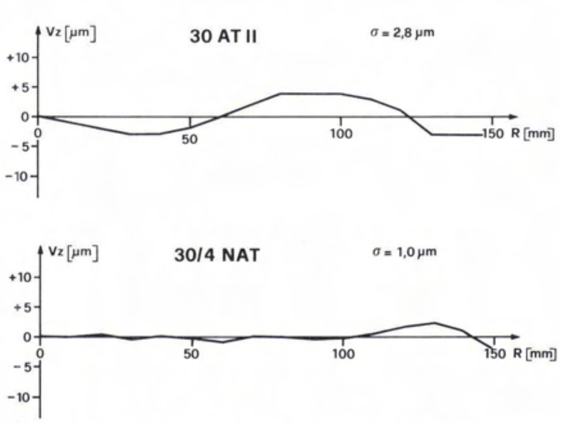

FIG. 13. 30AT II (old) and 30/4NAT (new): distortion.

SUMMARY

The new-generation objectives are characterized by a substantially increased information-transfer capacity, greater homogeneity of image quality, and reduced residual distortion as compared with their predecessors. Color fidelity (for color and false-color film) has also been increased. Taken all together, the improvements achieved have produced a very substantial increase in the functional values of these objectives.

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Wild Heerbrugg Ltd: lens manufacture, mechanical manufacture, lens assembly, lens testing. Without their intensive and successful cooperation, it would not have been possible to produce this new generation of objectives.

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