IMAGE QUALITY CRITERIA FOR AERIAL SURVEY LENSES

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1. Introduction

The technique for measuring the modulation transfer function (MTF) is well established. Different national and international organisations (DIN, ISO, NATO and ISP) have endeavoured to establish a basis for assessing image quality. Although phase measurement is particularly important for new designs, its evaluation and interpretation require further study and are outside the scope of the present paper.

The optical designer requires a lot of data such as OTF/MTF curves. The user, however, would prefer simplified MTF data for evaluating image quality or for locating the plane of best average definition. An approach to the development of suitable criteria based on reduced MTF data is here described. An objective marking procedure to rank evaluation systems by "quality numbers" according to their performance would be desirable. Before an appropriate evaluation system can be introduced, a number of interlaboratory comparisons will be necessary. One such evaluation system is described here.

2. Image quality criteria

Image quality criteria are different for microscopes, amateur cameras, magnifying or aerial survey lenses, and therefore need to be adapted to the practical applications of the particular optical system (14). This paper is concerned with image evaluation in aerial photography, where the requirements are:

- small or constant known distortion
- good image quality over the whole field
- longitudinal and transverse colour correction
- relative high aperture
- nearly equal intensity distribution over the whole image
- wide-band spectral transmission

For image quality criteria in photogrammetry the most widely-used method is the classical resolving power test. For locating the plane of best average definition, the area-weighted average resolution (AWAR) is commonly applied (1). It is obtained by multiplying the resolution at different field angles by a weighting factor proportional to the size of the corresponding image zone. Very frequently the geometric mean of the tangential and sagittal (radial) resolving power is used. Ideally, the area of the annular zones should be very small so that the AWAR can be expressed as a limit. In practice, the value of AWAR is computed for zones of finite areas.

For obtaining the resolving power a test chart is imaged on an emulsion. The analysis is carried out after development. Alternatively the resolving power can be found by the intersection of the MTF with the threshold curve. The threshold contrast curve takes into account the MTF of the emulsion as well as the threshold contrast of the eye (11). Fig.1a) and b) show measured MTF curves of a newer f/4 WILD aerial camera lens, focal length 210 mm (WILD 21 NAgII) together with the threshold curve for Agfapan 25 emulsion. In fig.2 the resolving power for this lens is plotted as a function of the field angle (image height) obtained:

- by classical imaging of a test chart and
- from the intersection of the MTF with the threshold curve.

Good agreement was found for the resolution with the two techniques. Furthermore, the AWAR of the lens was 52 Lp/mm.

3. Image evaluation techniques based on MTF

Image quality assessment of aerial survey lenses on the basis of resolution tests has some marked disadvantages; in particular, resolution can only be measured for a given object contrast. In recent years, the use of MTF for image evaluation has received considerable attention. MTF curves should permit the photogrammetrist to obtain a more reliable estimate of the performance of the lens.

Other image evaluation techniques such as those based on edge gradients and spread functions will not be discussed here.

The MTF approach can lead directly to system analysis. The MTF of the total system is basically the product of the MTF of the lens, of the emulsion, and of the environmental disturbances. For user handling of the MTF curves derived from different image planes, apertures and field angles are not always convenient.

Different authors (2-8) suggested averaging the MTF with respect to spatial frequency. In an early proposal (3) three criteria, namely resolution, sharpness and contrast, were considered. In later publications it was pointed out that only two of the previously-mentioned criteria are independent. In addition, some authors have taken the observer into account by evaluating the logarithm of the MTF (4,5,6 and 8).

In aerial photography, faithful geometrical reproduction is more important than in classical photography. The interpretation of images is usually carried out in specifically-designed devices such as autographs, where image pairs recorded with 60 to 80% overlap are analysed, and therefore high regularity of image quality over the whole field is required.

4. Quality numbers based on MTF

In most of the previous work on image quality, the MTF was averaged over the spatial frequency of the image. As indicated above, photogrammetric applications require a good quality image over the whole image field; furthermore the sagittal (radial) and tangential MTFs for different field angles should be nearly equal. On the basis of the above arguments it is proposed to incorporate the following criteria in an image-quality specification:

- the area below the MTF curve to a limiting spatial frequency
- small variation with respect to the tangential and sagittal MTF
- small variation of image quality over the whole image field

These three criteria will now be considered in more detail.

4.1 Averaging with respect to spatial frequency

The spatial frequency at which the product of the lens and film MTF has fallen to a predetermined value has been used as a criterion for analysing subjective judgments of picture quality in aerial photography. More recently several authors (5-16) have favoured MTF curves. In fig.3 the area between the lens MTF and the threshold contrast curve is indicated. It can, however, be shown that for practical purposes the area between the MTF and the abscissa up to the limiting frequency is adequate for comparison. The threshold curve in fig.1 assumes a 0.03 threshold contrast of the eye and the use of Agfapan Emulsion (11).

To allow for low-contrast situations in aerial photography the MTF can be scaled to any object contrast - a frequently-used low contrast is 0.23 at 0 Lp/mm. For comparison purposes, the intersection of the threshold with the MTF curve leads to the resolution as indicated earlier.

The area below the MTF curve requires weighting with the areal coefficient to which the chosen image point belongs. For direct comparison of different systems, the area can be normalized with respect to the diffraction-limited MTF for instance. For simpler test procedures the MTF for two or three selected spatial frequencies could be considered.

4.2 Regularity with respect to tangential and sagittal MTF

To take into account regularity with respect to tangential and sagittal MTF, the limiting frequency (R_g) for integration can be defined by the intersection of the threshold with the lower MTF curve. The same limiting spatial frequency R_g applies for the integration of the higher MTF curve. The geometrical mean of MTF_{sag}, (T_s), and MTF_{tan}, (T_t), is considered in further comparisons (dotted line in fig.3).

4.3 Averaging with respect to the image field

This is an important parameter for aerial survey lenses. For an image quality criterion, the MTF needs to be averaged with respect to the field angle w. The weights p(w) are similar to those used for the AWAR and are considered to take account of the appropriate area belonging to the chosen image point considered. Therefore averaging the areas of the MTF Q(w) with respect to the image field can be written:

$$Q = \int_0^{w_{max}} p(w)\ Q(w)\, dw, \quad \text{with} \int_0^{w_{max}} p(w)\, dw = 1$$

$$\text{where} \quad Q(w) = \int_0^{R_g} \left(T_s(R)\ T_t(R)\right)^{1/2} dR$$

$T_g = \left(T_s(R)\ T_t(R)\right)^{1/2}$ = geometrical MTF from T_s(sag.MTF) and T_t (tan.MTF)

R = spatial frequency (Lp/mm)

R_g = limiting spatial frequency (intersection of the threshold curve with the lower MTF of T_s , T_t)

For practical applications the integral is written as a sum, namely:

$$\overline{Q} = \sum_{k=1}^{N} p_k Q_k, \quad \text{where} \sum_{k=1}^{N} p_k = 1 \quad \text{and} \quad k = 1,2.......N$$

N = number of image points

For the analysis in stereoscopes a 60-80 percent overlap of the two images to be analysed is customary and therefore only small variations of image quality with respect to image field are acceptable. To take into account some information on the variation of image quality over the field we can write:

$$\overline{Q}_\alpha = \left[\sum_{k=1}^{N} p_k Q_k^\alpha\right]^{1/\alpha} \quad \text{for} \quad \alpha \neq 0$$

For a perfectly uniform image quality over the whole image field, $\overline{Q}_\alpha = \overline{Q}$ for all α .

According to customary usage we define $\bar{Q}_{\alpha}$ for:

$\alpha = 1$ arithmetic mean

$\alpha = 2$ quadratic-arithmetic mean

$\alpha = -1$ harmonic mean

$\alpha = -2$ quadratic-harmonic mean

We can now obtain a criterion on the variation of image quality over the image field by the ratios:

$$q_1 = \frac{\bar{Q}_{-1}}{\bar{Q}_1} \quad , \quad q_2 = \frac{\bar{Q}_{-2}}{\bar{Q}_2} \quad , \quad \text{where} \quad q_2 < q_1 < 1$$

They lead to a measure of the uniformity of image quality over the image field. Again the ratios q_1 and q_2 taking into account the variation of image quality over the field are unity for uniform image quality over the whole image field. q_1 or $q_2 \ll 1$ is therefore not desirable. Usually q_1 should be adequate because q_2 is roughly the square of q_1 and is therefore more sensitive to variation of image quality over the field.

5. Comparison of image quality of some aerial camera lenses

Different high quality aerial survey lenses were analysed with the proposed method. Averaging of the MTF with respect to spatial frequency and field angles led to useful image quality criteria. An important aspect of image quality in aerial survey lenses is the definition of the appropriate image plane, the choice of which depends very much on the averaging method with respect to image field. Fig.4 indicates a typical example of how the choice of the best image position depends on the image quality criterion chosen. For a typical super-wide angle lens the arithmetic mean $\bar{Q}_1$ has its maximum near the minimum of q_1 or q_2 i.e. at positions where the MTF over the field varies the most. A compromise seems appropriate where the chosen image plane is shifted from the best AWAM (areal weighted average modulation) towards a more homogeneous quality over the image field (10,11). The chosen image plane is indicated by the broken line in Fig.4.

Fig.5 illustrates examples for the proposed image quality criteria for some high-quality aerial survey lenses. Q_1, Q_2, Q_{-1}, Q_{-2} are respectively the arithmetic, quadratic, harmonic and quadratic harmonic means of the integrated MTF with respect to image field. Curves 1,4,6 and 7 correspond to wide-angle lenses ($2\,w = 90^o$, $f = 150$ mm) of different manufacturers. In addition, normal and super-wide angle lenses are presented. The ratios q_1, q_2 for different objectives vary as follows:

$$0.92 < q_1 < 0.5 \quad , \quad 0.85 < q_2 < 0.25$$

Furthermore, objectives 5,6 and 7 are of newer designs having vastly improved performance. The appropriate areas are not normalized to the diffraction-limited MTF. A comparison of different sets of quality curves, of which two are shown in fig.6, illustrates that the result of the evaluation of the image quality criterion depends not too much on whether the area below the MTF curves, limited by R_g, the spatial frequency, is chosen with or without the area below the threshold curve but on the averaging over the image field. It seems that for aerial survey lenses the area below the MTF curves up to a limiting spatial frequency, R_g, is adequate for practical comparisons. Typical curves in fig.6 are 1 and 2, they are not normalized; subtracting the threshold contrast curve leads of course to lower values but the shape and the differences between the curves are almost the same (1', 2'); q_1 and q_2 remain practically unaltered.

With the proposed image quality criterion the influence of gelatine filters on the image quality was analysed for two different objectives. Fig.7 illustrates the reduction of image quality as a result of gelatine filters for two aerial survey lenses. The new high quality lenses are developed to a point where gelatine filters as well as environmental conditions reduce the image quality considerably.

Images obtained for two different field angles of two objectives are shown in fig.8, and the corresponding MTF curves in fig.9 along with the threshold curves for high and low object contrast (1 resp. 0.23).

The object contrast is defined by:

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

The pictures were recorded at a height of 1050 m and enlarged 15 times. It was found from different comparisons that the MTF halfway between zero and the limiting spatial frequency is significant for judging the visual impression of the image. This could mean that the MTF for appropriately selected spatial frequencies could also be chosen to derive image quality criteria similar to those described. The requirement of regularity over the field remains.

6. Conclusions

An image quality criterion based on MTF is highly desirable. The quality specification should be appropriate for the application of the optical system and simple for the user. The proposed quality criteria look promising and comparisons with subjective image quality techniques commonly used are favourable. Further evaluations are needed before quality specification can be recommended.

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CAPTIONS TO FIGURES

1. MTF curves of 21 NAg, f = 210 mm, F/4 objective for "white light":
   a) sagittal
   b) tangential

2. Comparison of resolution of 21 NAg obtained by:
   ==== classical methods
   o, x intersection of MTF and threshold contrast curve

3. Integration of MTF curves with respect to spatial frequency

4. Quality criterion used to find the best image plane of an aerial survey lens

5. Image quality criteria applied to some typical aerial survey objectives

6. Image quality criteria obtained by integration of the MTF curves without subtracting the threshold contrast curves for two objectives, namely:
   —1— objective 1, -2-- objective 2

   By contrast subtraction of the area below the threshold contrast curves leads to the quality numbers shown for:
   —1'— objective 1, -2'-- objective 2

7. Image quality criteria applied to study the influence of a gelatine filter on the image quality for two wide angle lenses:
   —1— objective 1 without gelatine filters in front of the objective
   —1'— objective 1 with " " " " " " "
   -2-- objective 2 without " " " " " " "
   -2'-- objective 2 with " " " " " " "

8. Image of the same object taken successively with a WILD camera and two different objectives, flying height 1050 m:
   a) objective 1 , field angle $15^\circ \leq w_1 \leq 25^\circ$
   b) objective 1 , " " $35^\circ \leq w_2 \leq 45^\circ$
   c) objective 2 , " " $15^\circ \leq w_1 \leq 25^\circ$
   d) objective 2 , " " $35^\circ \leq w_2 \leq 45^\circ$

9. MTF curves corresponding to the images obtained in Fig.8.
   ++++ objective 1 , field angle $15^\circ \leq w_1 \leq 25^\circ$
   ΔΔΔΔ objective 1 , " " $35^\circ \leq w_2 \leq 45^\circ$
   .... objective 2 , " " $15^\circ \leq w_1 \leq 25^\circ$
   ---- objective 2 , " " $35^\circ \leq w_2 \leq 45^\circ$

   The threshold contrast curves for high (C=1) and low object contrast (C=0.23)are also depicted.

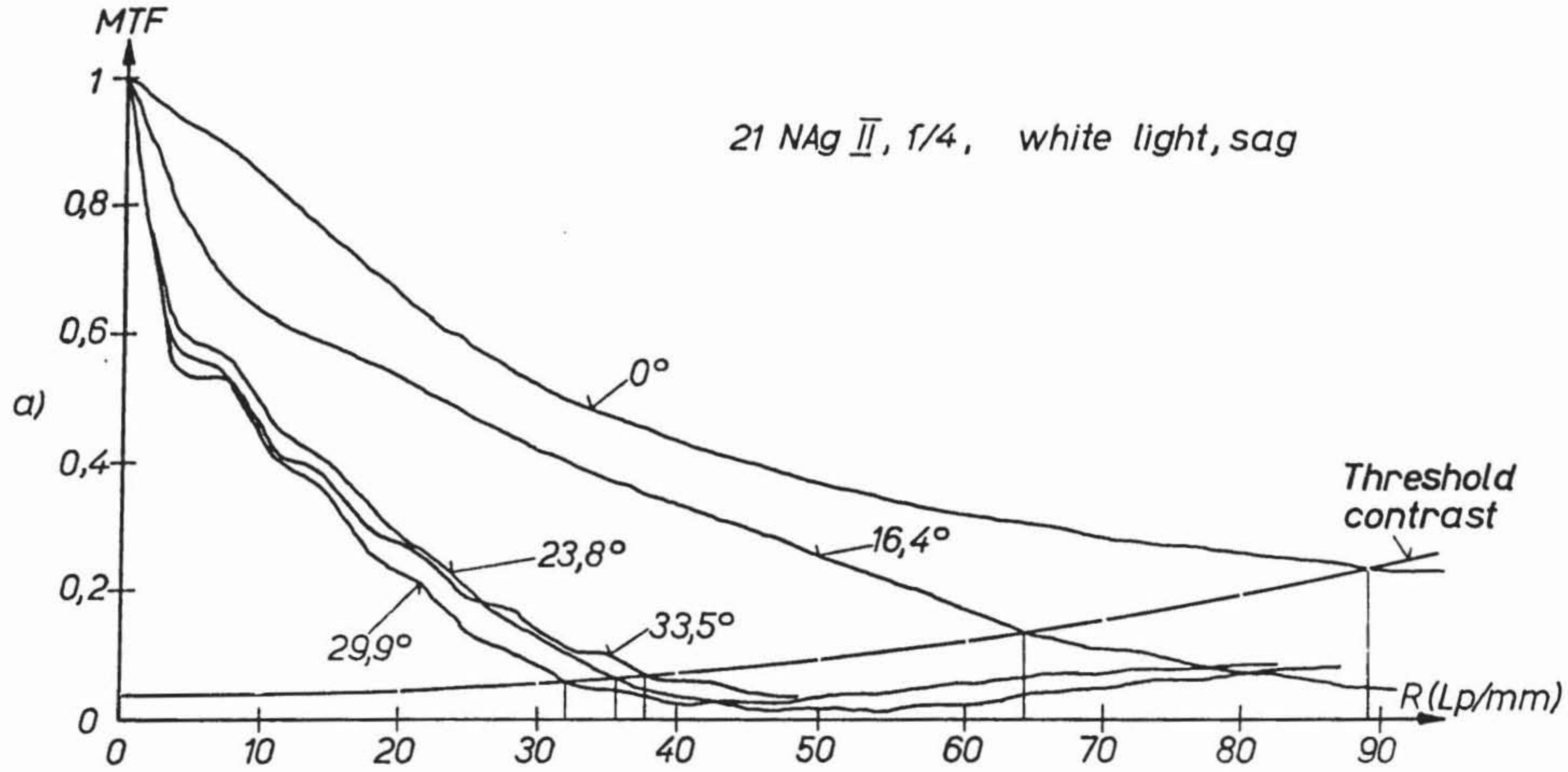

MTF
1
0,8
0,6
a)
0,4
0,2
0
21 NAg II, f/4, white light, sag
0°
16,4°
23,8°
29,9°
33,5°
Threshold
contrast
R(Lp/mm)
0
10
20
30
40
50
60
70
80
90

Fig.1 a

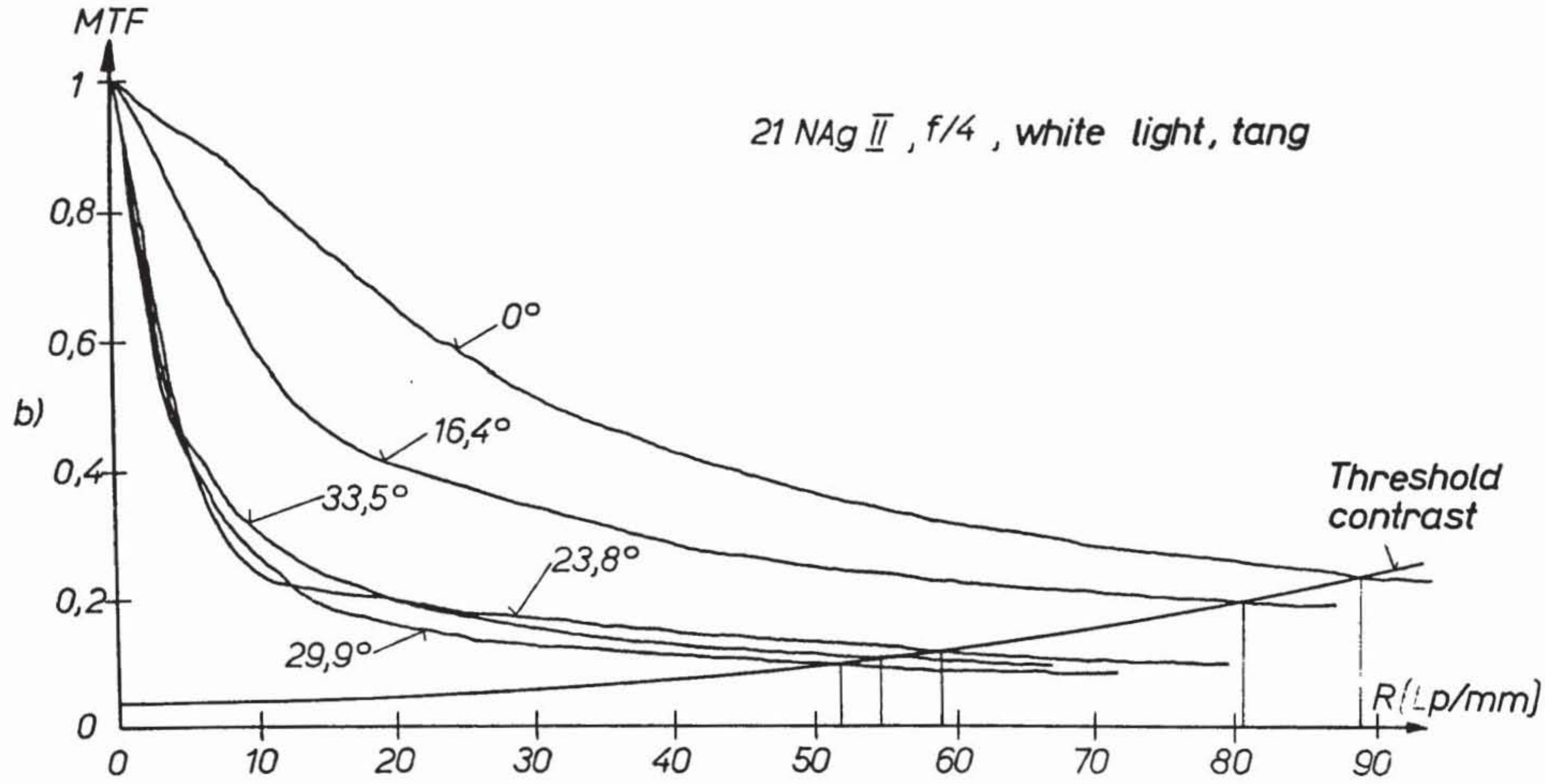

MTF
1
0,8
0,6
b)
0,4
0,2
0
21 NAg II , f/4 , white light, tang
0°
16,4°
33,5°
23,8°
29,9°
Threshold contrast
R(Lp/mm)
0
10
20
30
40
50
60
70
80
90

Fig.1b

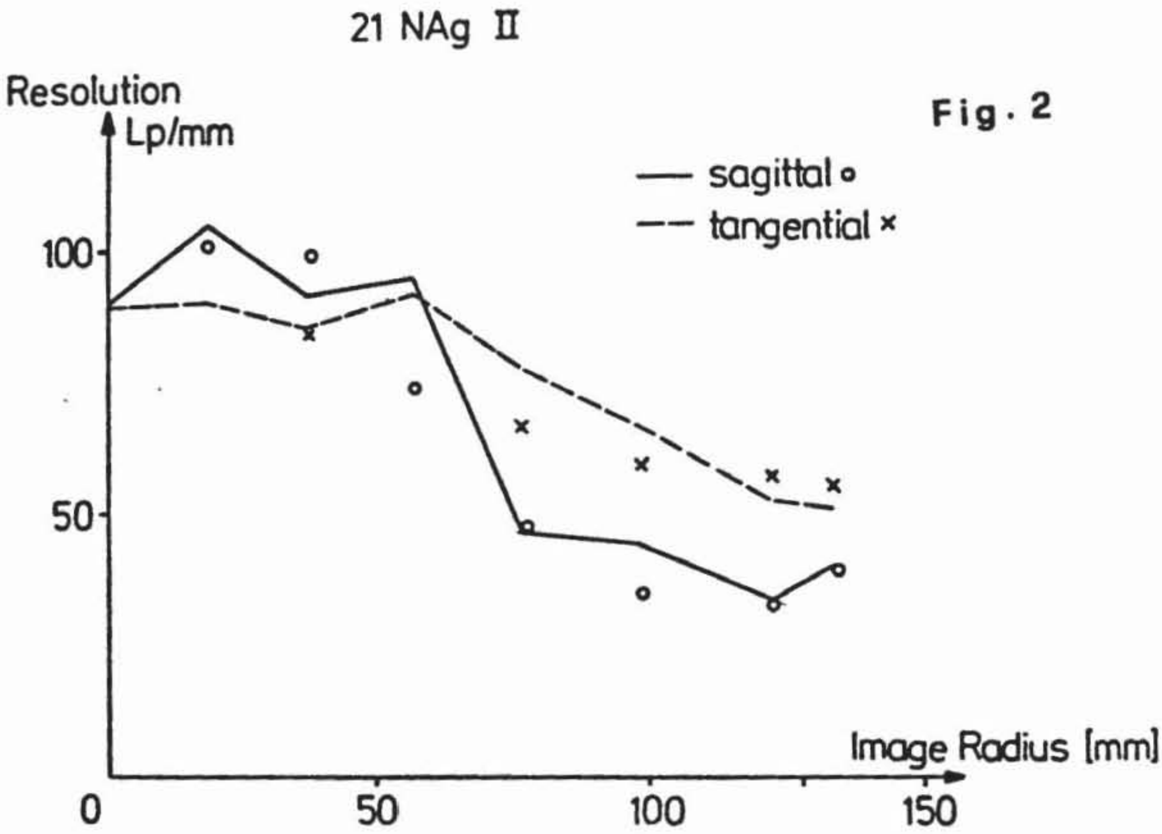

21 NAg II
Resolution
Lp/mm
— sagittal o
– – tangential ×
100
50
0
50
100
150
Image Radius [mm]

Fig. 2

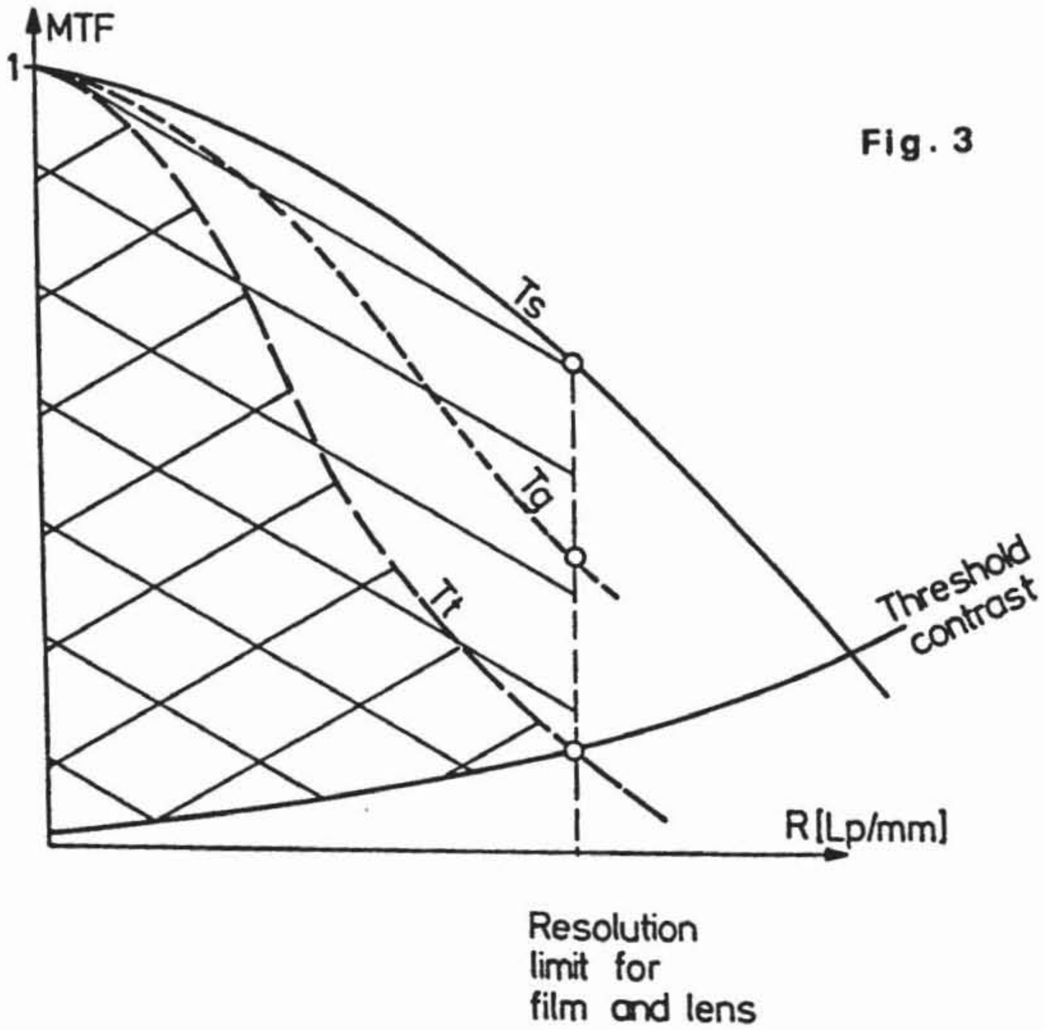

MTF
1
Ts
Tg
Tt
Threshold contrast
R [Lp/mm]
Resolution limit for film and lens

Fig. 3

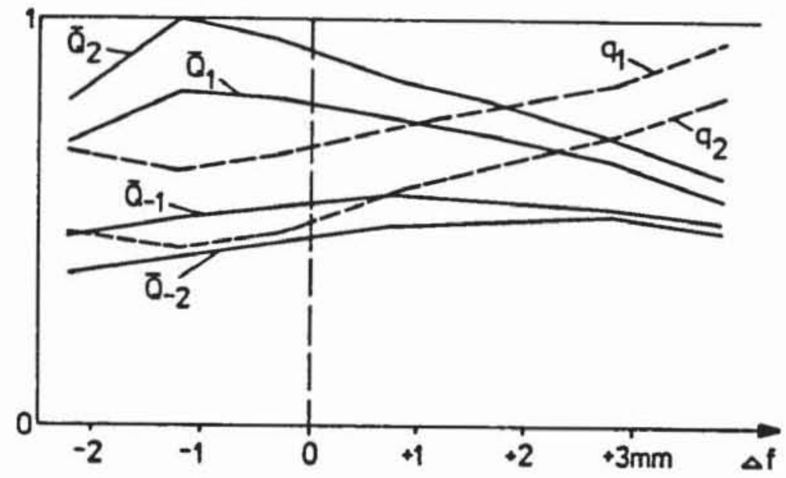

1
0
$\bar{Q}_2$
$\bar{Q}_1$
q_1
q_2
$\bar{Q}_{-1}$
$\bar{Q}_{-2}$
-2
-1
0
+1
+2
+3mm
Δf

Fig. 4

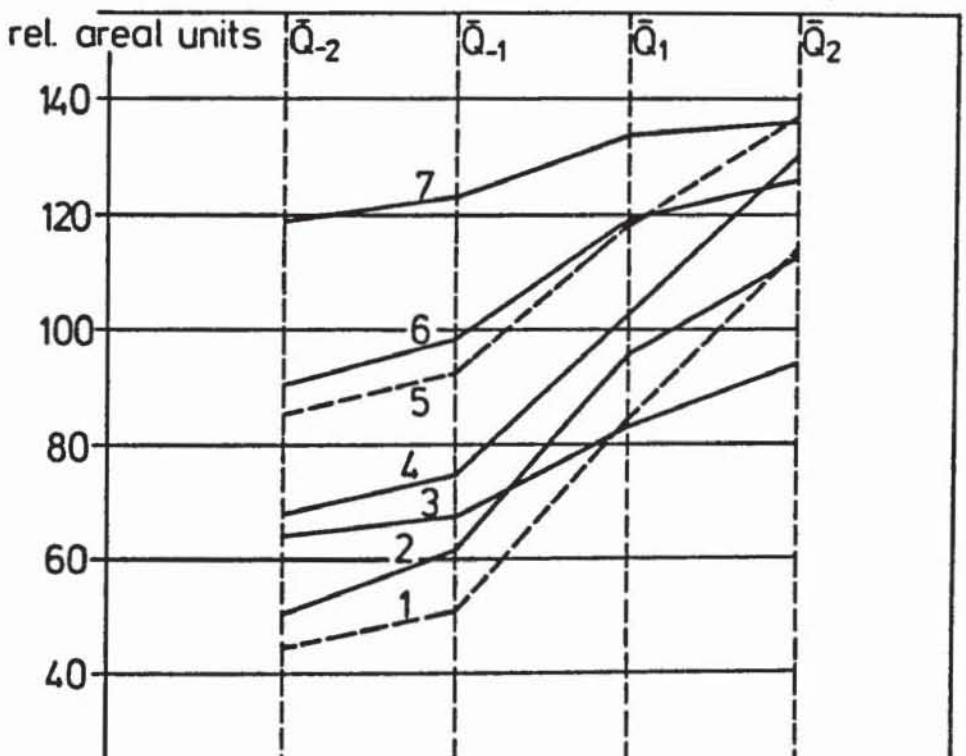
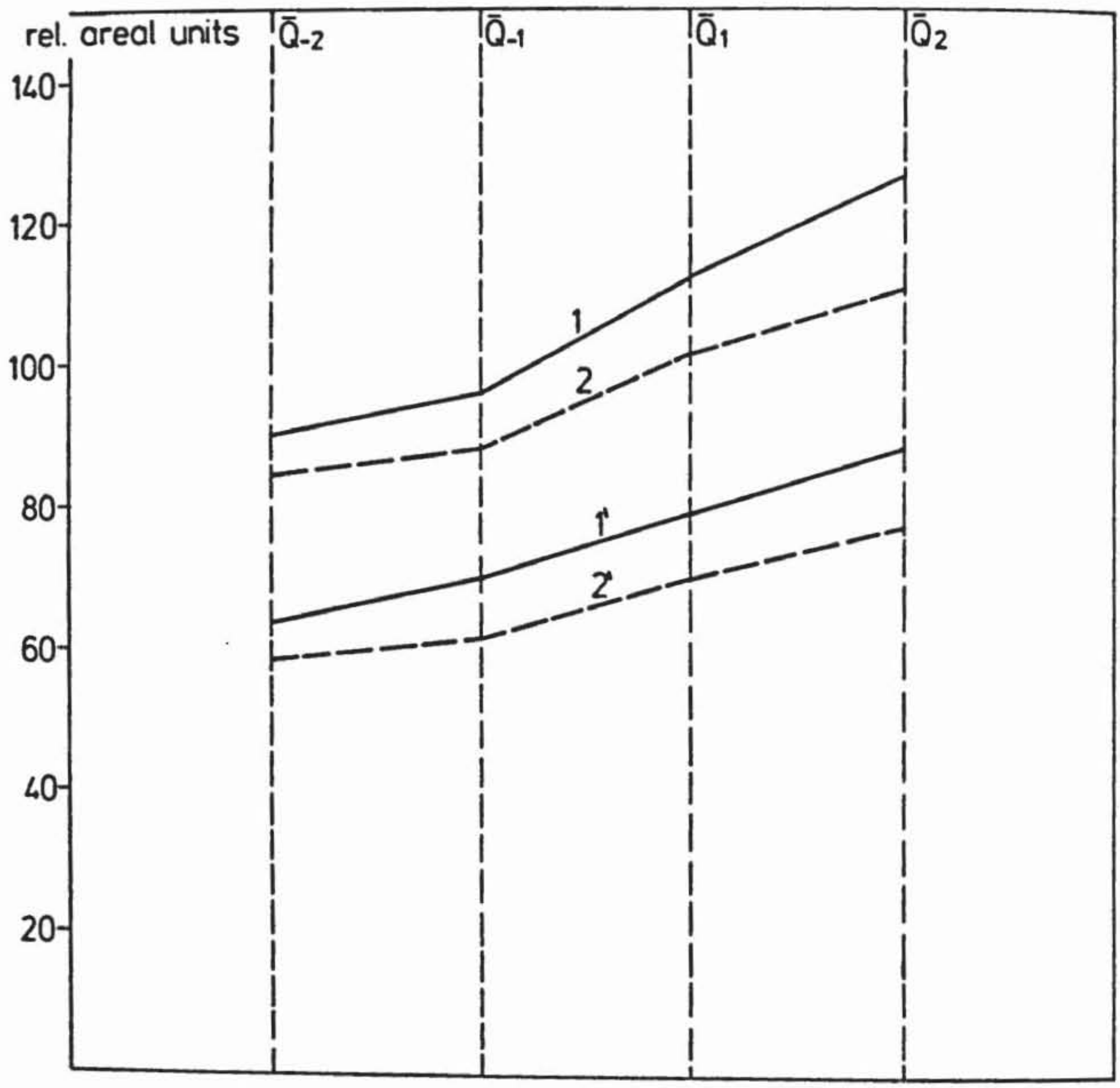
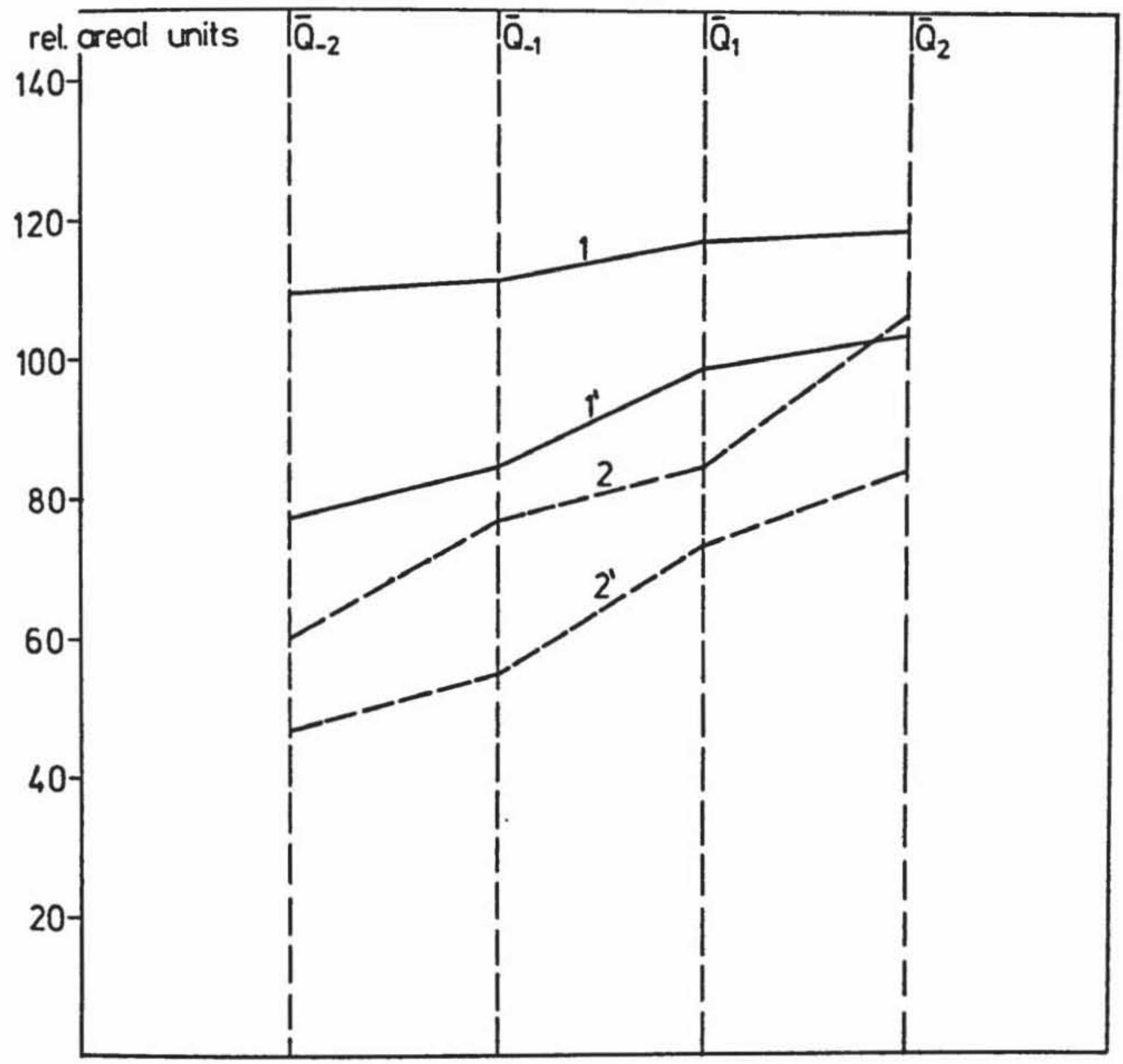
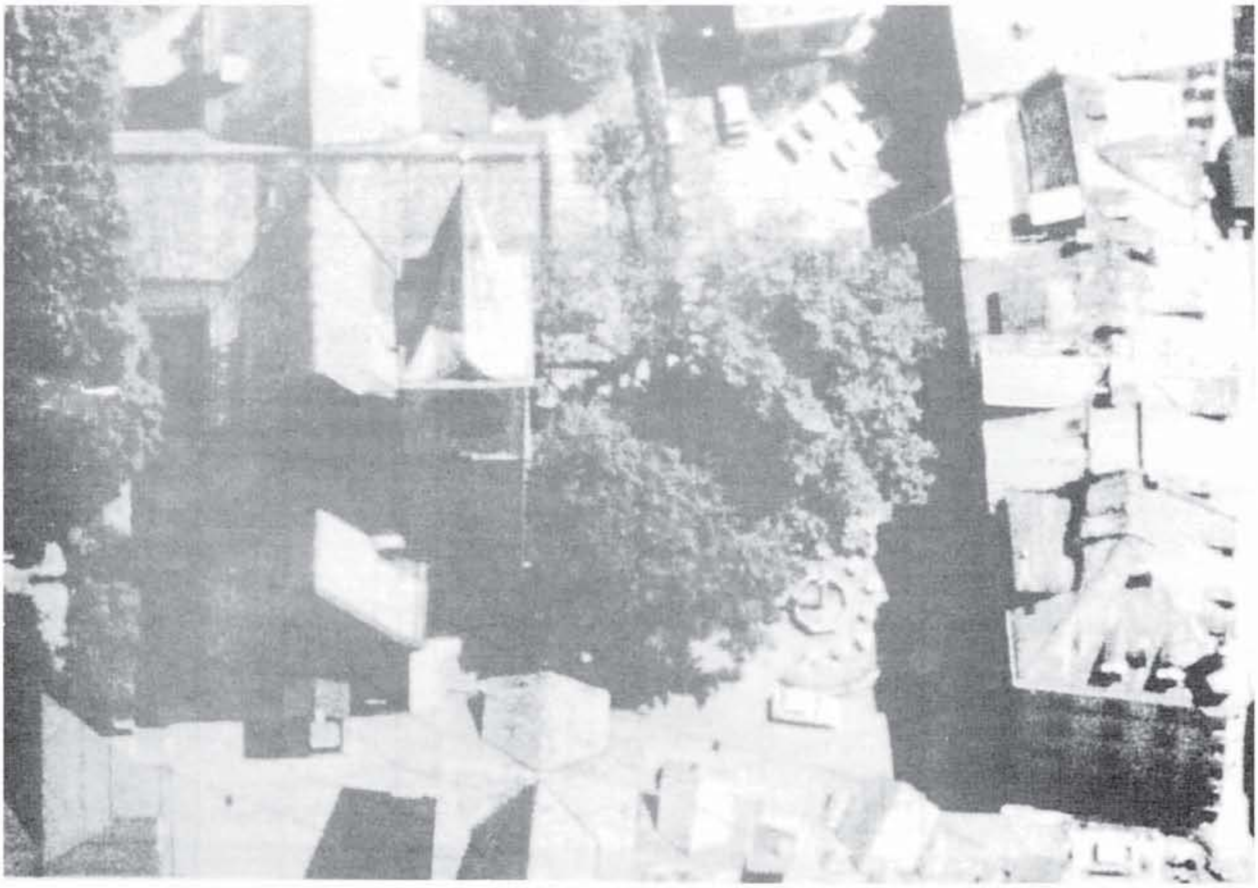

rel. areal units
$\bar{Q}_{-2}$
$\bar{Q}_{-1}$
$\bar{Q}_1$
$\bar{Q}_2$
140
120
100
80
60
40
20
7
6
5
4
3
2
1

Fig. 5

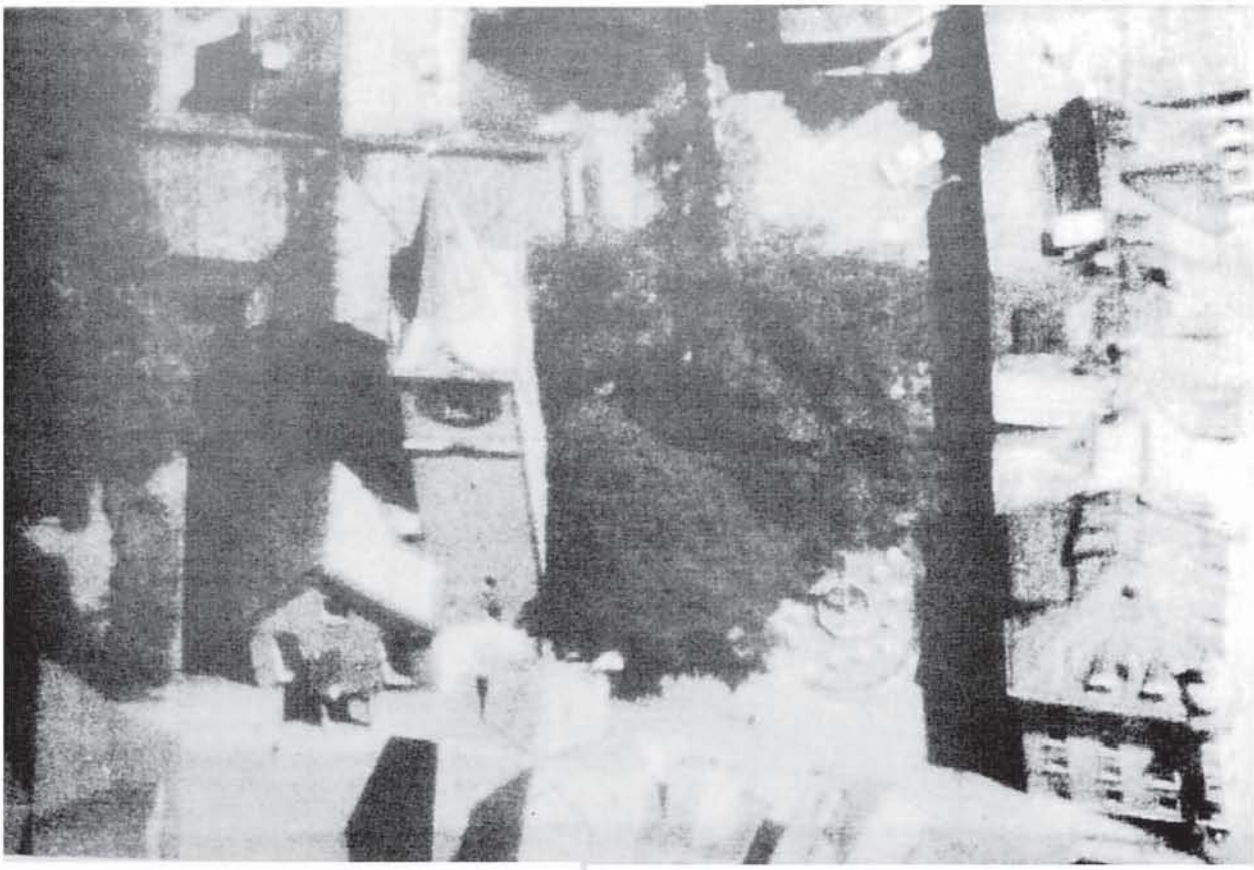

rel. areal units
$\bar{Q}_{-2}$
$\bar{Q}_{-1}$
$\bar{Q}_1$
$\bar{Q}_2$
140
120
100
80
60
40
20
1
2
1'
2'



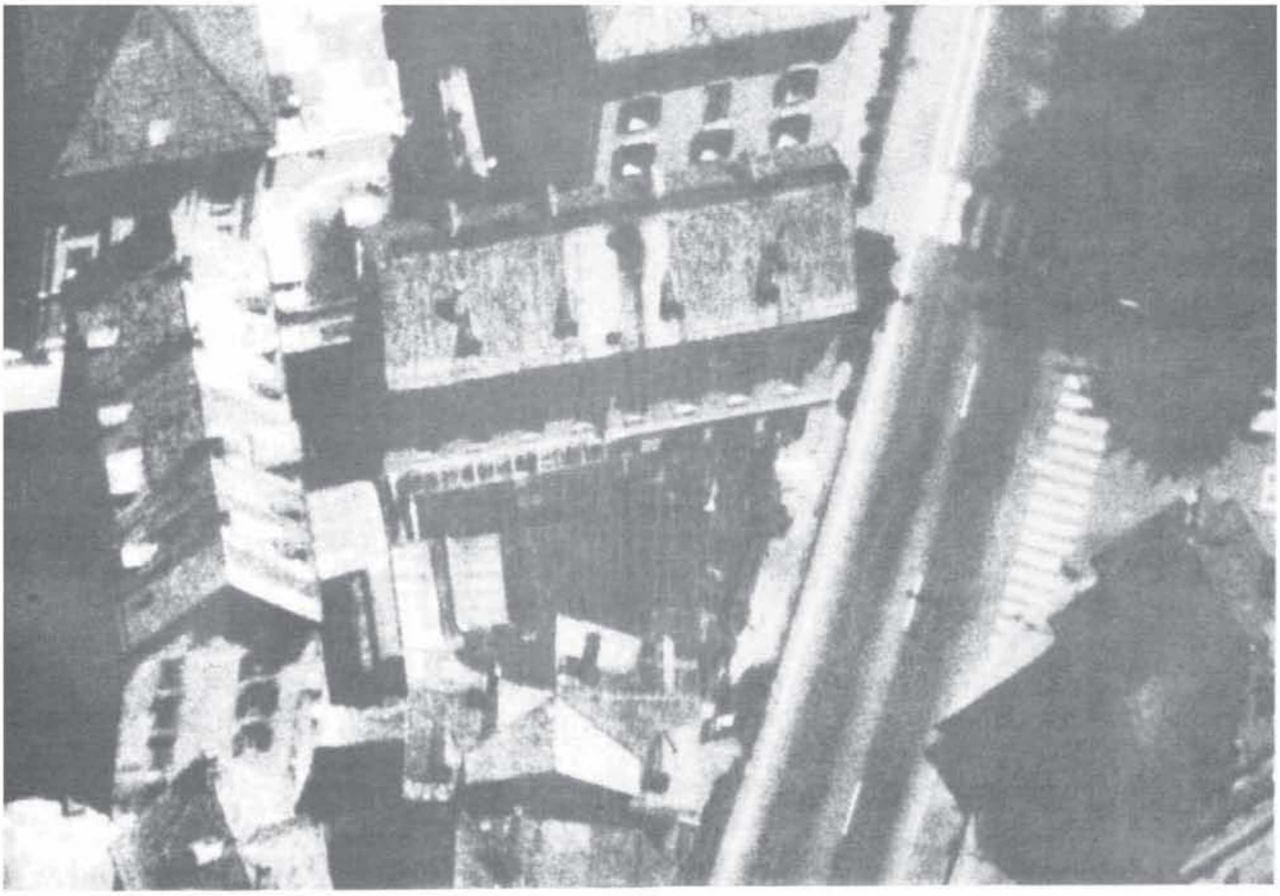
rel. areal units
140
120
100
80
60
40
20
$\bar{Q}_{-2}$
$\bar{Q}_{-1}$
$\bar{Q}_1$
$\bar{Q}_2$
1
1'
2
2'



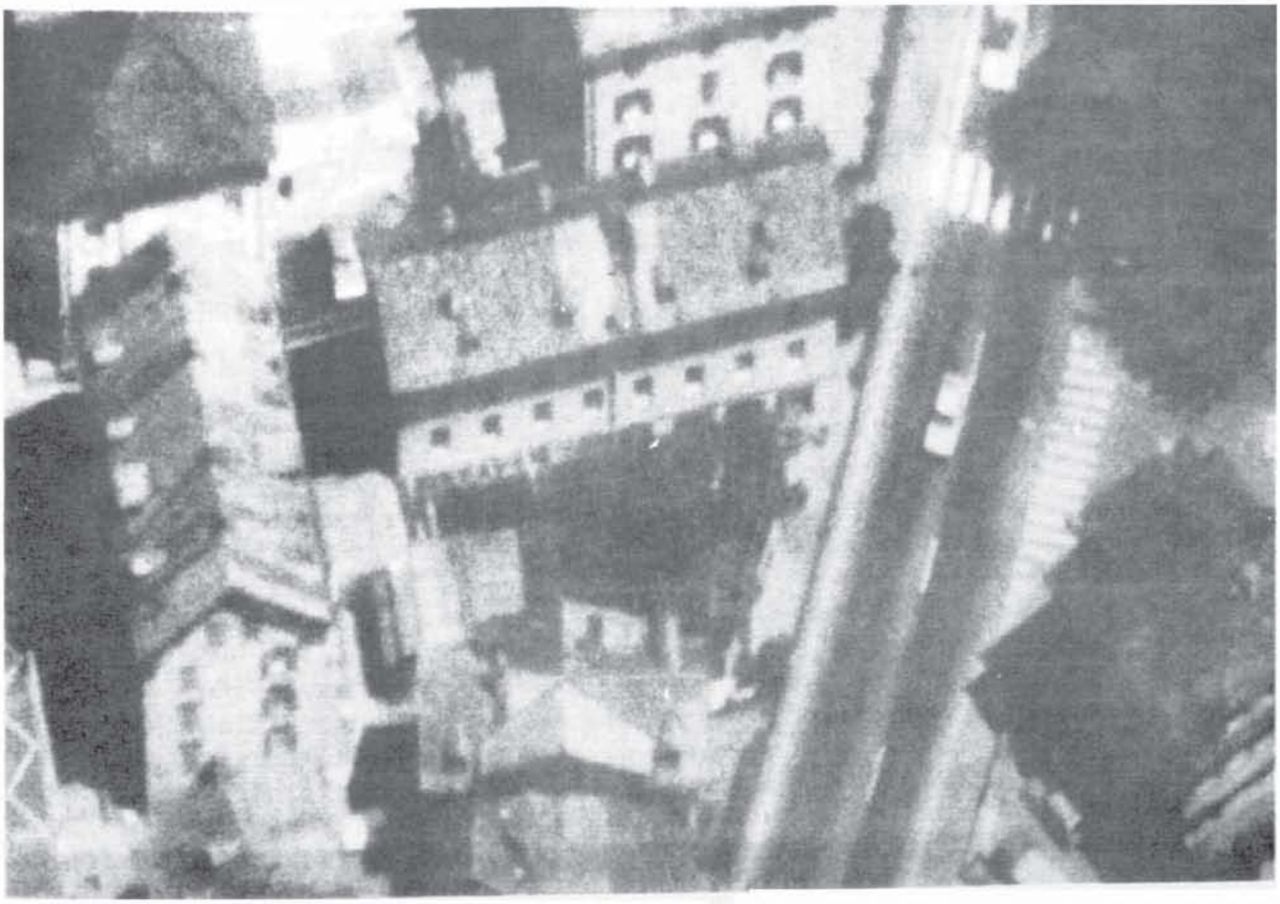
a



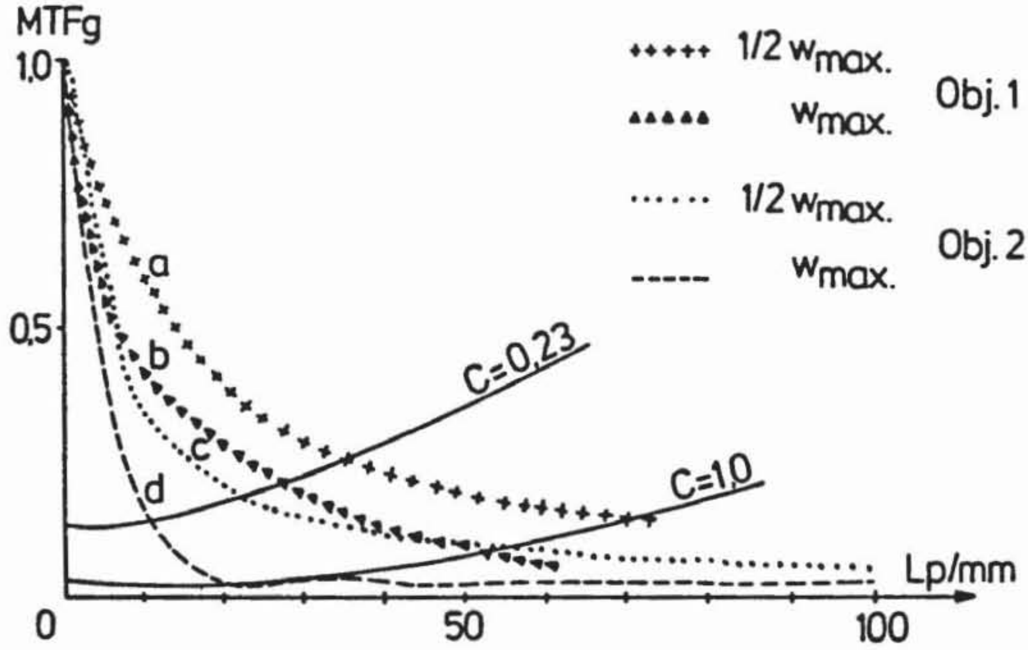
c



b



d


MTFg
1,0
0,5
0
50
100
Lp/mm
a
b
c
d
C=0,23
C=1,0
1/2 $w_{max.}$
$w_{max.}$
Obj. 1
1/2 $w_{max.}$
$w_{max.}$
Obj. 2