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PAR 25-3-8S/R1

FINAL REPORT

Image Evaluation Study
for Hexagon Support

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PAR 25-3-8S/R1

FINAL REPORT

Image Evaluation Study
for Hexagon Support

18 October 1974

Prepared by:

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Approved by:

R. A. Koch
R. A. Koch

Date: 11/29/74

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PAR 25-3-8S/R1

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FOREWORD

An extensive test program for the analysis of image quality for the Hexagon system was initiated in 1972. Before this test program was started, an effort was made to design and fabricate an entirely new array of targets for the chamber reticles so that the system itself could be used as a test bed to resolve some of the critical questions being asked. The test program was designed by the Program Office and run by the sensor manufacturer. B/H was asked to participate in the analysis of a major portion of this task, which was executed on unit SN-012. In response to Program Office request, PAR 25-3-8S was submitted at the January 1973 CCB meeting. The board approved the PAR as submitted.

The effort proposed was fourfold. Part I, which dealt with the generation of TM curves, was concerned with the problem of better GRD predictions. Part II, which was concerned with isolated line analysis, was prompted by the desire to produce better smear estimates. Part III, which dealt with multiple targets (lines, edges, log periodics, and tri-bars), was concerned primarily with intercomparisons that could simplify test arrays and increase the accuracy of readings. Part IV, which was concerned with imagery of the ITEK model, was related to the SN-012 test by its objective of comparing power spectral analysis techniques with visual edge matching (VEM) for application to focus assessment.

Early in the above effort, however, smear slits were introduced on the Hexagon system, which obviated the need to improve smear estimates from line analysis. For this reason, PAR 25-3-8S was revised at the September 1973 CCB Quarterly Progress Review Meeting to delete line target analysis from this PAR.

Because technical difficulties delayed the start of this effort for a considerable period, the applicability of the remaining tasks came into question because:

1. The multiple target work had lost much of its original utility because of a change in operational philosophy. In addition, the multiple target imagery was determined to be of poor quality.
2. The model imagery effort had been superseded by an off-line study of objective image quality measures using actual mission material from 1208.

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FOREWORD (Cont'd.)

For the above reasons, it was recommended that the TM work be completed, effort on the multiple targets be terminated, and the intended work on the model imagery be eliminated. These recommendations were accepted at the July 1974 CCB Quarterly Progress Review Meeting.

Over and above the PAR effort per se, B/H was involved in many meetings and exchanges of information with other analysts of various experiments connected with the SN-012 test. In this connection, B/H recently submitted an input for the SN-012 test group's test report that included all the raw data supporting the TM curve analysis task. The data for that report is not included in the final report on this PAR (25-3-8S/R1).

Findings on the TM task were presented at the September 1974 CCB Meeting. This final report on PAR 25-3-8S/R1 documents that analysis and includes a description of the focus assessment work performed on 1208.

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KEY WORDS

1. Threshold Modulation Curve
2. Aerial Image Modulation
3. Smear Transfer Function
4. Modulation Transfer Function
5. Signal-to-Noise Ratio
6. SN-012 Special Test

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SUBJECT: Image Evaluation Study for Hexagon Support

TASK/PROBLEM

Analyze imagery from test-chamber and model photography to gain a better understanding of the parameters involved in objective methods of image evaluation, for use in Hexagon system diagnostic effort.

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SECTION 1

SUMMARY

This final report documents the two efforts that were accomplished under PAR 25-3-88/R1: The first is the threshold modulation (TM) task; the second is the 1208 focus experiment.

The objective of the first task was to prepare TM curves from chamber data that would result in more accurate operational predictions of GRD's. This objective was not achieved. The best distillation of the tri-bar readings from TM plates in the SN-012 data base produced TM curves that were inconsistent with the optimal TM curves prepared in the laboratory, and which are used operationally.

Much of the data available for the above analysis had to be discounted because of anomalies in the reticles, particularly at the higher contrasts. Because of these inconsistencies in the tri-bar arrays on the TM plates (density levels simulating exposure not always matched for the five contrasts, and trends in the arrays shifting the exposure level as a function of spatial frequency), no firm conclusions that would have been valuable for operational use could be drawn about the effects of combined amounts of defocus and smear on TM curve generation.

For the above reasons, it is recommended that the TM curves resulting from the SN-012 test not be used for operation predictions of GRD's; it is recommended, however, that the question of best exposure/density of average transmittance for optimum tri-bar resolution be re-examined. Verification of a theory derived by Dr. Otto Schade for the generation of TM curves without the necessity of actual subjective readings should be considered.

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In the 1208 focus experiment, a test was performed in an off-line mode to determine whether the power spectral analysis technique could be used to assess focus for the 1200 series. The results of the test were sufficiently encouraging to warrant adding this technique to the PFA for 1209. Continuing evaluation will be conducted to determine its long-term utility.

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SECTION 2
CONCLUSIONS AND RECOMMENDATIONS

1. The best distillation of the tri-bar readings from the TM plates in the SN-012 data base produces TM curves inconsistent with the optimal TM curve produced in the laboratory.
2. Much of the data available for the TM analysis had to be discounted because of anomalies in the reticles, particularly at the higher contrasts.
3. The AFSPPF and FEAT Laboratory readers were in reasonably good agreement in the majority of cases.
4. Because of inconsistencies (exposure level and trends) in the tri-bar arrays on the TM plates, no firm conclusions can be drawn about the effects of combined amounts of defocus and smear on TM curve generation.
5. The results of this experiment suggest that the optimal exposure for operational imagery (general scenes) may not be the correct exposure to achieve maximum resolution of tri-bars.
6. There are theoretical descriptions of threshold modulation (such as Otto Schade's), that are sufficiently detailed to take into account the major parameter variations encountered here. These descriptions, if verified by laboratory testing, might be more cost effective than elaborate experiments.
7. The utmost care must be taken in applying a laboratory-derived TM curve for operational predictions. For example, it was found that significant errors will result if optimal exposure conditions (for tri-bars) do not exist during photography and an attempt is made to predict results using a TM curve derived from optimally exposed tri-bars.

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8. The TM curves resulting from the SN-012 test are not recommended for operational use.
9. It is recommended that the question of proper exposure/density for scenes versus optimum resolution of tri-bar images be re-examined. It is suggested that TM curves for operational use might be more aptly chosen at the exposure level which is optimum for scenes and not for peak resolution of tri-bars.
10. As a result of testing on 1208 material, it is recommended that the power spectral analysis technique of focus assessment be added to the PFA for the 1200 series.

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SECTION 3 INTRODUCTION

3.1 OBJECTIVES OF THE STUDY

One of the purposes of this effort was improvement of TM curves. It was hoped that through a better appreciation of the elements involved, TM curves could be provided which when utilized in a systems approach would result in more successful operational predictions of resolving power.

One way of assuring more appropriate TM curves would be to prepare them using a system similar to that for which they would be used. The problem with operational systems, however, is that although the optics may be identical, variations introduced by image motion result in what is in effect, a multitude of different system MTF's. The question to be determined then was what is the effect of these added complications.

For this study, imagery was produced in a chamber using real system optics that provided variations in operational parameters such as image motion and defocus over a considerable dynamic range. It was believed that by preparing TM curves from images of tri-bar targets under these different conditions, a better understanding of the subtleties involved would be possible.

It was also hoped to compare the TM curves prepared from imagery produced under nominal orbital conditions with that produced in the laboratory under ideal conditions. As the laboratory curve is currently being used in prediction programs, it was thought that some of the error in the predictions might be explained in terms of the difference between TM's.

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SECTION 4 DISCUSSION

To aid in understanding how threshold modulation curves are prepared, a brief history of their background is provided first.

4.1 BACKGROUND

Ever since Rayleigh did his classical work with telescopes and arrived at a criterion for resolving power, optical scientists and engineers have been predominantly occupied with the idea of resolution. Certainly, in a comparison of two similar systems designed for the particular task of resolving two closely spaced point objects such as binary stars, this criterion is of utmost importance. Unfortunately, in some respects, the same basis for comparison has been carried over into the photo-reconnaissance community since its earliest days. Many users are understandably reluctant to give up this criterion until a proven and preferred alternate comparison technique appears.

One of the obvious weak points of a resolution criterion is its subjective nature. While optical aspects of the human eye-brain system most certainly must be considered in any thorough evaluation, the statistical responses generated by different but controlled sets of observers contribute substantially to the problems of objective comparison.

The advent of modern communication theory and its adoption by the photographic community has supplied techniques that can provide this more objective approach. Fourier analysis techniques furnish the means for looking at the photo system in terms of its components in that the analytic description of the whole can be formed by the product of the descriptions of its parts.

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The Fourier techniques are only applicable to those components that can be described in a linear fashion with respect to light intensity. Therefore, while the strictly optical aspects of the photo system (the object, image-forming optics, and linear image/film relative motion) can be described, the non-linear chemical effects of the film component cannot. In addition, the complex eye-brain component is beyond the capability of mathematical description at this time.

In compromise, the components that can be treated with Fourier techniques have been treated; the remaining film-eye-brain components have been lumped into a "black box" approach. Although they cannot be strictly analytically described, they can at least be measured.

The Threshold Modulation (TM) curve that is the subject of this study is just that "black box". The TM curve when measured properly describes the modulation incident on the emulsion surface—the so called aerial image modulation (aim)—required to resolve a tri-bar target as a function of the frequency of the target at the film plane. Therefore, if Fourier techniques are used to describe the modulation that the other components of a photo system present to the film at a given frequency, the TM curve will indicate whether it is sufficient for resolution. The obvious advantage of this technique is that once the TM curve is measured, subjective resolution should not have to be measured for each new system, but could be predicted.

4.2 PREPARATION OF TM CURVES

TM curves are usually prepared in the laboratory under ideal conditions. Targets of different contrasts, each including a multitude of tri-bar elements each of a different frequency, are imaged onto the film being tested. The same targets are exposed a number of times at different light levels to obtain an exposure series. The images are then read,

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and the exposures that result in the highest resolved frequency for each contrast are chosen. The incident modulations corresponding to these elements are then calculated from a knowledge of the modulation transfer function (MTF) of the imaging optics. A TM curve is then fit to these chosen data points.

Due to the complex nature of the component that we are trying to describe, it is not surprising that different TM curves result when conditions are varied. Among the parameters that may affect the results are the film type, exposure level, development conditions, and geometry of the aerial image.

Because the tri-bar target used in resolution determinations has a complex Fourier description, the geometry of its image varies with the system imaging it. While the modulation in the image may be the same for two different systems, the shape may not be the same. The result of these differences may be different resolved frequencies for the same modulation. Consequently, there is some doubt whether a TM curve measured on a lab bench can be properly used for a dynamic system that uses different optics and includes image motion.

Ideally, one would be able to convert a TM curve prepared for one set of optics for use in predictions for another set by a knowledge of the MTF's of the two systems. Theoretical considerations by Dr. Otto Schade indicate that this may in fact be possible.¹ The essence of Schade's theory is the assumption that the detection of an optical image in the noisy background of the emulsion requires a certain threshold signal-to-noise ratio for that image. In his article,¹ Schade derives an equation relating the signal-to-noise ratio of the tri-bar image to its frequency

¹ Otto Schade, "An Evaluation of Photographic Image Quality and Resolving Power." J. Soc. Mot. Pict. and Tel. Engr., Feb. 1964

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through the optical system and film parameters. A discussion of his equation is contained in Appendix A. It concludes that when a measured TM curve is used, it must be done with full appreciation of the parameters that applied during measurement. Unfortunately, in the past, regard for the proper application of the TM curve has not always been the case. A better understanding of the nature of the TM curve should result in greater success in its use in the future.

As stated previously, these curves are prepared by imaging tri-bar targets onto the surface of the emulsion and then reading the resulting image to determine resolution. In this study, the tri-bar targets were in the form of reticles in a chamber collimator and were imaged by the SN-012 system mounted in the chamber.

Figure 4-1 shows the layout of the targets. The target reticles each consisted of 15 rows of 42 tri-bar elements. The frequency of the tri-bar elements of each row ran from 8 to 80 cycles/mm which when reduced by the collimator/system optics appeared as approximately 60-600 cycles/mm in progression of $12\sqrt{2}$ at the film.

The 15 rows were differentiated into 3 sets of 5 adjacent rows. The outside sets differed from the center set in their average transmittance. One resulted in nominally 0.15 log E less exposure and the other 0.15 log E greater exposure than the center set.

The illumination of the target reticle was nominally chosen so that the center set would have optimum exposure. The bracketing sets were used to provide an exposure close to optimum even if slight variations occurred in the illumination.

Within each of the exposure sets, each of the five rows had a different modulation/contrast. The modulations were nominally 10, 30, 50, 75, and 95 percent.

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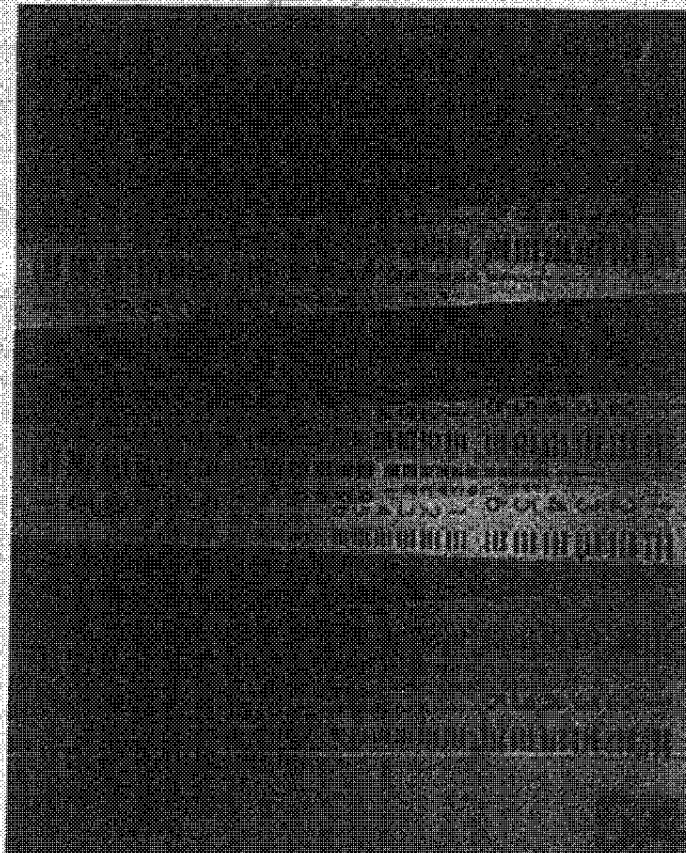


Figure 4-1. Tri-Bar Targets for TM Curves

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A synch-flash C target located in the vicinity of the tri-bar reticle was used to measure the film motion relative to the reticle image during exposure. The image motion was assumed to be linear and the measurement was used to produce a smear transfer function (STF) that was multiplied by the optics MTF to produce a system transfer function.

Image motion was purposely introduced into the system along with a range of defocus of the optics. This produced the range of system MTF's required to prepare TM curves under varying conditions.

In all, there were four collimators of interest in this experiment. One of the two collimators for the forward (A) optics had a target reticle oriented in the in-track direction; the other had a reticle in the cross-track or scan direction. A similar setup existed for the aft (B) optics.

The system parameters were varied nominally as shown in the chart in Figure 4-2. Approximately six frames of interest to this experiment were exposed of the IT and XT reticles for each system at each crossed parametric setting.

Both the forward and aft system optics had been studied previously to determine their MTF's for the defocus parameters used and corresponding to the appropriate field angle.

As stated above, the synch-flash technique was used to determine the smear for each frame of imagery. The smear parameter in the chart was simply a guide, and true measured smear was used in the calculations.

After the imagery was exposed, it was processed according to standard operating procedures. The developed imagery was then read by two Air Force readers at AFSPPF and by three readers of the FEAT Lab. On each

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SMEAR (μ) (μ) DEFOCUS		(0) OCP 77 FRMS	(1) OCP 100 FRMS	(2) OCP 102 FRMS	(4) OCP 104 FRMS	(8) OCP 106 FRMS
(0)	A FOC 20	2-7	2-7	2-7	2-7	2-7
	B FOC 74	2-7	2-7	2-7	2-7	2-7
(4)	A FOC 26	12-17	12-17	12-17	11-16	11-16
	B FOC 76	9-14	9-14	9-14	9-14	9-14
(8)	A FOC 30	20-24	20-24	19-24	19-24	19-23
	B FOC 82	17-21	17-21	16-21	17-22	17-21
(16)	A FOC 38	30-35	30-35	30-35	30-34	29-34
	B FOC 88	26-31	26-31	26-31	26-31	27-32
(32)	A FOC 54	42-46	43-47	43-47	42-46	41-46
	B FOC 106	39-44	40-44	39-44	40-44	39-44

Figure 4-2. Nominal System Parameters

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frame of imagery, there were images of both the in-track and cross-track reticles containing 15 rows each. For each row, readers were asked to specify from among the 42 existing tri-bar elements the tri-bar element that was just-resolved.

For each tri-bar element resolved, the frequency was known and the corresponding incident modulation was calculated. The target reticle modulation M_o of the particular element was known from microdensitometry, the MTF of optics at the defocus setting of that frame was known, and the smear was measured for the particular image location/direction. The corresponding smear transfer function STF_w (a sinc function) was calculated. By multiplying the product of the target modulation and the optics MTF by the smear factor, the aerial image modulation corresponding to the resolved element was found.

Due to the large quantity of data involved (2 systems x 140 frames x 2 directions x 15 rows x 5 readers = 42,000 data points), a computer program was written to handle all the calculations. In addition to computing the incident modulation versus frequency for the data points, the program was written to group the data by classes; i.e., by reader, target direction, and system MTF quality; and to fit TM curves to the grouped data and plot the results on a Calcomp plotter. Once the TM curves were plotted, they were compared with each other and with the laboratory-generated curves.

4.3 RESULTS

A list of the results was prepared in terms of frequency resolved versus incident modulation for each frame. The results from the two target images in-track and cross-track were listed next to each other on the same page. An example of the results for one frame is shown in Figure 4-3. The page is identified in the upper left-hand corner by the OCP, focus setting (FOC), and frame number (FRM) of the imagery it represents.

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DCP 77 FOC 20 FRM 2

PLT 54

PLT 52

SMR = 2.29 RNK = 6 XFR = 239

SMR = 2.29 RNK = 46 XFR = 277

CINT

EXP 1

EXP 2

EXP 3

EXP 1

EXP 2

EXP 3

RDA	GE	FREQ	IM	GE	FREQ	IM	GE	FREQ	IM	GE	FREQ	IM	GE	FREQ	IM	GE	FREQ	IM	
1	1	13	64.7	0.066	16	76.7	0.054	23	91.6	0.058	14	68.5	0.057	14	68.5	0.052	15	72.6	0.066
	2	14	68.5	0.064	15	72.6	0.056	16	76.7	0.066	16	76.7	0.048	11	57.6	0.057	34	141.6	0.030
	3	12	61.0	0.068	16	76.7	0.054	21	81.6	0.063	16	76.7	0.049	15	72.6	0.050	21	81.6	0.061
	4	1	0.0	0.0	1	0.0	0.0	21	81.6	0.063	1	0.0	0.0	1	0.0	0.0	15	72.6	0.066
	5	1	0.0	0.0	1	0.0	0.0	21	81.6	0.063	13	64.7	0.059	1	0.0	0.0	15	72.6	0.066
2	1	24	97.0	0.115	25	102.6	0.143	25	102.6	0.143	25	102.6	0.086	26	108.8	0.111	26	108.8	0.111
	2	24	97.0	0.115	25	102.6	0.143	25	102.6	0.143	31	119.3	0.075	24	97.0	0.126	12	61.0	0.172
	3	24	97.0	0.115	24	97.0	0.156	25	102.6	0.143	23	91.6	0.097	26	108.8	0.111	31	119.3	0.099
	4	26	108.8	0.103	33	134.0	0.105	33	134.0	0.105	26	108.8	0.080	26	108.8	0.111	32	126.3	0.089
	5	26	108.8	0.103	31	119.3	0.122	32	126.3	0.110	25	102.6	0.086	26	108.8	0.111	32	126.3	0.089
3	1	32	126.3	0.171	34	141.6	0.162	32	126.3	0.170	33	134.0	0.133	36	159.1	0.110	35	150.0	0.107
	2	32	126.3	0.171	34	141.6	0.162	32	126.3	0.178	31	119.3	0.154	33	134.0	0.145	24	97.0	0.195
	3	32	126.3	0.171	34	141.6	0.162	32	126.3	0.178	32	126.3	0.147	34	141.6	0.134	33	134.0	0.130
	4	36	159.1	0.116	36	159.1	0.138	36	159.1	0.122	35	150.0	0.107	42	178.6	0.089	35	150.0	0.107
	5	32	126.3	0.171	35	150.0	0.149	36	159.1	0.122	33	134.0	0.133	33	134.0	0.145	34	141.6	0.120
4	1	35	150.0	0.209	35	150.0	0.209	41	168.8	0.170	36	159.1	0.153	41	168.8	0.131	43	189.1	0.106
	2	35	150.0	0.209	35	150.0	0.209	33	134.0	0.246	34	141.6	0.184	34	141.6	0.183	26	108.8	0.257
	3	35	150.0	0.209	35	150.0	0.209	41	168.8	0.170	36	159.1	0.153	35	150.0	0.165	41	168.8	0.131
	4	43	189.1	0.131	43	189.1	0.127	42	178.6	0.149	36	159.1	0.153	42	178.6	0.116	35	150.0	0.167
	5	42	178.6	0.149	42	178.6	0.145	41	168.8	0.170	36	159.1	0.153	41	168.8	0.131	36	159.1	0.149
5	1	34	141.6	0.318	34	141.6	0.315	26	108.8	0.432	42	178.6	0.175	42	178.6	0.174	36	159.1	0.212
	2	33	134.0	0.344	32	126.3	0.368	25	102.6	0.458	35	150.0	0.242	34	141.6	0.265	35	150.0	0.234
	3	34	141.6	0.318	35	150.0	0.289	31	119.3	0.386	42	178.6	0.175	42	178.6	0.174	35	150.0	0.234
	4	35	150.0	0.292	35	150.0	0.289	32	126.3	0.360	41	168.8	0.195	41	168.8	0.193	34	141.6	0.257
	5	34	141.6	0.318	34	141.6	0.315	26	108.8	0.432	36	159.1	0.218	34	141.6	0.265	33	134.0	0.278

Figure 4-3. Frequency Resolved Versus Incident Modulation for One Frame

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The results are broken down into three columns for each reticle plate (PLT) corresponding to the three exposure sets (EXP) and into five rows, one for each of the five contrasts (CONT) of each exposure. Contrasts 1-5 of exposure 1 correspond to rows 1-5 of the target reticle; contrasts 1-5 of exposure 2 correspond to rows 6-10; contrasts 1-5 of exposure 3 correspond to rows 11-15.

Within each exposure/contrast group, the results of each of the five readers (RDR) are given in terms of the group/element (GE) resolved, the frequency (FREQ) corresponding to this GE, and the calculated incident modulation (IM) for that element of the image. Readers 1-3 were FEAT Lab personnel; readers 4 and 5 were the AFSPPF readers. A GE equal to 1 meant that the reader could not resolve any of the elements; a 0 meant that the reader had not examined that particular frame.

For each plate, the adjusted synch-flash measured smear (SMR) appropriate for the location and for the direction across the width of the tri-bars, is given in micrometers. The synch-flash smear was adjusted by multiplying it by the ratio of the exposure time to synch-flash intervals, assuming linear image motion. In all cases, the exposure time was 3.14ms and the SF interval was 1.78ms; the corresponding factor was therefore 1.76.

To analyze these results in terms of quality of system MTF, each of the approximately 140 frames for each plate were ranked (RNK). The ranking was according to the frequency (XFR) at which the system MTF (including smear perpendicular to tri-bar length) crossed the 0.1 level. For those cases for which this crossing frequency was greater than 280 cy/mm, XFR was listed as 281. These rankings were compiled and listed by plate (see Figure 4-4). Frames that had an XFR of 281 are ranked further according to the system MTF at this frequency MTF (XFR).

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RANK	XFR	MTF(XFR)	QCP	FDC	ERM	PLT	SMR
1	281	-100	77	20	4	54	1.06
2	275	-100	77	26	15	54	1.06
3	268	-100	77	26	12	54	1.23
4	258	-100	100	22	6	54	1.76
5	258	-100	100	26	13	54	1.58
6	239	-100	77	20	2	54	2.29
7	239	-100	77	20	7	54	2.29
8	239	-100	77	26	14	54	2.11
9	225	-100	100	22	5	54	2.64
10	223	-100	77	30	24	54	2.29
11	220	-100	77	36	30	54	0.70
12	218	-100	77	30	21	54	2.46
13	218	-100	77	30	23	54	2.46
14	218	-100	100	26	15	54	2.64
15	218	-100	100	26	17	54	2.64
16	218	-100	100	30	24	54	2.46
17	218	-100	102	26	16	54	2.64
18	213	-100	77	20	5	54	2.99
19	213	-100	100	26	12	54	2.82
20	212	-100	100	38	31	54	1.23
21	207	-100	102	26	13	54	2.99
22	200	-100	77	30	22	54	2.99
23	200	-100	100	22	2	54	3.34
24	191	-100	77	26	16	54	3.52
25	191	-100	77	38	35	54	2.29
26	191	-100	100	30	21	54	3.34
27	191	-100	102	26	12	54	3.52
28	186	-100	77	38	32	54	2.46
29	186	-100	77	38	34	54	2.46
30	182	-100	77	20	3	54	3.37
31	180	-100	100	30	22	54	3.70
32	180	-100	102	26	17	54	3.87
33	180	-100	104	30	23	54	3.70
34	173	-100	77	20	6	54	4.22
35	173	-100	77	38	33	54	3.17
36	169	-100	100	38	34	54	3.34
37	163	-100	100	22	4	54	4.58

Figure 4-4. Frames Ranked by System MTF

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From the mass of data available, selective groupings were made for analysis and curve fitting. One of the main purposes of this experiment was to determine the change in TM curve due to the variation in system MTF (including smear). To investigate these changes, curves were prepared for each of the reader groups using data points selected from groups of 10 frames, the groups corresponded to ranks 1-10, 11-20, etc. Figure 4.5 displays the data points used and the curve fits for readers No. 1 and 3,* and No. 4 and 5 for ranks 1-10 of plate 54.

Each page lists the data points used in the curve fit listed underneath. For the frames corresponding to each of the ten ranks, results for the three exposures were compared for the two readers for each of the four contrasts used. Since it was found that none of the three exposure columns consistently had the best results, a selective technique was used in the hope of getting the best of the three exposures available in each case. Data points from the exposure having the lowest incident modulation-to-frequency ratio were selected for each contrast.

In order to force the TM curve to go through the contrast 1 points, these points were weighted by a factor of 7 in the least-squares fit. Contrasts 1-4 were the only ones used. Contrast 5 data indicated an anomaly in that the resolved frequency was often less than that for the lower contrast 4. This was a clue to the fact that exposure may not have been close to optimum for any of the three exposures.

For each grouping of data points, the parameters of the least squares linear fit were calculated. (Note that the contrast 1 points were included 7 times in the curve fits.) A is the intercept of the curve with the TM axis, SIGMAA is the standard deviation on A, B is the slope of the TM curve, SIGMAB is the standard deviation on B, and R is the correlation coefficient.

* Reader 2 proved to be inconsistent with others and subsequent analyses do not include those readings.

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PLATE	CONTRAST	READER	RANK
54	1 - 4	1 3	1 - 10

64.7	0.058	68.5	0.056	68.5	0.059	72.6	0.057	76.7	0.053	76.7	0.053	76.7	0.068	81.6	0.063
81.6	0.064	81.6	0.064	81.6	0.066	81.6	0.066	81.6	0.066	81.6	0.066	81.6	0.054	86.5	0.054
91.4	0.057	91.4	0.057	91.4	0.058	91.4	0.061	91.4	0.061	97.0	0.115	97.0	0.115	102.6	0.105
102.6	0.143	102.6	0.144	108.8	0.112	108.8	0.112	108.8	0.130	108.8	0.141	119.3	0.116	119.3	0.121
119.3	0.122	119.3	0.128	119.3	0.128	119.3	0.132	119.3	0.132	119.3	0.198	126.3	0.124	126.3	0.124
134.0	0.112	134.0	0.160	134.0	0.166	134.0	0.175	134.0	0.175	134.0	0.175	134.0	0.189	141.6	0.152
141.6	0.161	141.6	0.162	141.6	0.162	141.6	0.165	141.6	0.165	141.6	0.186	141.6	0.201	141.6	0.201
141.6	0.213	141.6	0.227	141.6	0.235	150.0	0.146	150.0	0.146	150.0	0.161	150.0	0.162	150.0	0.162
150.0	0.175	150.0	0.235	159.1	0.172	159.1	0.186	159.1	0.206	159.1	0.223	168.8	0.166	168.8	0.170
168.8	0.170	168.8	0.183	168.8	0.184	168.8	0.184	168.8	0.192	168.8	0.196	168.8	0.196	178.6	0.188

A --6499E-01 SIGMAA =0.5003E-02 B =0.1586E-02 SIGMAB =0.4888E-04 R =0.9175E 00

PLATE	CONTRAST	READER	RANK
54	1 - 4	4 5	1 - 10

61.0	0.073	81.6	0.063	81.6	0.063	81.6	0.066	86.5	0.054	86.5	0.055	86.5	0.058	86.5	0.058
91.4	0.057	97.0	0.053	97.0	0.053	97.0	0.057	97.0	0.057	97.0	0.057	97.0	0.052	102.6	0.052
102.6	0.054	102.6	0.056	108.8	0.098	108.8	0.130	108.8	0.134	119.3	0.128	126.3	0.104	126.3	0.104
126.3	0.110	126.3	0.116	126.3	0.121	134.0	0.105	134.0	0.107	134.0	0.107	134.0	0.168	134.0	0.168
141.6	0.101	141.6	0.111	141.6	0.137	150.0	0.105	150.0	0.150	159.1	0.084	159.1	0.105	159.1	0.105
159.1	0.121	159.1	0.121	159.1	0.121	159.1	0.131	159.1	0.131	159.1	0.136	159.1	0.172	159.1	0.172
168.8	0.113	168.8	0.126	168.8	0.155	168.8	0.184	178.6	0.102	178.6	0.114	178.6	0.145	178.6	0.145
178.6	0.164	189.1	0.055	189.1	0.084	189.1	0.103	189.1	0.109	189.1	0.126	189.1	0.126	189.1	0.126
189.1	0.131	189.1	0.131	189.1	0.155	189.1	0.155	200.9	0.130	200.9	0.130	212.8	0.115	226.1	0.115

A --1800E-02 SIGMAA =0.4947E-02 B =0.7090E-03 SIGMAB =0.4200E-04 R =0.7846E 00

Figure 4-5. Data Points and Curve Fits

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Figures 4-6 to -13 show the results of these fits plotted by plate and reader group. Curve number 1 is a plot of the fit to data from ranks 1-10, curve 2 from ranks 11-20, etc. In addition, the dashed lines represent a plot of the curves corresponding to curve 1 parameters $\pm 2\sigma$; i.e., $A \pm 2 \text{ SIGMA}_A$, $B \pm 2 \text{ SIGMA}_B$. These give a good indication of the spread in the data points for curve 1.

In Figure 4-14, the TM curve published by the FEAT Lab for optimum exposure is shown. It is apparent from comparison of the SN-012 curves with the FEAT curve that any attempt to have predicted the results of this study using the optimum curve would have failed.

According to Schade's theory, there are three possible explanations for the disagreement between the curves: difference in imaging optics, different signal-to-noise requirements for the different readers, and different conditions resulting from exposure/development differences. As is demonstrated in Appendix A, a ratio of 1.4 between modulation requirements would call for an extreme difference in system MTF for the two cases. Figure 4-15 is a plot of the MTF of the optics used to produce the FEAT TM curve plotted alongside the infocus case for SN-012 plate 54. Both curves were multiplied by 0.33 so that they could be plotted on the same scale as the TM curves. A comparison of the two shows that the differences are not large enough to explain the observed differences in their TM curves.

The readers that were used to produce the FEAT TM curve were not the same as readers 1-3 in this experiment. To determine whether reader differences could explain these results, a limited number of frames of plate 52 were read by one of the readers used previously to prepare the FEAT TM curve. The results of this test demonstrated good agreement with SN-012 readers.

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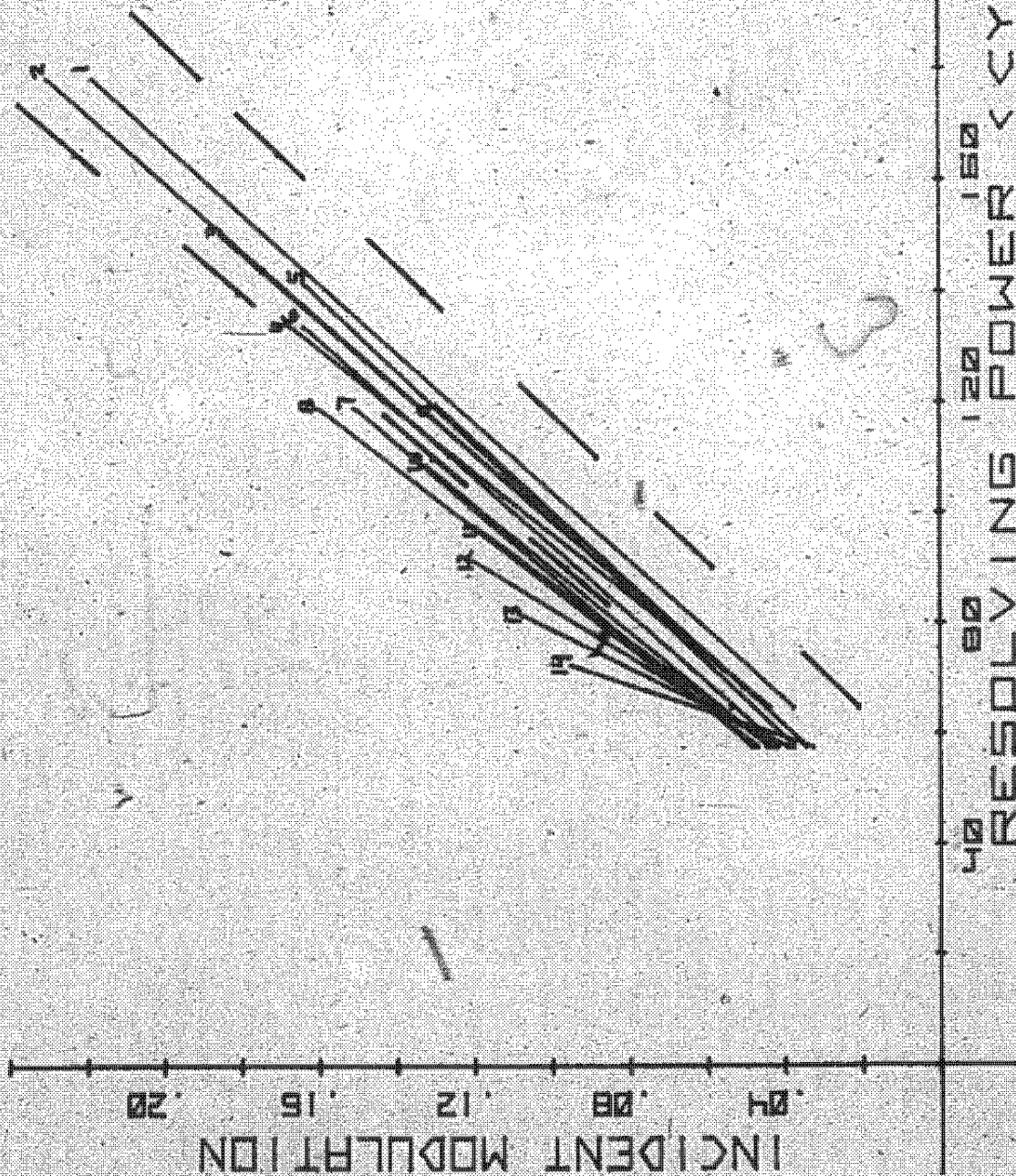


Figure 4-6. Fit of Data from Various Ranks (1-10, 11-20, etc)
Plotted for Plate 54 and Readers 1 and 3

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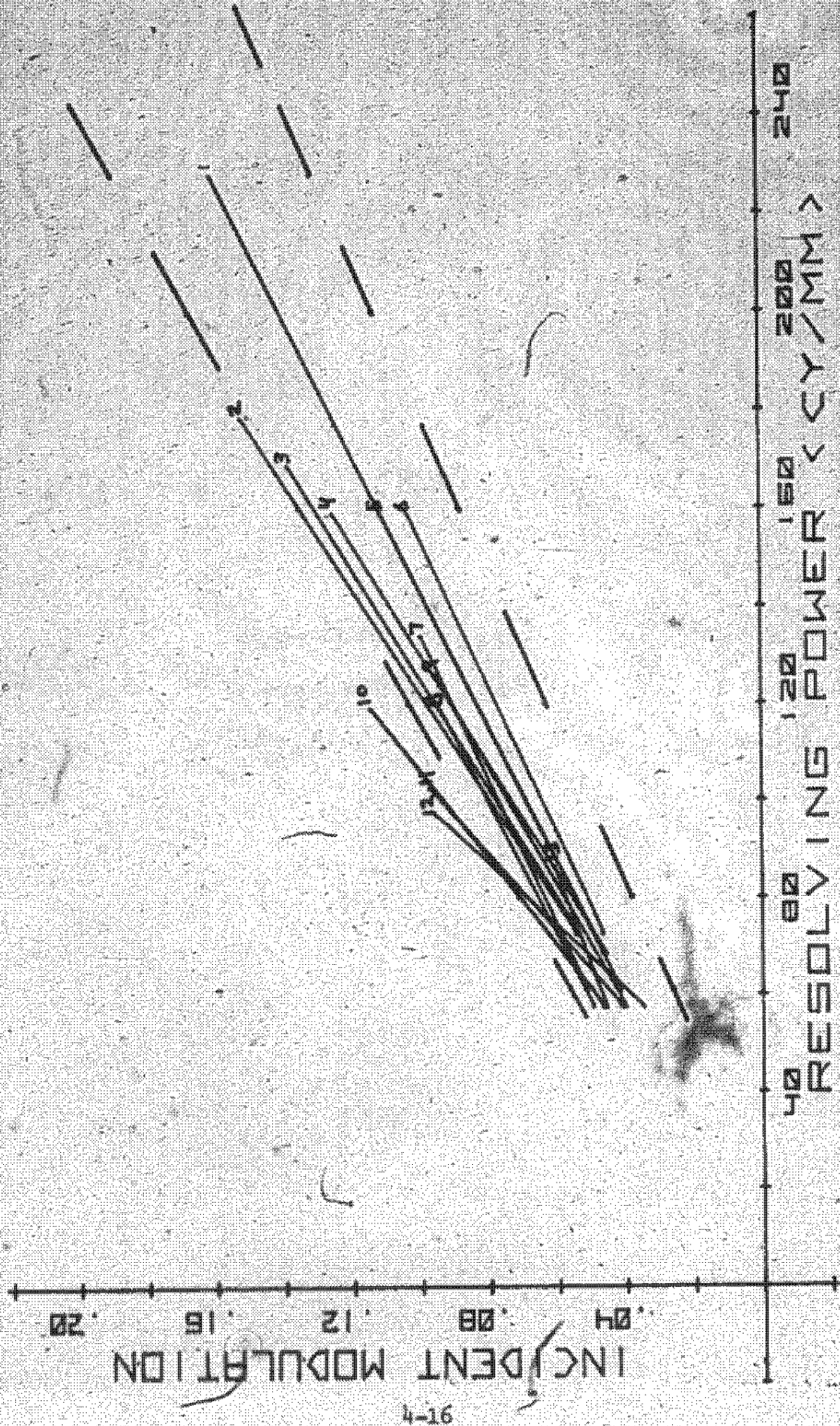


Figure 4-7. Fit of Data from Various Ranks (1-10, 11-20, etc)
Plotted for Plate 54 and Readers 4 and 5

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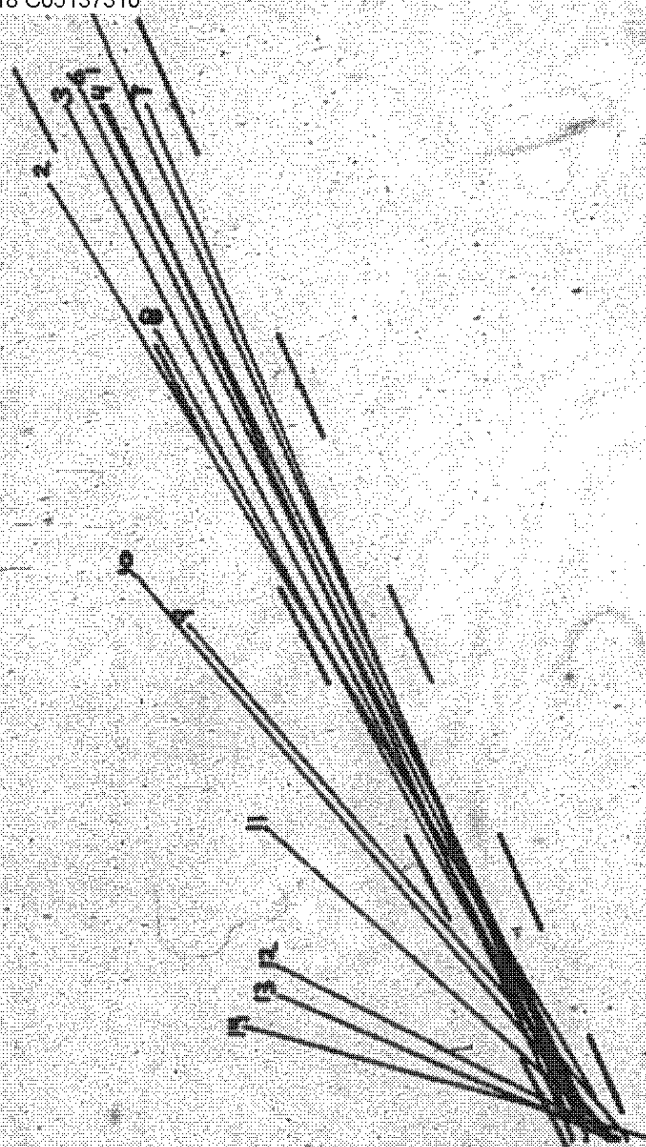
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Figure 4-8. Fit of Data from Various Ranks (1-10, 11-20, etc.)
Plotted for Plate 52 and Readers 1 and 3

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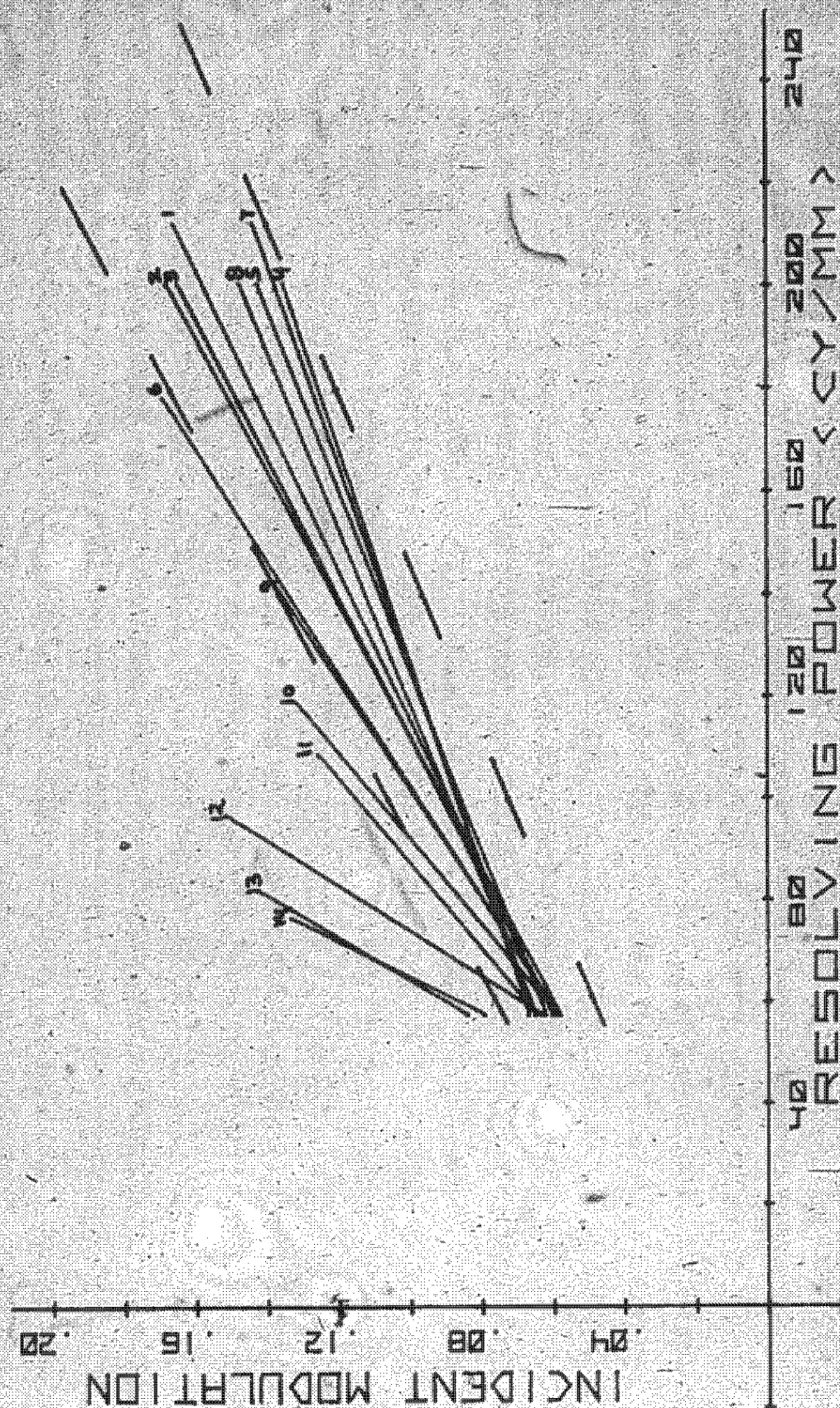


Figure 4-9. Fit of Data from Various Ranks (1-10, 11-20, etc)
 Plotted for Plate 52 and Readers 4 and 5

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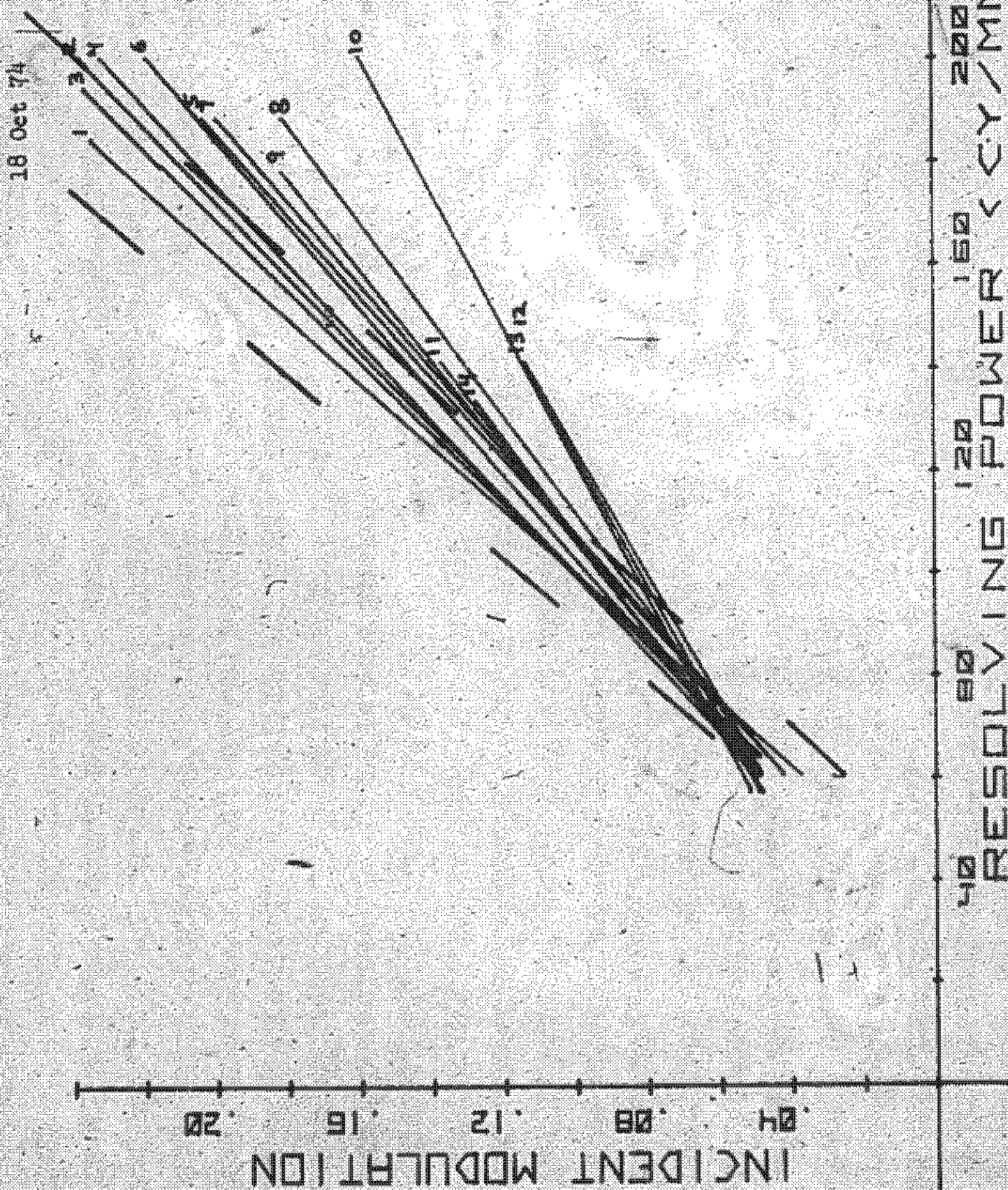


Figure 4-10. Fit of Data from Various Ranks (1-10, 11-20, etc)
 Plotted for Plate 51 and Readers 1 and 3

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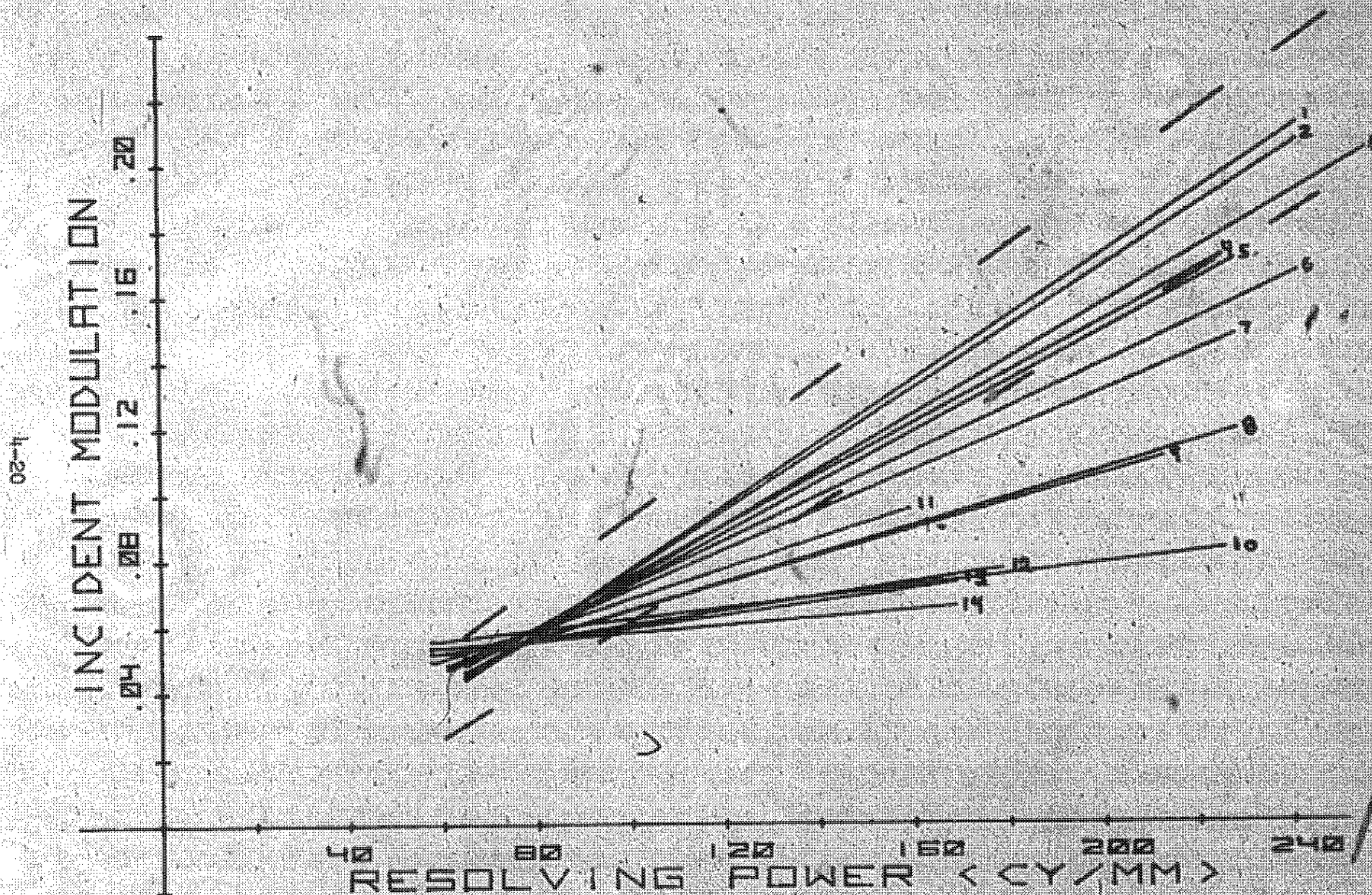


Figure 4-11. Fit of Data from Various Ranks (1-10, 11-20, etc)
 Plotted for Plate 51 and Readers 4 and 5

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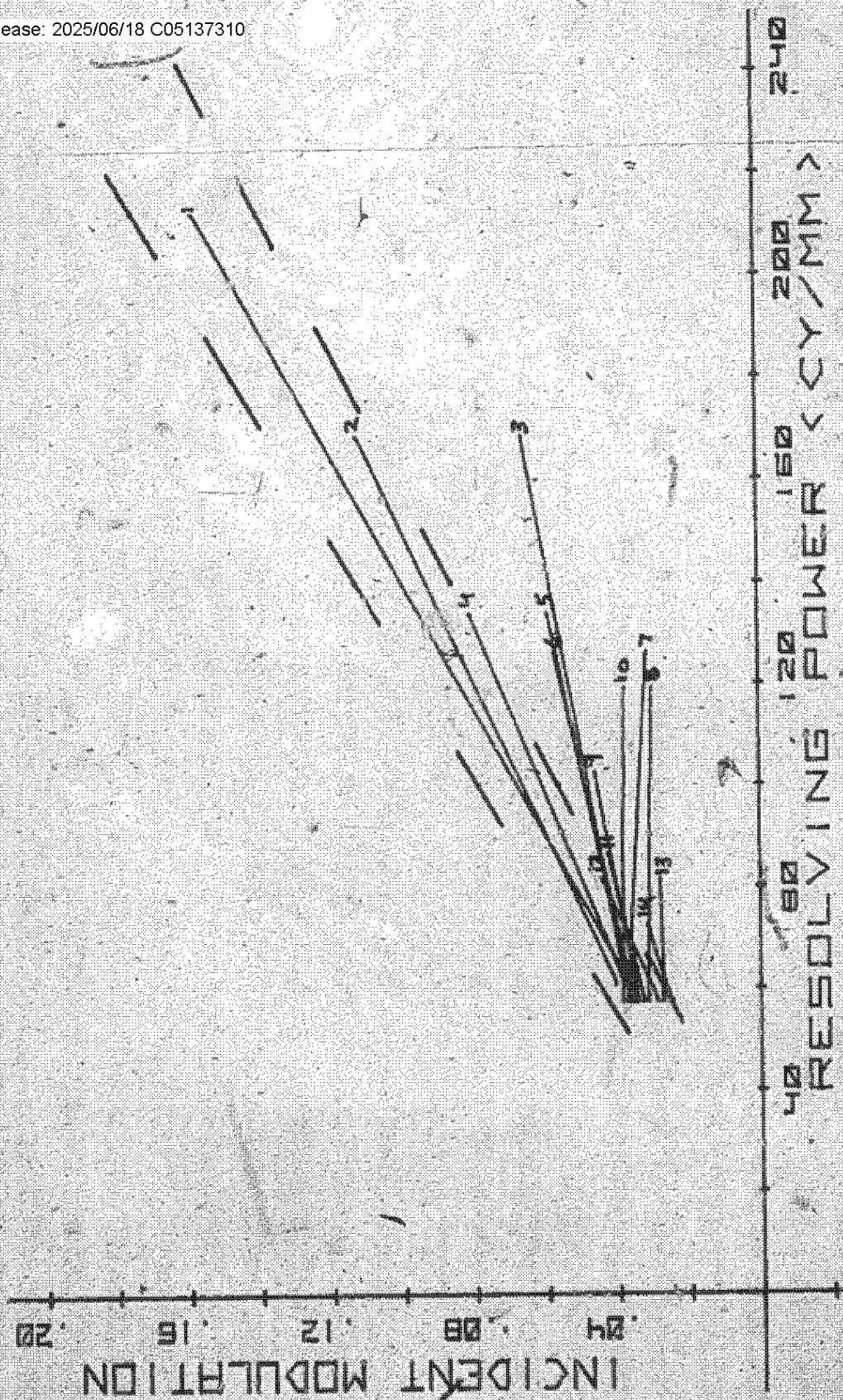


Figure 4-12. Fit of Data from Various Ranks (1-10, 11-20, etc.)
 Plotted for Plate 55 and Readers 1 and 3

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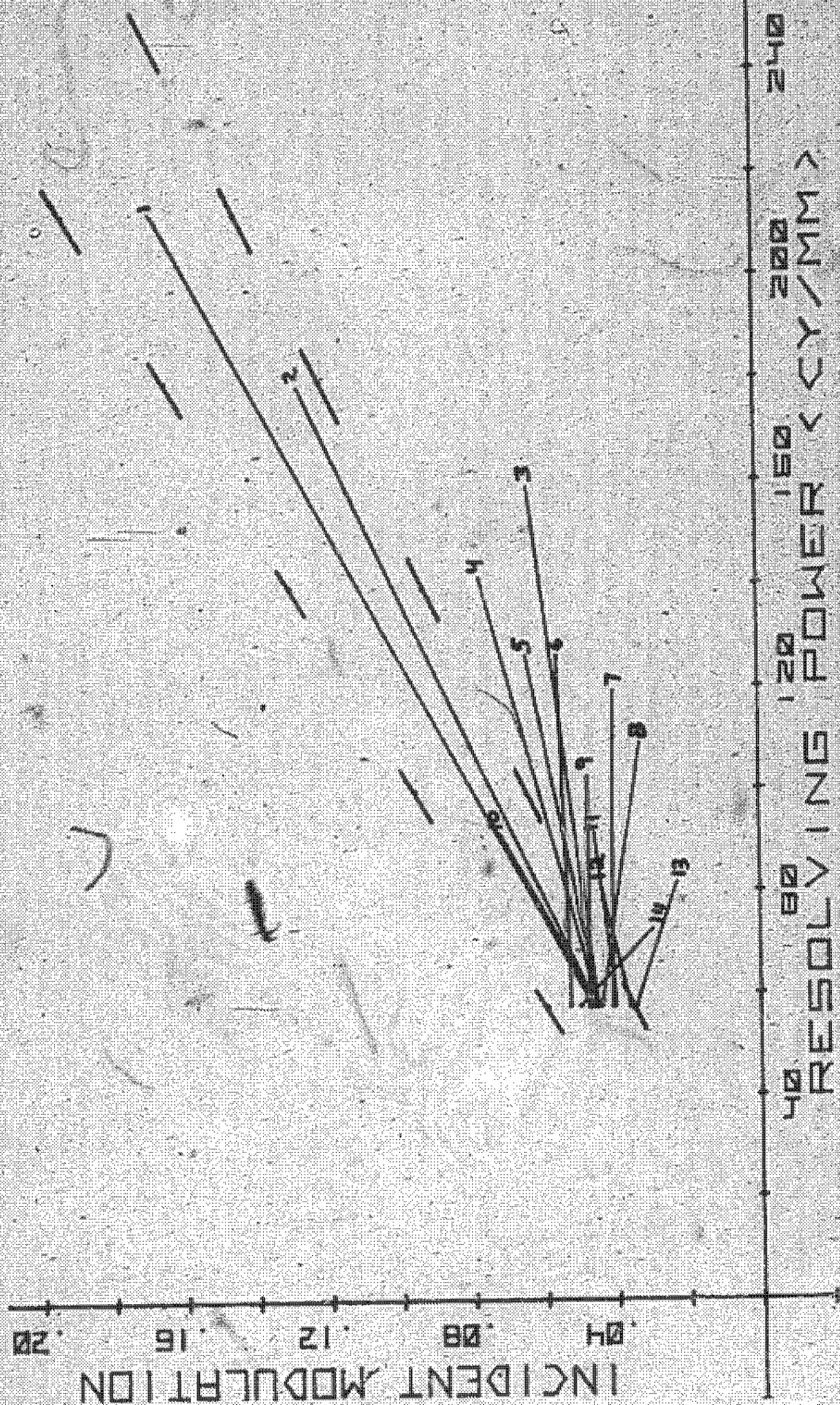


Figure 4-13. Fit of Data from Various Banks (1-10, 11-20, etc)
 Plotted for Plate 55 and Readers 4 and 5

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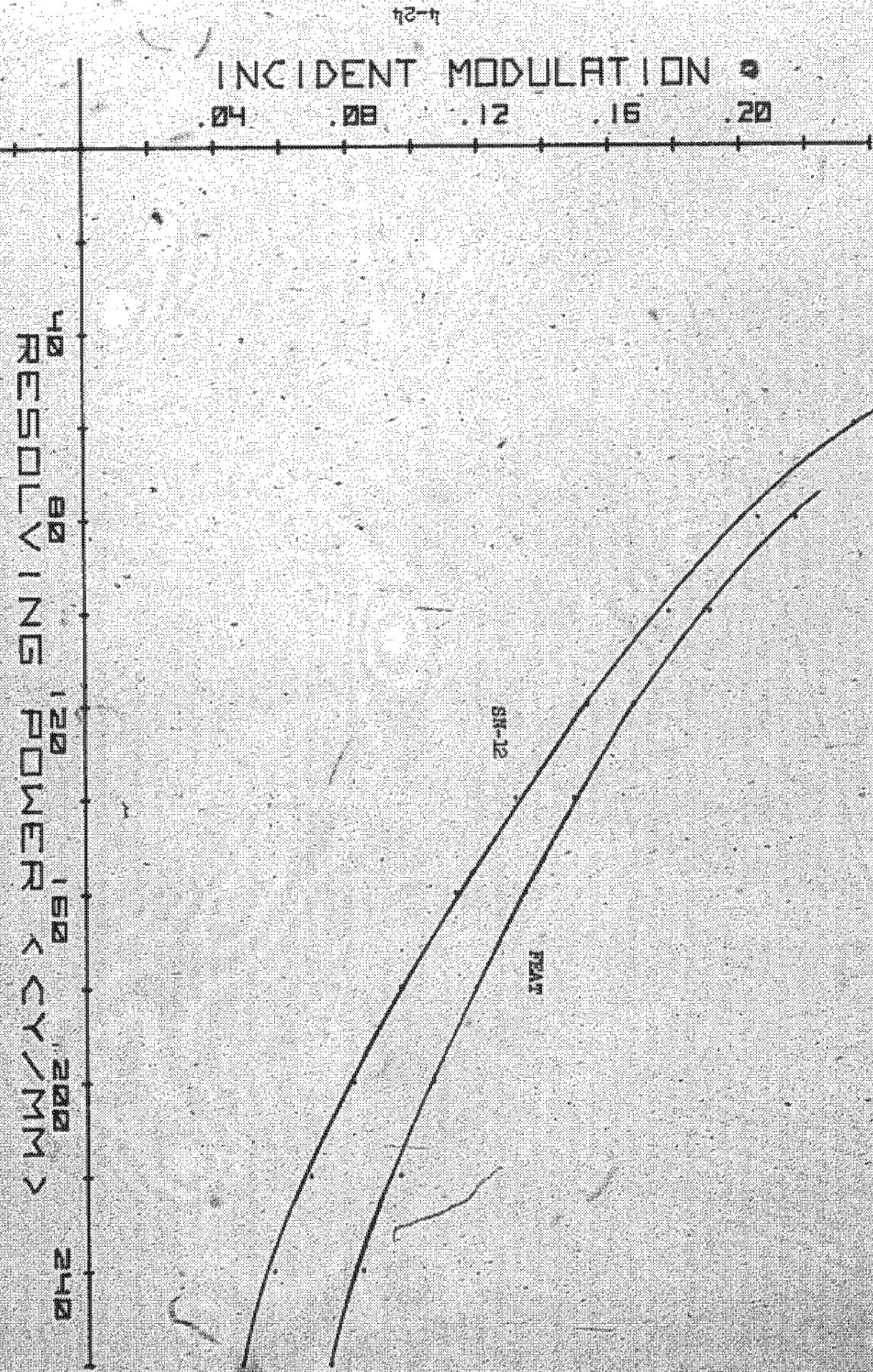
Figure 4-14. The FEAT Lab's TM Curve for Optimum Exposure

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Figure 4-15. Comparison of the Optics Used to Produce the
FEAT Lab Curve and the SN-012 Curve

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Elimination of the imaging optics and reader differences leaves the possibility that exposure/development conditions may not have been optimal. In Table 4-1, the TM curve parameters for curve number 1 of each of the plate/reader groups of the SN-012 experiment are compared with the FEAT Lab TM curves for optimum and non-optimum conditions. Figures 4-16 and 4-17 are plots of the TM curves compared in Table 4-1. It can be seen that underexposure by approximately 0.35 log E results in TM curves similar to those found in the SN-012 study. The even steeper curves, 7 and 8, were the in-track results for the FEAT Lab readers. It has not been determined why these curves differ from the other six so dramatically.

Figures 4-18 through -20 are FEAT Lab data sheets for the film/development combination used in this experiment. Figure 4-18 shows the variation in resolving power with exposure for tri-bar targets at several contrasts. It can be seen from the H&D curve given on this plot that optimum resolution apparently occurs at densities of approximately 1.5.

Microdensitometric scans of one of the FEAT Lab images used to produce the above results for 1.7:1 contrast showed that the average density was approximately 1.3 for the optimum resolution condition.

To investigate whether the SN-012 tri-bar imagery suffered from non-optimum exposure, microdensitometric scans were made. For each of the four plates, scans were made of each of the 15 rows with a 2 micrometer spot. The scan direction was across the tri-bar elements from lowest to highest frequency. In addition, the H&D curve corresponding to this imagery was also scanned to obtain a chart scale-density calibration.

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TABLE 4-1
TM CURVE COMPARISONAIM AS A FUNCTION OF FREQUENCY
(CY/MIN)

CURVE	DIRECTION	PLATE *	HDPS	INTCP	SLOPE	80	120	160	200
1	IT	52	1+3	7.1E-3	6.6E-4	6.0E-2	8.6E-2	1.13E-1	1.39E-1
2	IT	54	4+5	-1.8E-3	7.1E-4	5.6E-2	8.4E-2	1.12E-1	1.40E-1
3	XT	55	1+3	-1.1E-2	7.9E-4	5.2E-2	8.4E-2	1.15E-1	1.47E-1
4	XT	55	4+5	1.9E-3	7.8E-4	6.4E-2	9.6E-2	1.27E-1	1.58E-1
5	XT	52	4+5	2.2E-2	6.8E-4	7.6E-2	10.4E-2	1.31E-1	1.58E-1
6	IT	51	4+5	-1.7E-2	9.4E-4	5.8E-2	9.6E-2	1.33E-1	1.71E-1
7	IT	54	1+3	-6.5E-2	1.6E-3	6.3E-2	12.7E-2	1.91E-1	2.55E-1
8	IT	51	1+3	-6.0E-2	1.6E-3	6.8E-2	13.2E-2	1.96E-1	2.60E-1
A	OPTIMUM			1.7E-2	3.7E-4	4.7E-2	6.1E-2	0.76E-1	0.91E-1
B	-.3 LOG E			1.1E-2	5.4E-4	5.4E-2	7.6E-2	0.97E-1	1.19E-1
C	-.35 LOG E			1.6E-2	3.9E-4 ²	4.1E-2	7.2E-2	1.16E-1	1.72E-1
D	-.4 LOG E			1.2E-2	5.0E-4 ²	4.4E-2	8.4E-2	1.24E-1	2.12E-1

- * Plates 52 and 54: FWD Camera
Plates 55 and 51: AFT Camera

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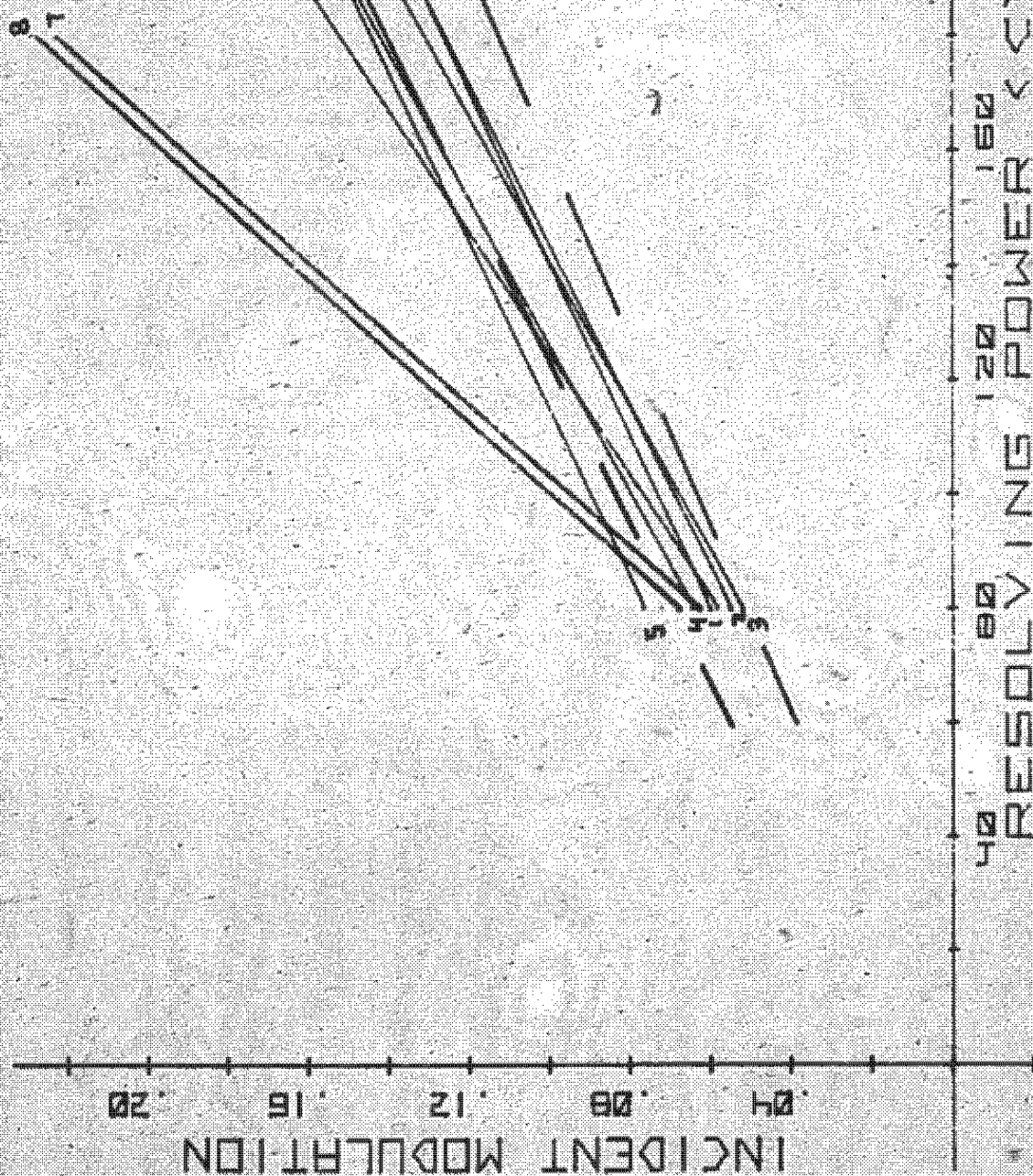


Figure 4-16. Graph of the Curve-Fit Coefficients in Table 4-1

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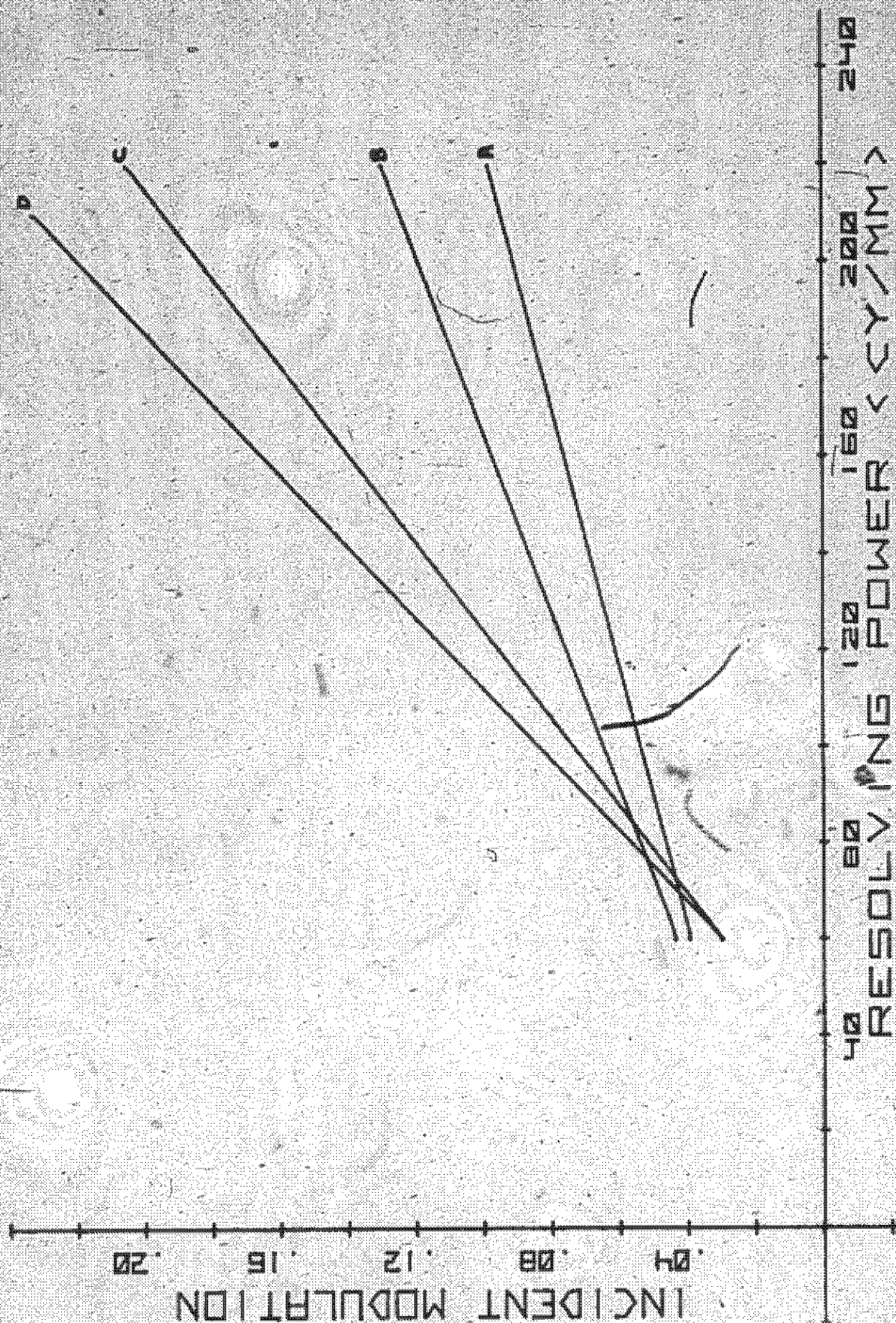


Figure 4-17. Graph of the Curve-Fit Coefficients in Table 4-1 (Continued)

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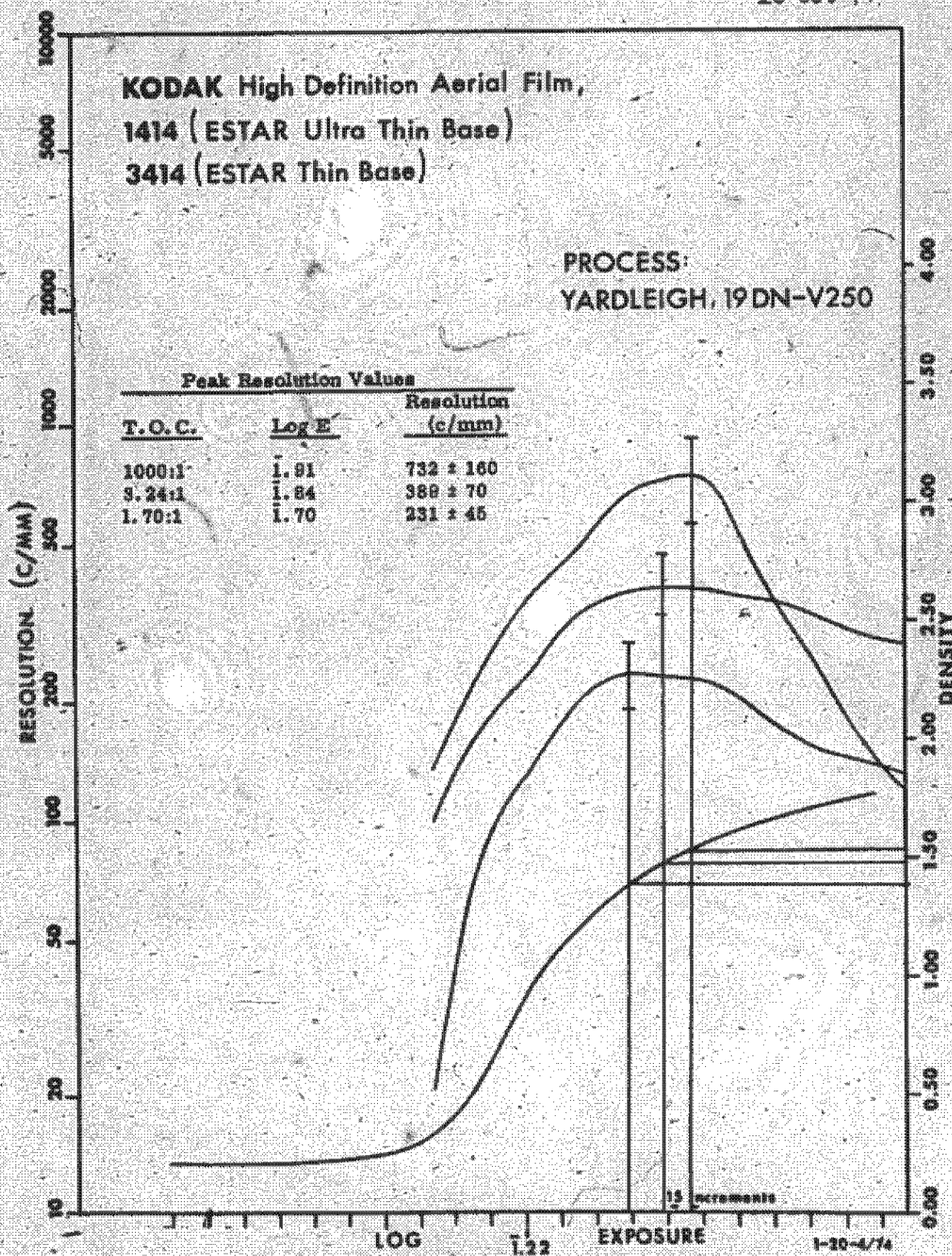


Figure 4-18. FEAT Lab Data Sheet for KODAK High Definition Aerial Film, Sheet 1

4-29

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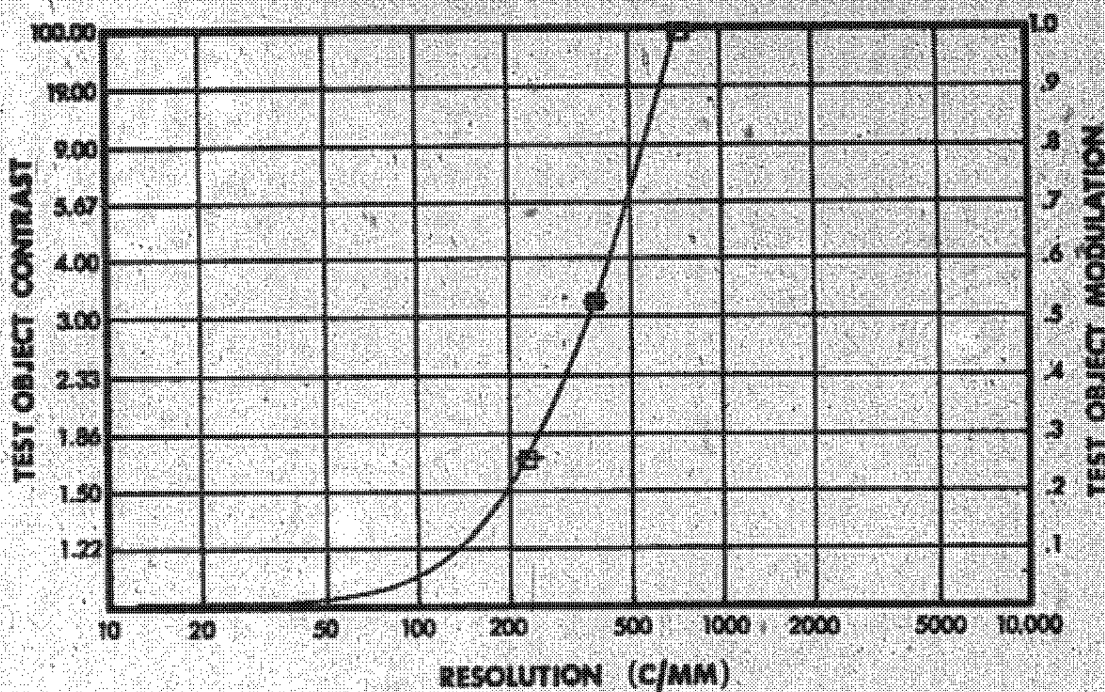
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TEST OBJECT CONTRAST vs RESOLUTION

1414/3414 YARDLEIGH, 19DN-V250

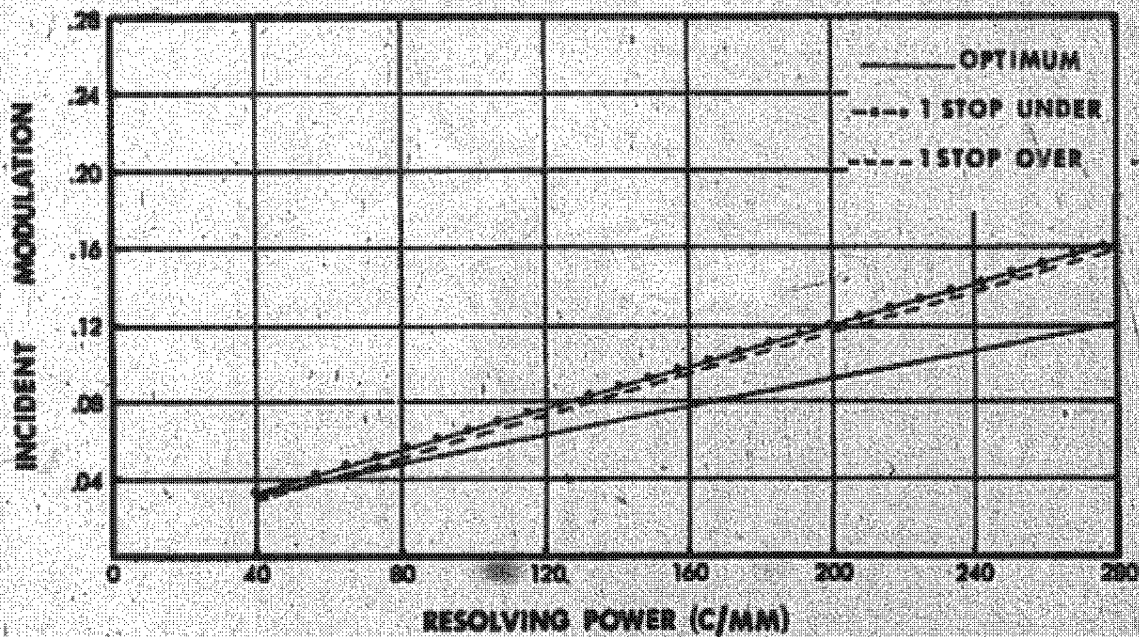
THRESHOLD MODULATION

Figure 4-19. FEAT Lab Data Sheet for KODAK High Definition Aerial Film, Sheet 2

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1414/3414 YARDLEIGH, 19DN-V250

Exposure Series	Resolving Power (c/mm)		
	± 2 Sigma		
	1000:1	3.24:1	1.70:1
OVER	116±15	272±65	127±30
	160±35	289±75	138±45
	257±105	327±65	150±25
	392±95	354±75	181±45
	676±175	370±70	215±55
	724±160	389±70	226±50
	643±105	366±80	229±45
	469±100	320±70	190±50
	354±85	226±60	128±35
	237±55	166±30	76±25
UNDER	132±50	98±30	20 --

→: Location of OPTIMUM EXPOSURE

Physical Dimensions	(Thickness)			
	1414		3414	
	Mils	μm	Mils	μm
Base	1.50	38.10	2.50	63.50
Emulsion	0.25	6.35	0.25	6.35
Dyed Gel Backing	0.23	5.84	0.24	6.10
Total Thickness	1.98	50.29	2.99	75.95

Step No.	Sensitometric Curve	
	Absolute Log E	Density ±2 Sigma
01	0.76	1.78±.01
02	0.80	1.74
03	0.47	1.70
04	0.30	1.68
05	0.16	1.61
06	0.00	1.55
07	1.84	1.48
08	1.70	1.38
09	1.54	1.28
10	1.38	1.12
11	1.22	0.90
12	1.08	0.61
13	2.82	0.41
14	2.77	0.30
15	2.62	0.25
16	2.46	0.22
17	2.30	0.22
18	2.14	0.22
19	2.00	0.21
20	3.82	0.21
21	3.67	0.21

Exposure Condition
I-B Sensitometer: Daylight.
1/25 Second

Threshold Modulation	
Incident Modulation	Resolving Power (c/mm)
Optimum Exposure	(±2 Sigma)
0.116	253±42
0.102	208±16
0.089	191±18
0.072	141±28
0.059	128±21
0.052	78±9
0.037	45±6

Optimum: $TM = 0.017 \pm 3.7 \times 10^{-4} f$
 Over: $TM = 0.008 \pm 5.4 \times 10^{-4} f$
 Under: $TM = 0.011 \pm 5.4 \times 10^{-4} f$

Halation Coefficient: 1.45

RMS Granularity

At 1.0 net density 2.0 μm - 103.1
 12.7 μm - 16.3

Effective Aerial Film Speed: 14.7

(3/2 E at 0.30 Density above Gross Fog)

Figure 4-20. FEAT Lab Data Sheet for KODAK High Definition Aerial Film, Sheet 3

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Figure 4-21 is a copy of the scan of row 5 of the plate 55 image for OCP 77, frame 21. This frame was chosen because of its relatively small image motion. The fall in average density for higher frequencies was very peculiar. Because the target nominally had 95 percent modulation, the predicted resolution was quite high. However, at the range of expected resolution, the average density had fallen causing the target to be much underexposed. It therefore had a much lower resolved frequency.

Similar phenomena were found for the other images corresponding to the high-contrast rows of the four plates. The effect was in fact most pronounced for the high-contrast rows and diminished until it was slight for the 10 percent modulation rows. However, in addition to the peculiar shapes found, the general level of density was found to vary considerably for corresponding rows of different plates.

Since it was not expected that the peculiar results found could be due to the SN-012 system, the quality of reticles themselves was questioned. Subsequent consultation with the people who made the reticles confirmed the fact that they were of poor quality. The degradation with frequency was apparently caused by high flare light—a result of the technique used in producing them.

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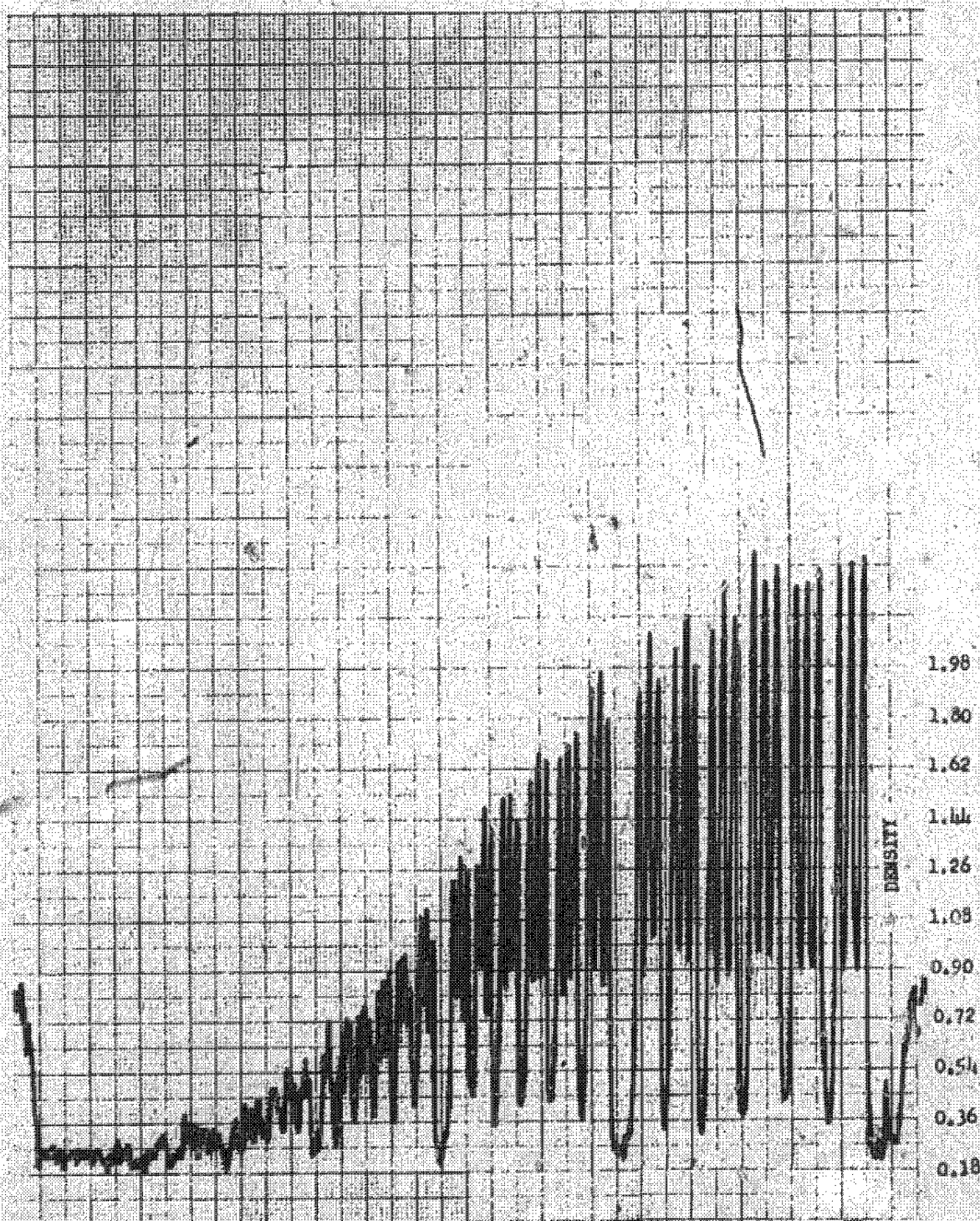


Figure 4-21. Scan of Row 5 of the Plate 55 Image.
for OCP 77, Frame 21

4-33

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SECTION 5

FOCUS ASSESSMENT EXPERIMENT

Conversations with the PFA chairman and representatives of the sensor subcontractor resulted in a request for support work for focus assessment for the 1200-series via power spectral analysis. It was agreed that an off-line experiment on 1208-1 would be performed as an effort under this PAR, which would be consistent with the task to evaluate power spectral analysis vice VEM for focus evaluation.

The Eikonix Power Spectrum Analyzer was the instrument used to collect the data. Table 5-1 below indicates the material utilized.

TABLE 5-1
IMAGERY UTILIZED FOR FOCUS WORK ON 1208-1

<u>Operation</u>	<u>Frame</u>	<u>Camera</u>	<u>Platen Position</u>	<u>Scan Angle (Degrees)</u>
114	4	FWD	+16	+15
114	5	FWD	+ 8	+15
114	6	FWD	0	+14
114	7	FWD	- 8	+14
54	11	FWD	-16	+ 1
14	2	AFT	+16	+ 1
14	3	AFT	+ 8	+ 1
54	9	AFT	0	+15
114	7	AFT	- 8	+15
54	13	AFT	-16	+ 3

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Data was taken at eleven positions across the format at half-inch intervals. Four spectra were derived at each position and averaged. Data was restricted to plus or minus three degrees from the nominal scan angle listed in Table 5-1. A frequency of peak information was derived for each position. The average frequency of peak information for each frame was then plotted against platen position. The results are shown in Figures 5-1 and -2. Only one result appeared anomalous; namely, the zero platen position on the AFT camera. Another frame (OP 14, FR 4) which was not much better from a detailed structure standpoint, was substituted, with the indicated results.

Subsequent discussions of these results with the sensor subcontractor, the program office, and a representative of Bldg 213 resulted in a recommendation to implement this technique of focus assessment on 1209 as a routine operation for generating additional information for the PFA on this difficult task.

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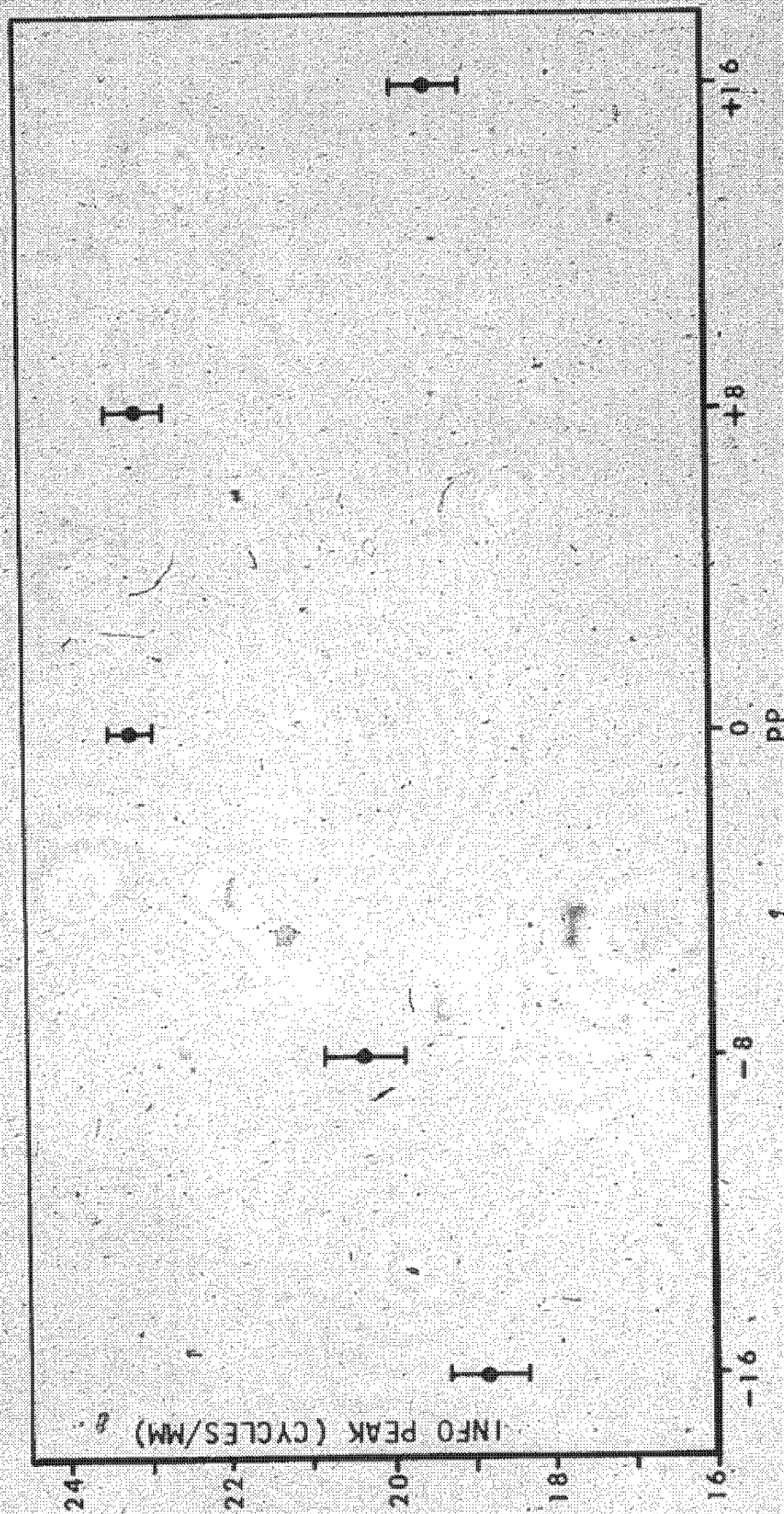


Figure 5-1. 1208-1 FWD Camera, 11 Positions for Each Frame Averaged

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PAR 25-3-85/RL
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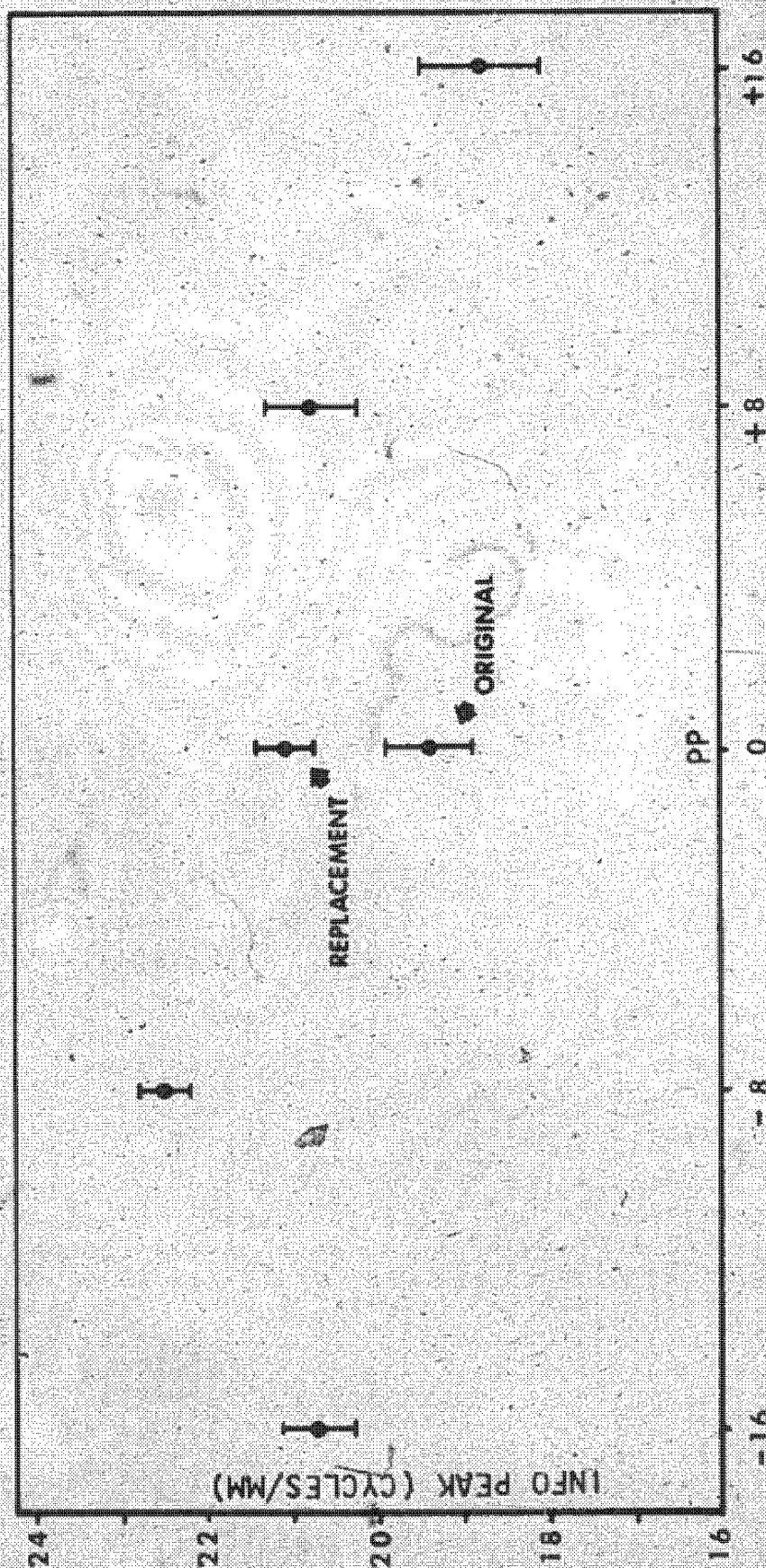


Figure 5-2. 1208-1 APT Camera, 11 Positions Averaged

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APPENDIX A

DISCUSSION OF EQUATION RELATING THE
SIGNAL-TO-NOISE RATIO OF THE TRI-BAR IMAGE
TO ITS FREQUENCY

Dr. Otto Schade uses the optical system and film parameters to derive the following equation relating signal-to-noise ratio of the tri-bar image to its frequency, as follows.

The equation for tri-bar objects with a 5:1 aspect ratio is:

$$[R]_N = [R]_1 \gamma \beta 1/N (25/b)^{1/2} (\Delta \bar{I}_0 / \bar{I}_0) r_{\Delta W}(w) \quad (1)$$

$$b = [25 + (N/N_{e(s)L})^2]^{1/2}$$

Where:

N is the line number of the target in line/mm at film

$N = 2 * f$ where f is the frequency in cy/mm

$[R]_N$ is the calculated signal-to-noise ratio for one bar at line number N

$[R]_1$ is the measured signal-to-noise ratio of a flat patch of the film of unit area exposed at a level equal to the mean exposure $\bar{I}_1$ of the image bar-space

γ is the measured point gamma - slope of the H&D curve at point corresponding to $\bar{I}_1$

β is a correction factor for the fact that film noise is not "white" noise; $\beta = 1$ in our case

b is a geometrical factor due to the smearing of the bar image in its length direction, L

$N_{e(s)L}$ is the noise equivalent bandwidth of the system in length direction

A-1

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$$N_{e(s)L} = (MTF_{oL} * STF_L * MTF_e)^2 \Delta N \quad (2)$$

Where:

MTF_{oL} is the optics MTF in length direction

STF_L is the smear transfer function along L

MTF_e is the emulsion MTF

$\Delta I_o / \bar{I}_o$ is the $I_{max} - I_{min} / [(I_{max} + I_{min})/2]$ for the object; hence it equals 2 times the object modulation M_o

$r_{\Delta y(w)}$ is the square wave transfer factor for the entire system in the width direction of the bars - w

It is proportional to the product of the sine wave MTF's of the components of the system in the width direction

$$r_{\Delta y(w)} = k * MTF_{ow} * STF_w * MTF_e$$

According to Schade, the proportionality factor k is approximately 0.81.

A-2

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In order to detect the image, its signal-to-noise ratio $[R]_N$ must be equal to or greater than some threshold K . Schade has found K to have a value of approximately 3.8. The threshold, of course, varies somewhat from reader to reader depending on their experience and other psycho-physiological factors.

By substituting K for $[R]_N$ and by regrouping terms, we may arrive at an equation that relates the aerial image modulation (aim) required to resolve a target to the line number N . The aerial image modulation is equal to the product of the target modulation, the optics MTF across the bars, and the smear transfer factor across the bars, that is:

$$\text{aim} = \frac{1}{2} * \Delta \bar{I}_0 / \bar{I}_0 * \text{MTF}_{\text{ow}} * \text{STF}_w$$

Hence, two of the factors are removed from the $r_{\Delta V(w)}$ term.

$$K = [R]_1 \dot{\gamma} \beta 1/N (25/b)^{1/2} 2[\frac{1}{2} \Delta \bar{I}_0 / \bar{I}_0 \text{MTF}_{\text{ow}} \text{STF}_w] k \text{MTF}_e(N)$$

By isolating the aim term on one side, we arrive at

$$\text{aim} = [K/(10k[R]_1 \dot{\gamma} \beta \text{MTF}_e(N))] [25 + (N/N_{e(s)L})^2]^{1/2} N \quad (3)$$

Examination of this equation shows that it is similar to the straight-line fit of the laboratory-produced TM curve: $\text{aim} = a + bf$ for those frequencies for which $bf > a$, and for which $N_{e(s)L} > N$ (and $\text{MTF}_e(N)$ changes slowly with N).

The variation in aim required for a given frequency due to changes in system MTF in the length direction of the bars; i.e., due to image motion along the bars, is described by the geometrical factor b . In

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most cases, the effect of this term will not be large. As an example, we may calculate the ratio of aim required for two extreme cases. Suppose $N_e(s)_1$ without image motion were equal to 200 lines/mm, and due to large motion along the bars, was reduced to 40 lines/mm. The ratio of aerial image modulation required for resolution of 400 lines/mm in these two cases, all other factors being the same, would be equal to the ratio of the two b factors. In this extreme case:

$$\text{aim}(1)/\text{aim}(2) = [25 + (400/40)^2]^{1/4} / [25 + (400/200)^2]^{1/4} = 1.44$$

Approximately 1.4 times as much aerial image modulation would be required to resolve the same 400 lines/mm target element.

The other factors in the Schade equation should not be overlooked. Both $\dot{\gamma}$ and $[R]_1$ contribute directly to the slope of the TM curve and are known to vary with exposure levels and development conditions. It is therefore not surprising that studies of resolving power versus exposure demonstrate significant effects.

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MAR 10, 1976