THE EFFECT OF FORWARD MOTION COMPENSATION (FMC) ON RESOLVING POWER OF AERIAL PHOTOGRAPHS

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Abstract:

Test flights with aerial survey cameras equipped with Forward Motion Compensation were carried out in May 1987 in Finland. To determine the resolving power a bar test pattern with low, medium and high contrast was used.
Different film types were tested and the camera was operated with FMC on and off. The scale of the photographs was approx. 1 : 10 000.
This paper presents the test results for a camera of 150 mm focal length.

1. Introduction

In May 1987 a test flight campaign was carried out at Nummela airfield (West of Helsinki) to determine the resolving power of various combinations of Aerial Survey Cameras and Aerial Films. In particular the effect of Forward Motion Compensation on resolving power should be investigated. The following cameras and films were used:
Cameras: RMK A 15/23, RMK A 30/23, RMK A 8.5/23
Films: Panatomic-X, Plus-X, Double-X, CIR-2443, SO-131, SO-242.
The cameras were operated in a two engine turboprop aircraft of the type Do 228/100 in an unpressurized cabin. The aircraft and the cameras were provided by the German Aerospace Research Establishment (DFVLR).
To determine the resolving power aerial photographs were taken over a resolution test field on the ground. This test field was produced by J. Hakkarainen, University of Joensuu. The films were developed at the photo lab of the National Board of Survey and Topographic Service, Helsinki.
In this report only results for the RMK A 15/23 camera will be presented.

2. The Test Field

A sketch of the test field used to determine the resolving power is shown in Fig. 1. The test field was produced of 30 hard board plates, which were painted with mat paint. It also comprised a 6-step grey wedge for controlling the film development.

At an image scale of 1 : 10 000 the spatial frequencies of the bar test pattern corresponded to 20, 30, 40, 50, 60, 70 and 80 lp/mm which were arranged in five parallel rows each with a different contrast. The test field was composed of two identical sets of these bar test pattern arranged perpendicular to each other. The various contrasts of the bar test pattern are given in Table 1.

In this report not all contrasts have been used for data evaluation; for the black/white films only 1 : 20, 1 : 3 and 5 : 1 contrasts have been applied and for the colour films only the 1 : 20, 1 : 3 and green/red contrasts.

No.	Background Density	Bars Density	Density Difference	Contrast Ratio	Remarks
1	black 1.60	white 0.30	1.30	1 : 20	high contrast
2	grey 0.85	black 1.60	0.75	5.5 : 1	shadow contrast
3	grey 0.85	white 0.30	0.55	1 : 3.5	low contrast
4	blue 0.85	yellow 0.15	0.70	1 : 5	colour contrast I
5	green 0.80	red 0.60	0.20	1 : 1.5	colour contrast II

Table 1: Contrast ratios for the bar test pattern.

3. Test Flight Program

Table 2 gives an overall view on the flights, which were carried out with the RMK A 15/23.

The nominal flight altitude was 1530 m over ground to obtain an image scale of 1 : 10 000. Only for the flights with the SO-131 and SO-242 films the altitude was increased because a higher resolution than 80 lp/mm was expected.

To image the test field at different look angles four consecutive overflights were made with an overlap of the photographs of 90 % and higher. The flight pattern which was applied for every flight series is shown in Fig. 2.

Date	Time	Sun Elevation	Altitude [m] over ground	Film	Filter	f-Stop / 1/t	Image Motion [µm]	FMC	No. of Images
8 May 87	12.10-12.24	44°	1530	PAN X	B	5.6 / 250	28	Yes	48
	12.28-12.40	45°	1530	PAN X	B	4.0 / 500	14	No	42
8 May 87	12.44-12.54	45°	1530	DX	B	5.6 / 600	12	Yes	34
	12.55-12.59	45°	1530	DX	B	5.6 / 600	12	No	14
9 May 87	14.32-14.46	43°	1530	Plus-X	B	5.6 / 450	16	Yes	52
	14.49-14.59	42°	1530	Plus-X	B	5.6 / 450	16	No	43
9 May 87	15.03-15.13	41°	1530	CIR-2443	B	5.6 / 250	28	Yes	41
	15.17-15.29	40°	1530	CIR-2443	B	5.6 / 350	20	Yes	54
10 May 87	10.07-10.20	34°	2020	SO-131	KL	4.0 / 100	53	Yes	46
10 May 87	10.24-10.39	36°	2020	SO-242	KL	4.0 / 100	53	Yes	60

Table 2: Parameters of Test Flights with the RMK A 15/23.

4. Data Evaluation Method

4.1 Abreveations

T-lines: bars of the test pattern perpendicular to the flight direction

R-lines: bars of the test pattern parallel to the flight direction

T: Resolution in lp/mm for the T-lines
R: Resolution in lp/mm for the R-lines

M: Average Resolution = Arithmetric Mean of T and R

ΔT: Improvement in Resolution with FMC for T

r: radial distance from the image center

G/R: Green/Red-contrast

4.2 Determination of the Resolving Power (RP)

The following criteria were used for determining RP:

1. A bar target ist accepted as resolved, if the number of lines is correct, all lines of the test figure are recognizable and not more than 20 % of the target is damaged.

2. A target ist not accepted as resolved, if the preceding target was not acceptable.

3. Visual interpolation is used between two targets, if the resolving power is obviously between these two targets.

For visual interpolation every interval of 10 lp/mm was subdivided in 4 sections of 2.5 lp/mm and the following rules were applied (e.g. for 30 and 40 lp/mm targets):

30	40	lp/mm
still acceptable	fully grey	30.0
clearly seen	fully grey	32.5
very clearly seen	fully grey	35.0
very clearly seen	direction of lines seen	37.5
very clearly seen	still acceptable	40.0

The determination of the RP was made from the original films by means of a binocular microscope with a 20 x magnification;
only for the Panatomic-X and the SO-242 films the magnification was increased. Both authors made the observation indepently, Juhani Hakkarainen in June 87 in Joensuu, Finland and Manfred Schroeder in July 87 in Oberpfaffenhofen, FRG. Final RP values are average values of both observers.

For those points for which the difference between the RP of the two observers was more than 25 % the RP was determined for a second time by both observers. Such cases were less than 5 % of all observations. For the controlled points 4 observations were then available. The highest and lowest value were then dropped as a cross error control and the final RP was the average of the two center values.

For scale control the image scale was determined by measuring the size of the test field in two images per test flight strip. A scale correction was needed only for few flights.

The RP values can be plotted as function of the radial distance; this is shown e.g. for the Plus-X film with FMC 'on' in Fig. 3 a. The dispersion of the RP points is considerable. For fitting a curve through these points the RP values were averaged for radial intervals of $\Delta r \approx 25$ mm; the average RP points were then connected resulting in the 'resolution curve' (Fig. 3 b).
The standard deviation of the resolution curve is indicated in Fig. 3 c.

4.3 Area Weighted Average Resolution (AWAR)

If R (r) is the resolution as function of the radial distance then the AWAR is given by

$$AWAR = \int_0^d R(r) \cdot G(r)\, dr \; ; \; d = 162{,}6 \text{ mm}$$

G (r) is the Area Weighting Function and is given by:

$$G(r) = \frac{2\pi \cdot r}{F} \quad \text{for } 0 \leq r \leq S$$

$$\text{and } G(r) = \frac{(\pi/2 - 2 \arccos \frac{S}{r}) \cdot r}{F/4} \quad \text{for } S < r \leq d$$

S = 115 mm F: total area of photograph = $(230)^2$ mm²

The AWAR was determined for T - and R-lines from the resolution curves (s. 4.2); the RP was determined graphically from this curves at distances of Δr = 15 mm. For numerical integration the following values for G(r)·dr were used:

r	G(r)·dr	r	G·dr	r	G·dr
15 mm	0.027	60	0.107	105	0.187
30	0.053	75	0.134	120	0.142
45	0.080	90	0.160	145	0.100

For determination of the RP for r ≥ 120 mm the resolution curves were graphically extrapolated is some cases.
AWAR values will be given in the next section (5).

5. Resolving Power Results

5.1 Panatomic-X Film

For the Panatomic-X film two flight series were carried out:

> one with FMC 'on' and the settings 5.6 - 1/250 and another with FMC 'off' at 4 - 1/500.

The results are shown in Fig. 4.

For all contrast the T-lines are better resolved with FMC 'on'. For the R-lines the resolution is better in the center (r ≤ 50 mm) with FMC 'off', whereas it is the same for the other part of the image (r > 50 mm). The difference in the center part can be explained by the shorter exposure time for the flights with FMC 'off', which minimize the influence of aircraft attitude movements. For the R-resolution the curves from the flights with FMC 'off' can be regarded as the more representative values.
From the curves in Fig. 4 the following AWAR-values can be derived:

Contrast	R	FMC on T	FMC on M	FMC off T	ΔT
1 : 20	60 lp/mm	65	63	53	23 %
5 : 1	43	51	47	39	31 %
1 : 3	50	55	53	47	17 %

The T-resolution with FMC is always higher than the R-resolution. The improvement in T-resolution with FMC varies between 17 % and 31 %.
Curves for the average resolution (with FMC) for different contrasts are shown in Fig. 5.

5.2 Plus-X Film

Two flights series - one with FMC 'on' and one with FMC 'off' - were carried out with the Plus-X film. The exposure settings for both series were 5.6 - 1/450.

The obtained resolution curves are shown in Fig. 6.

For all contrasts the T-lines are better resolved with FMC 'on'. For the R-lines there is no difference in resolution between FMC 'on' and FMC 'off'. From the curves in Fig. 6 the following AWAR-values were derived:

		FMC on		FMC off	
Contrast	R	T	M	T	Δ T
1 : 20	39 lp/mm	42	41	36	17 %
5 : 1	25	27	26	25	8 %
1 : 3	32	34	33	30	13 %

With FMC 'on' the T-resolution is slightly higher than the R-resolution, whereas with FMC 'off' R is slightly higher or equal T. The increase in T-resolution with FMC 'on' is between 8 and 17 %.

5.3 Double-X Film

For the two flight series with the Double-X film - one with FMC 'on' and one with FMC 'off' - the exposure settings were 5.6 - 1/600. Due to the short exposure time the image motion, which had to be compensated for, was only 12 µm.

The resolution curves for the T- and R-lines are shown in Fig. 7. For the FMC-off flights only 14 points were available to derive these resolution curves.
For the T-lines the resolution for the FMC-on flights is slightly higher for all contrasts for radial distances $r \leq 90$ mm, wheras for $r > 90$ mm the resolution seems to be the same. For the R-lines there is no significant difference in resolution.

From the curves in Fig. 7 the following AWAR-values were obtained:

Contrast	R	FMC on T	M	FMC off T	Δ T
1 : 20	35 lp/mm	39	37	37	5 %
5 : 1	23	26	25	22	18 %
1 : 3	27	31	29	30	3 %

The gain in resolution for the T-lines can clearly be observed only for the 5 : 1 contrast.

5.4 CIR-2443 Film

Two flight series with FMC 'on' were carried out for the CIR-2443 film with different exposure settings: 5.6 - 1/250 and 5.6 - 1/350. As no significant difference in resolution was observed for the two exposure times, the data sets from both flights were jointly evaluated. The results are shown in Fig. 8.
The resolution for T- and R-lines are nearly the same, although T is always slightly higher than R.

The following AWAR-values were derived from the curves in Fig. 8.

Contrast	R	T	M
1 : 20	28 lp/mm	30	29
1 : 3	24	26	25
G/R	25	27	26

The resolution for the G/R-contrast is nearly the same as for the 1 : 3 black and white contrast.

5.5 CIR - SO-131 Film

The SO-131 film was flown with FMC 'on' and an exposure of 4 - 1/100. At this exposure time 53 µm image motion had to be compensated for. The resolution curves are shown in Fig. 8. No distinct difference in resolution between R and T can be observed.

For determining the AWAR the curves in Fig. 8 were linearly extrapolated. The following AWAR-values were obtained:

Contrast	R	T	M
1 : 20	33 lp/mm	34	34
1 : 3	28	28	28
G/R	33	34	34

The resolution for 1 : 20 black and white - and for the G/R-contrast is the same. For R- and T-lines resolutions between 50 and 60 lp/mm can be reached in the image center.

5.6 Colour SO-242 Film

The SO-242 film was exposed with 4 - 1/100 and with FMC on. The image motion at this exposure time was 53 µm. The resolution curves are shown in Fig. 9.
The T-lines are for all contrasts better resolved than the R-lines.
For determining the AWAR the curves were linearly extrapolated and the following AWAR-values were obtained:

Contrast	R	T	M
1 : 20	52 lp/mm	57	55
1 : 3	49	55	52
G/R	40	44	42

For the high contrast the T-lines reach over 80 lp/mm in the image center. There is only a slight difference in resolution between contrasts 1 : 20 and 1 : 3.

6. Conclusions

- The FMC has only an effect on the lines perpendicular to the flight direction.
- With FMC the resolution of the lines perpendicular to the flight direction (T) is always higher than for the lines parallel to the flight direction (R).
  Without FMC T is less or equal R.
- The improvement in resolution perpendicular to the flight direction (T) can be as much as 30 % depending on the contrast. This effect is most pronounced for the PAN-X film, less pronounced for the Plus-X film and is relatively weak for the Double-X film.
- Improvement of the AWAR for lines perpendicular to the flight direction (T) for the various contrasts:

Film\Contrast	1 : 20	1 : 3	5 : 1
PAN-X	23 %	17	31
Plus-X	17 %	13	8
Double-X	5 %	3	18

- With the PAN-X film and the SO-242 film resolution values over 80 lp/mm can be obtained for high contrast in the central part of the image.

- The ranking of the films by AWAR-values is as follows:

  black/white-films

	1 : 20	1 : 3	5 : 1
PAN-X	63 lp/mm	53	47
Plus-X	41	33	26
Double-C	37	29	25

  Colour-films

	1 : 20	1 : 3	G/R
SO-242	55 lp/mm	52	42
SO-131	34	28	34
CIR-2443	29	25	26

  Plots of the average resolution (M) for different film types for a contrast 1 : 3 are shown in Fig. 10.

- The gain in resolution with the PAN-X film in comparison to the Plus-X and Double-X is between 50 and 80 % depending on the contrast.

- With the Colour SO-242 film nearly the same resolution can be obtained as with the PAN-X film.

- The gain in resolution with the SO-131 film in comparison to the CIR-2443 film is not as high as one would expect because of their difference in granularity. The reason for this is obviously that the resolution for Colour-Infrared films is limited by the inadequate colour correction of the lens.

- For exposure times longer than 1/300 sec it was often observed that also the lines in flight direction were partly deteriorated by pitch movements of the aircraft.

References

M. Schroeder, Auflösungstests mit Reihenmeßkammern aus großer Flughöhe. Proceedings of the 37th Photogrammetric Week, Stuttgart 24.-28.09.1979.

J. Hakkarainen, Resolving Power of Aerial Photographs, Surveying Science in Finland, Vol. 4, No. 2, Nov. 1986.

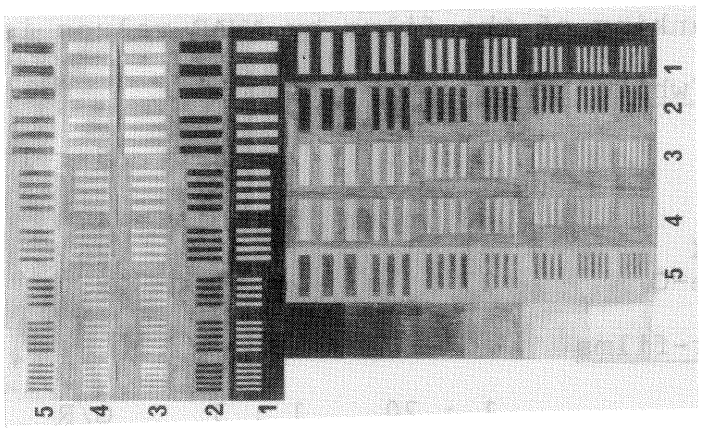


Fig. 1: Test field with bar targets of different contrast ratios. The spatial frequencies correspond to 20, 30, 40, 50, 60, 70 and 80 lp/mm for a 1 : 10 000 scale. For more details refer to Table 1.

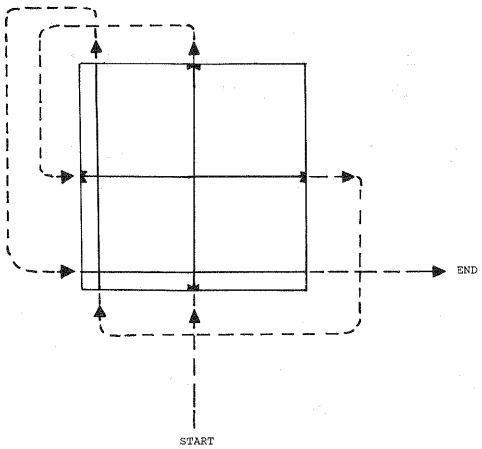


Fig. 2: Flight pattern for recording the test field on consecutive image frames during four overflights.

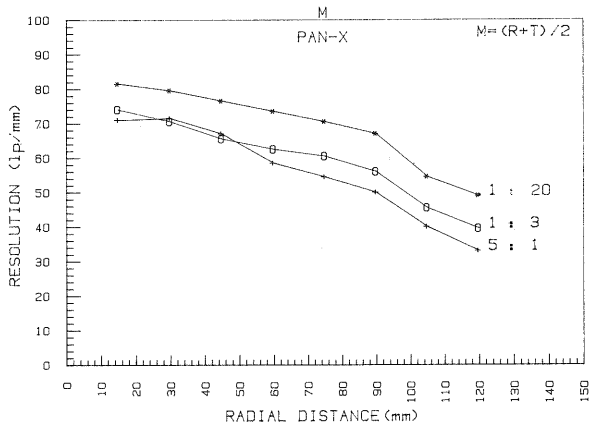


Fig. 5: Average Resolution (M) of RMK A 15/23 with Panatomic-X film for the contrast ratios 1 : 20, 1 : 3 and 5 : 1.

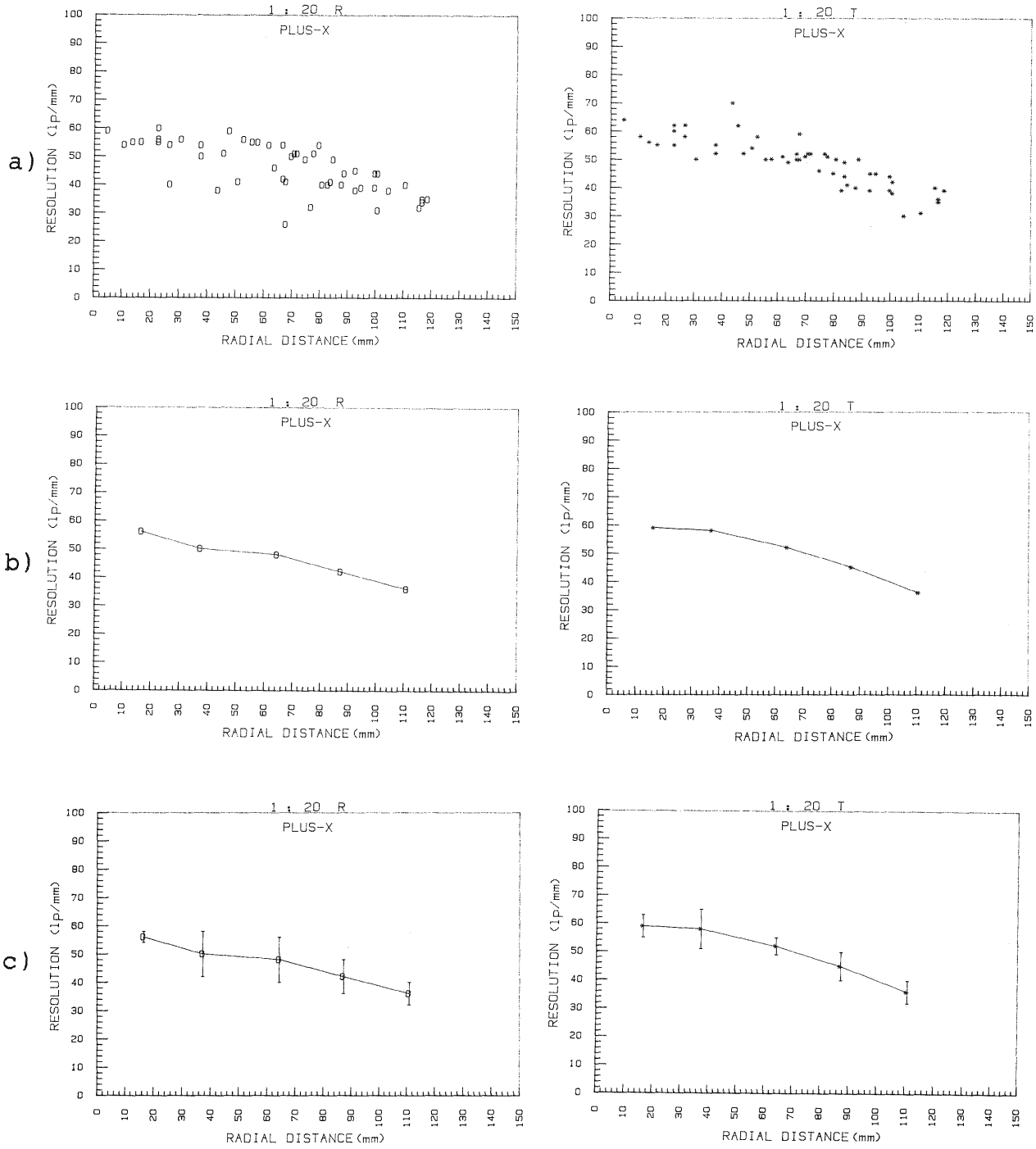


Fig. 3: Data Evaluation Method: (a) Resolving Power for various radial distances. (b) Deriving 'resolution curves' by averageing over radial intervals of $\Delta r \approx 25$ mm. (c) Standard deviation of resolving power values.
Left: Lines in flight direction (R)
Right: Lines perpendicular to flight direction (T).

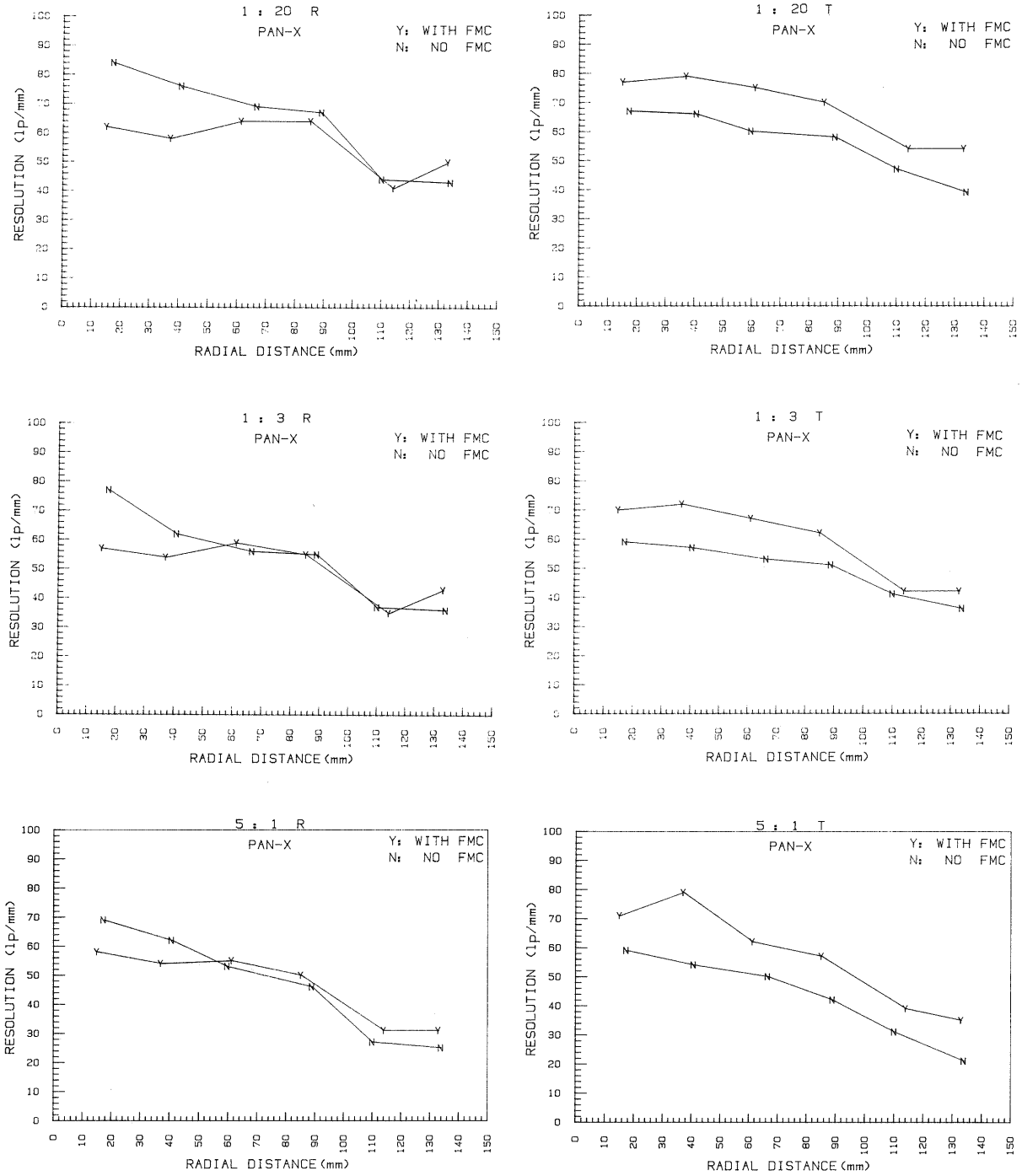


Fig. 4: Resolution Curves of RMK A 15/23 with Panatomic-X film for contrast ratios 1 : 20, 1 : 3, 5 : 1 and for FMC on and off.
Left: Lines in flight direction (R).
Right: Lines perpendicular to flight direction (T).

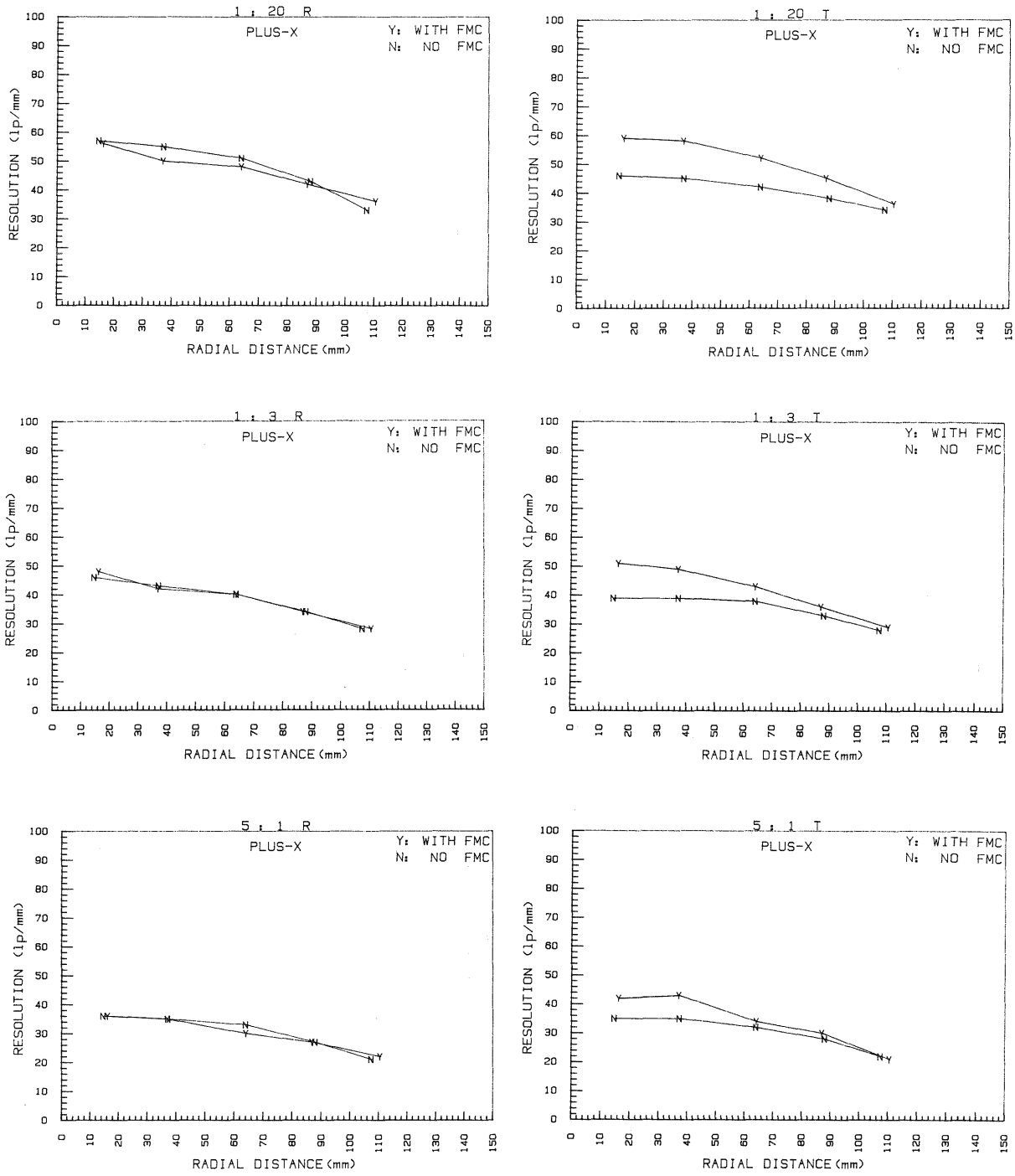


Fig. 6: Resolution Curves of RMK A 15/23 with Plus-X film for FMC on and off.
Left: Lines in flight direction (R).
Right: Lines perpendicular to flight direction (T).

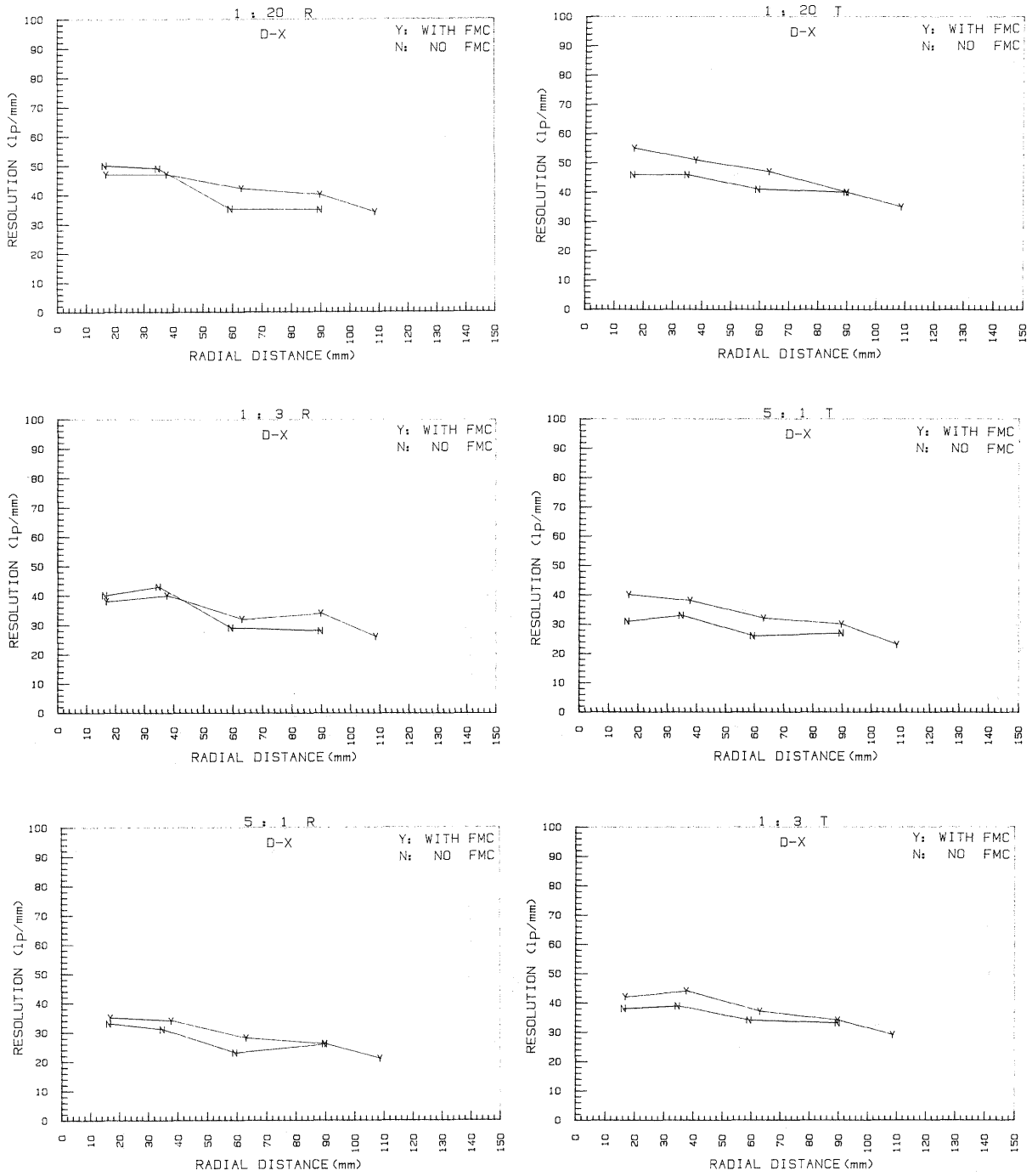


Fig. 7: Resolution Curves of RMK A 15/23 with Double-X film for contrast ratios 1 : 20, 1 : 3, 5 : 1 and for FMC on and off.
Left: Lines in flight direction (R).
Right: Lines perpendicular to flight direction (T).

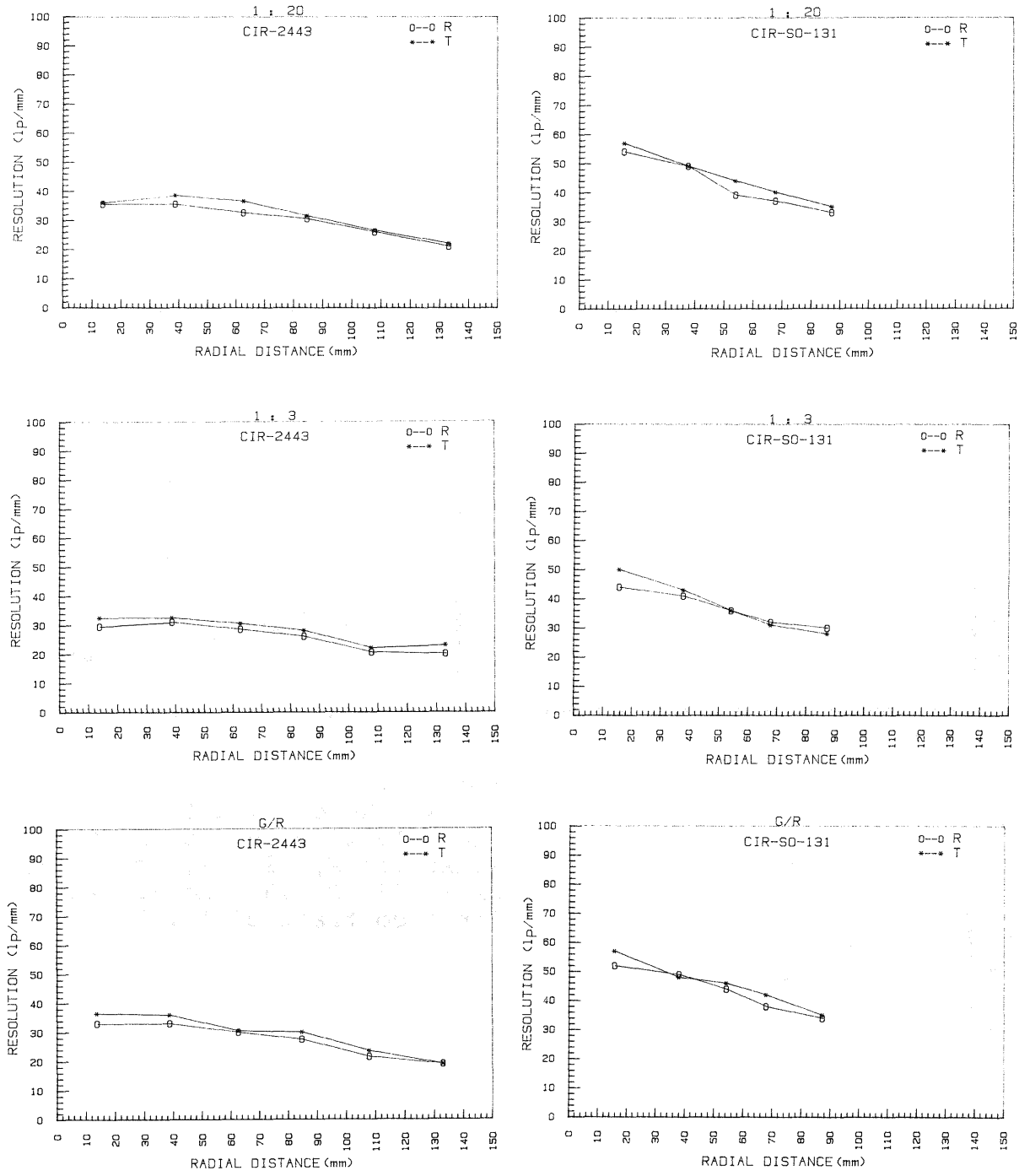
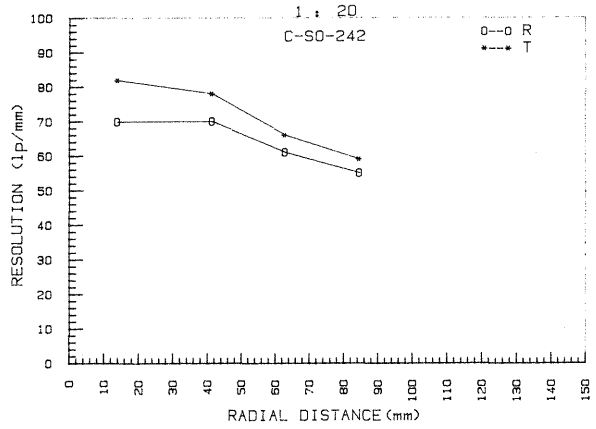
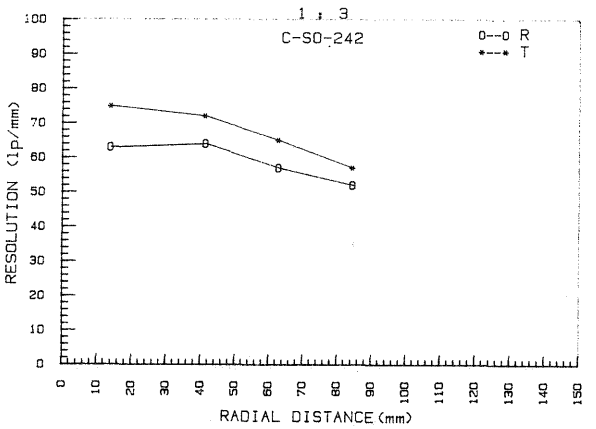


Fig. 8: Resolution Curves of RMK A 15/23 with CIR-2443 film (left) and SO-131 film (right) for the contrast ratios 1 : 20, 1 : 3 and green/red (G/R).





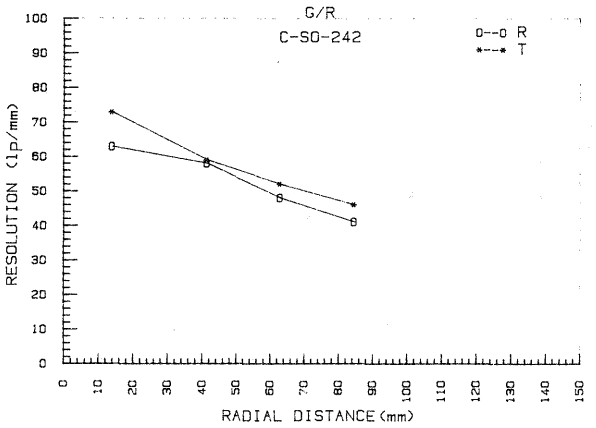
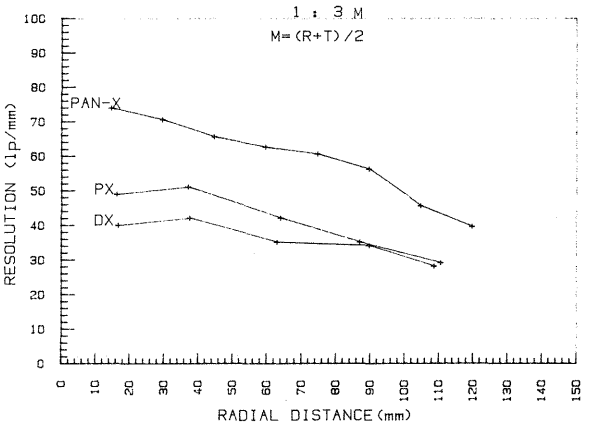


Fig. 9:
Resolution Curves of RMK A 15/23 with SO-242 film for the contrast ratios 1 : 20, 1 : 3 and green/red (G/R).



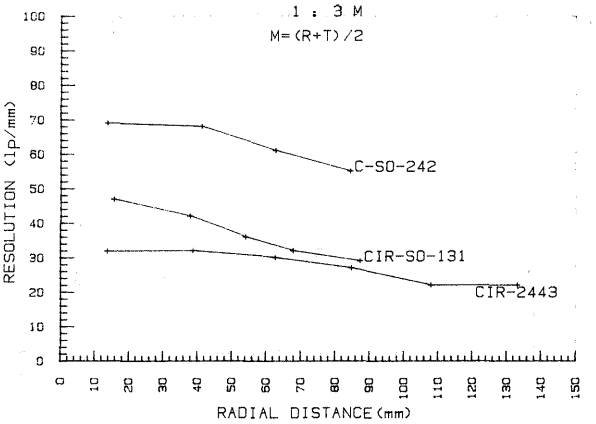


Fig. 10:
Average Resolution (M) of RMK A 15/23 with the films Panatomic-X, Plus-X, Double-X, CIR-2443, SO-131 and SO-242 for a contrast of 1 : 3.