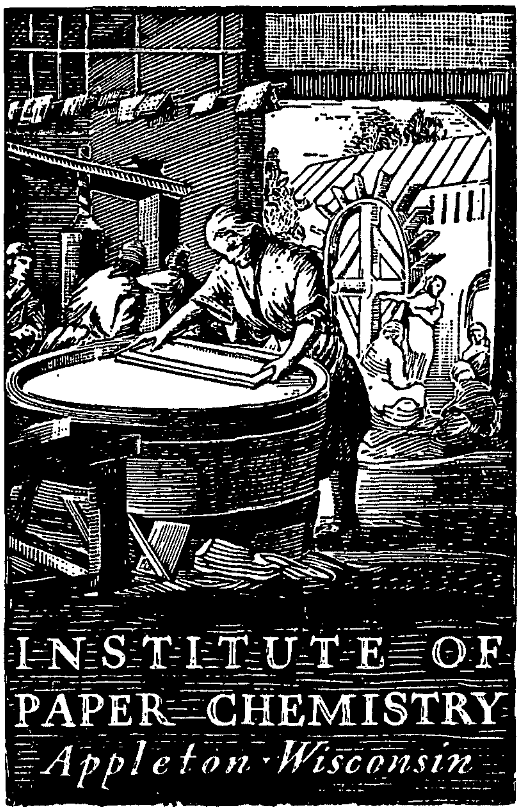

THE MEASUREMENT OF OPTICAL UNEVENNESS

Project 3270

Report Three
A Progress Report
to
MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

August 18, 1978

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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SUMMARY

Project 3270, Measurement of Optical Unevenness, has been completed with conversion of the research instrument to one which is suitable for use in routine measurements. The time-consuming operations of data logging, digitizing and subsequent calculation by computer have been eliminated. Computation now occurs in the instrument during scanning and a number proportional to the variance of the reflectance difference signal is displayed digitally.

Two different unevenness numbers are readily obtainable from the number displayed by the instrument. When the integrated reflectance variation is due to variable area of the high contrast elements of ink and paper, as with "rough" halftones or solids which tend to "break up," the standard deviation of the reflectance difference signal is clearly the preferred statistic. A number proportional to this standard deviation is easily obtained by extracting the square root of the number displayed by the instrument. Excellent correlation with visual assessment is obtained even when the samples vary in average darkness.

When the unevenness is truly at low contrast even over short distances, as in the mottle of coated unbleached board and the samples do not have the same average reflectance, it is desirable to express the variation on a visually uniform tone scale such as the Munsell value scale. This is well approximated by correcting the previously described unevenness number by the factor $(\log \bar{Y})/\bar{Y}$ where $\bar{Y}$ is the average luminous reflectance of the sample.

INTRODUCTION

Report One of this project described the development of the unevenness test instrument which detects the difference between the reflectance of a small spot along a scanning line and the average reflectance of the immediately surrounding area. This report also discussed some of the single number statistical descriptions of the detected variation which might be expected to correlate with visual assessments of unevenness.

Report Two described the evaluation of these statistical descriptions for use as unevenness numbers. The instrument output was recorded on magnetic tape and then digitized so the computer could be used to calculate the various statistics and these were correlated with the results of subjective evaluation of the samples by a panel of judges. Contrary to expectation, the standard deviation of the direct instrument output was found to correlate best with these visual evaluations.

The present report describes the completion of the project. The choice of unevenness number has been verified. The instrument has been provided with analog computation and direct digital read out of a number which is proportional to variance. Finally, the relationship of these numbers to previous data has been examined and new sample sets have been evaluated.

SELECTION OF THE UNEVENNESS NUMBER

Report Two describes the comparison of various statistical descriptions of instrumental unevenness data to subjective evenness values as a means of selecting the most useful statistic for use as an unevenness number. Correlation with the logarithm of the subjective evenness was used as the criterion for selection. Although it does not change the statistic selected, it is now believed that correlation with the subjective value rather than its logarithm is preferable. Use of the logarithm was based on four experiments (two different subjective evaluations and two different instrument apertures) with a single set of letterpress halftone prints. The correlation coefficients with both the subjective values and their logarithms were shown in Table VI of Report Two. This set included one print which was very much more uneven than any of the others. The higher correlation coefficients with the logarithms are due almost entirely to this one sample. It is now believed that this is caused by the inability of the judges to assign proper values to a sample which differed so much from any other in the set. Subsequent experience with more closely spaced sample sets indicate that the instrumental values are more nearly linear with the subjective values rather than with the logarithms as is illustrated by the plots of gravure print data shown as Fig. 1. In some other cases the scatter of data does not permit a clear choice between the linear and logarithmic dependence. However, the logarithmic relationship is considered to be unlikely. Linear sensations are sometimes the result of a logarithmic stimulus but a logarithmic sensation due to a linear stimulus would be unusual.

It had been anticipated that the use of a visually uniform scale, such as the Munsell value ($\underline{V}$) or the Wyszecki lightness ($\underline{W}$) would be needed to properly describe unevenness in a set of samples which vary in average reflectance. In Report One it was shown that multiplication of the luminous reflectance variation

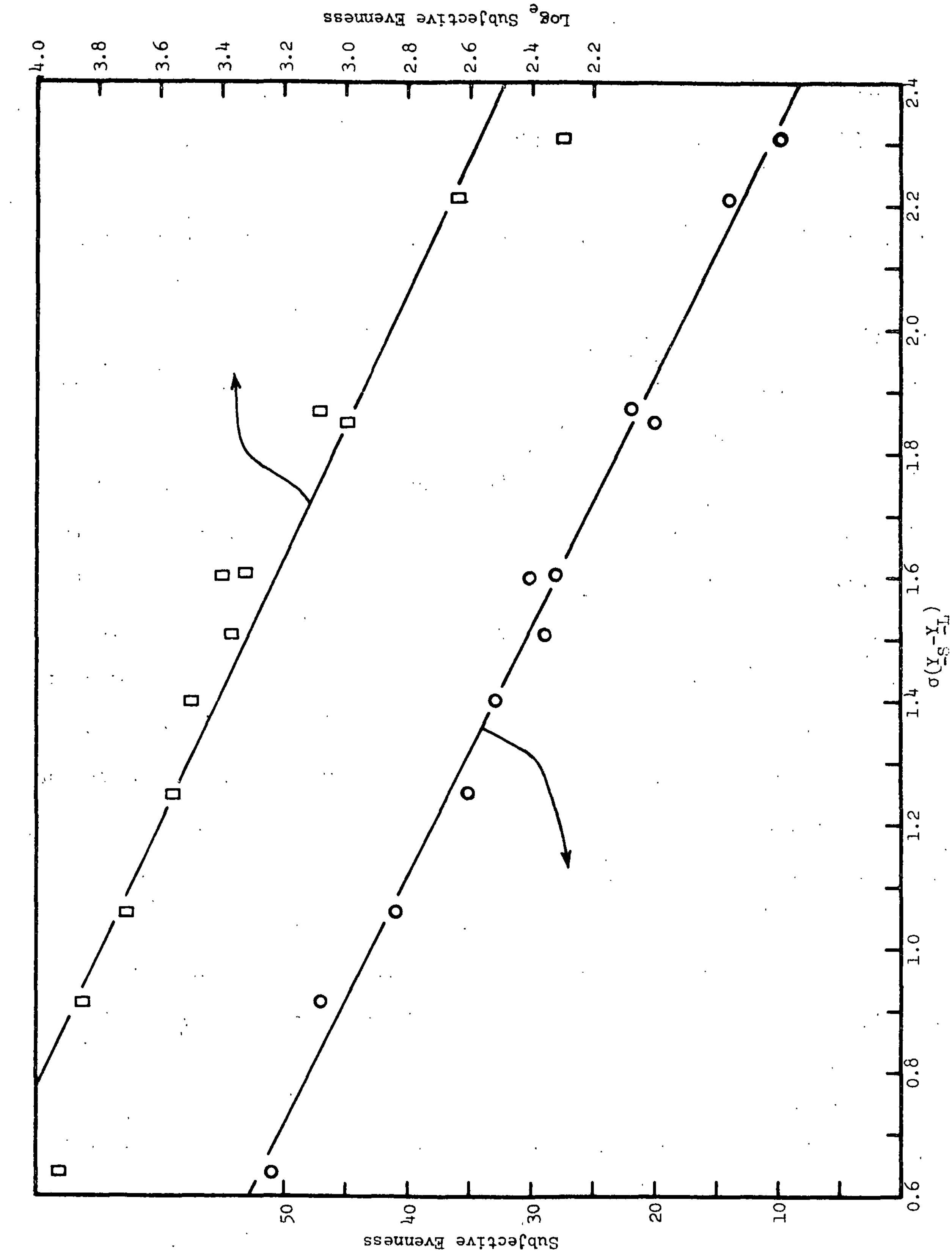


Figure 1. Standard Deviation of $Y_S - Y_L$ vs. Subjective Evenness and $\log_e$ Subjective Evenness for Gravure Prints of Report Two

by $(\log \overline{Y})/\overline{Y}$, as recommended by Makkonen and Nordman (1), approximates the use of the Munsell Value, V, when $V > 2$. In Report Two, experimental evidence was presented which shows that this procedure provides unevenness numbers which are substantially proportional to those obtained using the V or W scales. Parsons and Abson (2) have reported measurements made from them at 0°-0° viewing geometry for determination of gloss mottle. In this case, correlation coefficients with the logarithms of subjective evenness judgments of -0.94 were obtained for $\sigma(Y_S \cdot \log \overline{Y})/\overline{Y}$, σV_S and σW_S, as compared to -0.82 and -0.83 for $\sigma(Y_S - Y_L)$ and σY_S, respectively. However, the exact meaning of these unevenness numbers is somewhat clouded by the necessity of using an arbitrary reflectance standard (in this case glossy photographic paper) for calibration at the glare angle. For measurements at 45°-0° these unevenness numbers assume more precise meaning because a paper of known absolute diffuse reflectance is used for calibration.

The 45°-0° unevenness data for the set of gravure prints shown in Report Two give correlation coefficients of -0.96 or -0.97 with the logarithm of subjective evenness regardless of which of the five unevenness numbers is used. This result was not unexpected because these measures of unevenness should be equally useful when the samples are of uniform average reflectance. However, it was also shown in Report Two that either $\sigma(Y_S - Y_L)$ or σY_S graded the samples in a set of halftone letterpress prints of mixed darkness in essentially the same way as the logarithms of the subjective evaluations of a judging panel. Multiplication of σY_S by $(\log \overline{Y})/\overline{Y}$ to allow for the expected effect of darkness variation, or use of σV_S or σW_S resulted in lower correlation due to rating the darker samples as much too uneven. This result with the letterpress halftone prints was so unexpected that verification using carefully selected samples seemed necessary.

A large number of prints were made with black ink on a variety of papers using the Vandercook proof press. Two plates, one with approximately 20% and the other with about 50% printing area but both at 120 lines per inch, were used. Impression was varied to give a large population of prints which differed widely in visual evenness. From these a set of 10 light prints (20% printing area) and a set of 12 dark prints (50% printing area) were selected. Each set was subjectively graded for evenness. Each of the prints was then scanned with a 2-dot and then again with an 8-dot small aperture and the unevenness numbers obtained were correlated with the subjective values and their logarithms. Next, 7 samples were selected from each set to form a closely spaced set of 14 mixed light and dark samples and this new set was subjectively graded for evenness. Correlation coefficients for these new subjective values and their logarithms with the objective values were calculated. The portion of the variation that can be accounted for by a related quantity is given by the square of the correlation coefficient, $\underline{r}^2$. The $\underline{r}^2$ values for the five statistics discussed above as well as the standard deviation of density difference, $\sigma(\underline{D}_{\underline{S}}-\underline{D}_{\underline{L}})$, the average syzygetic density difference, $|\overline{\underline{S\Delta D}}|$, and the standard deviation of syzygetic density difference, $\sigma(|\underline{S\Delta D}|)$, vs. both the subjective values and their logarithms are given in Tables Ia and Ib, respectively. It is clear that $\sigma(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$ is the preferred unevenness number whether comparison is made to the subjective evaluation or to its logarithm.

These data confirm the findings from previous experiment that the subjective unevenness of halftone prints of mixed darkness is satisfactorily indicated by $\sigma(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$ but not by $\sigma\underline{V}_{\underline{S}}$, $\sigma\underline{W}_{\underline{S}}$ of $\sigma\underline{Y}_{\underline{S}}\cdot(\log \overline{\underline{Y}})/\overline{\underline{Y}}$. In Fig. 2, which is a plot of $(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$ vs. subjective evenness, the data points of the light and dark samples are identified to show how they fall along the same line. The corresponding plot for $\sigma\underline{V}_{\underline{S}}$ vs. subjective evenness, shown as Fig. 3, reveals that $\sigma\underline{V}_{\underline{S}}$ rates the dark

TABLE Ia

SQUARE OF CORRELATION COEFFICIENT FOR SELECTED OBJECTIVE UNEVENNESS STATISTICS VS. SUBJECTIVE EVENNESS

Statistic	10 Light Samples[a]		12 Dark Samples[b]		14 Mixed Samples[c]		14 Mixed Samples	
	2 Dot	8 Dot	2 Dot	8 Dot	2 Dot	8 Dot	2 Dot[d]	8 Dot[d]
σV_S	0.66	0.72	0.64	0.52	0.09	0.04	0.04	0.05
σW_S	0.66	0.72	0.64	0.50	0.15	0.15	0.04	0.05
$\sigma Y_S \log \overline{Y}_S/\overline{Y}_S$	0.67	0.72	0.62	0.49	0.08	0.00	0.04	0.05
σY_S	0.61	0.77	0.77	0.72	0.50	0.31	0.55	0.21
$\sigma(Y_S - Y_L)$	0.86	0.88	0.81	0.81	0.98	0.98	--	--
$\sigma(D_S - D_L)$	0.85	0.85	0.72	0.74	0.23	0.25	--	--
$\lvert\overline{S\Delta D}\rvert$	0.76	0.71	0.61	0.62	0.15	0.15	0.03	0.03
$\sigma\lvert S\Delta D\rvert$	0.86	0.83	0.67	0.72	0.28	0.25	0.08	0.08

[a] Letterpress 120 line/inch halftone of 20% printing area.
[b] Letterpress 120 line/inch halftone of 50% printing area.
[c] 7 Light and 7 dark samples from the previous sets.
[d] Scanned with only the small aperture.

TABLE Ib

SQUARE OF CORRELATION COEFFICIENT FOR SELECTED OBJECTIVE UNEVENNESS STATISTICS VS. LOGARITHMS OF SUBJECTIVE EVENNESS

Statistic	10 Light Samples[a]		12 Dark Samples[b]		14 Mixed Samples[c]		14 Mixed Samples	
	2 Dot	8 Dot	2 Dot	8 Dot	2 Dot	8 Dot	2 Dot[d]	8 Dot[d]
σV_S	0.67	0.77	0.81	0.66	0.11	0.05	0.06	0.06
σW_S	0.67	0.77	0.79	0.66	0.10	0.05	0.06	0.06
$\sigma Y_S \log \overline{Y}_S/\overline{Y}_S$	0.69	0.77	0.77	0.64	0.10	0.00	0.06	0.05
σY_S	0.61	0.85	0.94	0.88	0.50	0.31	0.56	0.19
$\sigma(Y_S - Y_L)$	0.94	0.94	0.96	0.96	0.96	0.94	--	--
$\sigma(D_S - D_L)$	0.90	0.90	0.85	0.86	0.26	0.27	--	--
$\lvert\overline{S\Delta D}\rvert$	0.83	0.77	0.74	0.74	0.19	0.18	0.04	0.05
$\sigma\lvert S\Delta D\rvert$	0.92	0.88	0.74	0.79	0.35	0.30	0.11	0.07

[a] Letterpress 120 line/inch halftone of 20% printing area.
[b] Letterpress 120 line/inch halftone of 50% printing area.
[c] 7 Light and 7 dark samples selected from the previous sets.
[d] Scanned with only the small aperture.

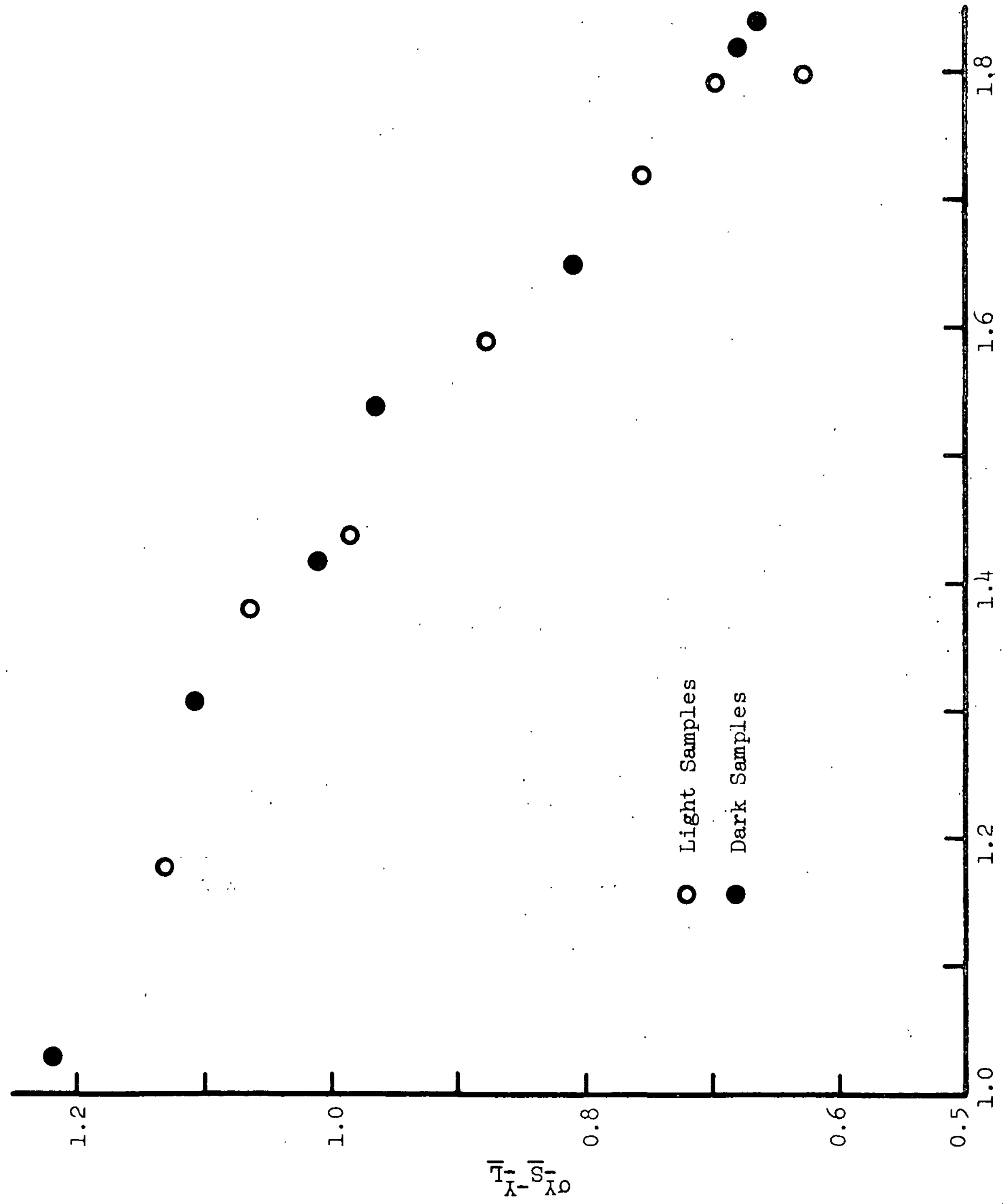


Figure 2. The Standard Deviation of $Y_S - Y_L$ vs. the Logarithm of Subjective Unevenness for the 14 Letterpress Halftones of Mixed Darkness

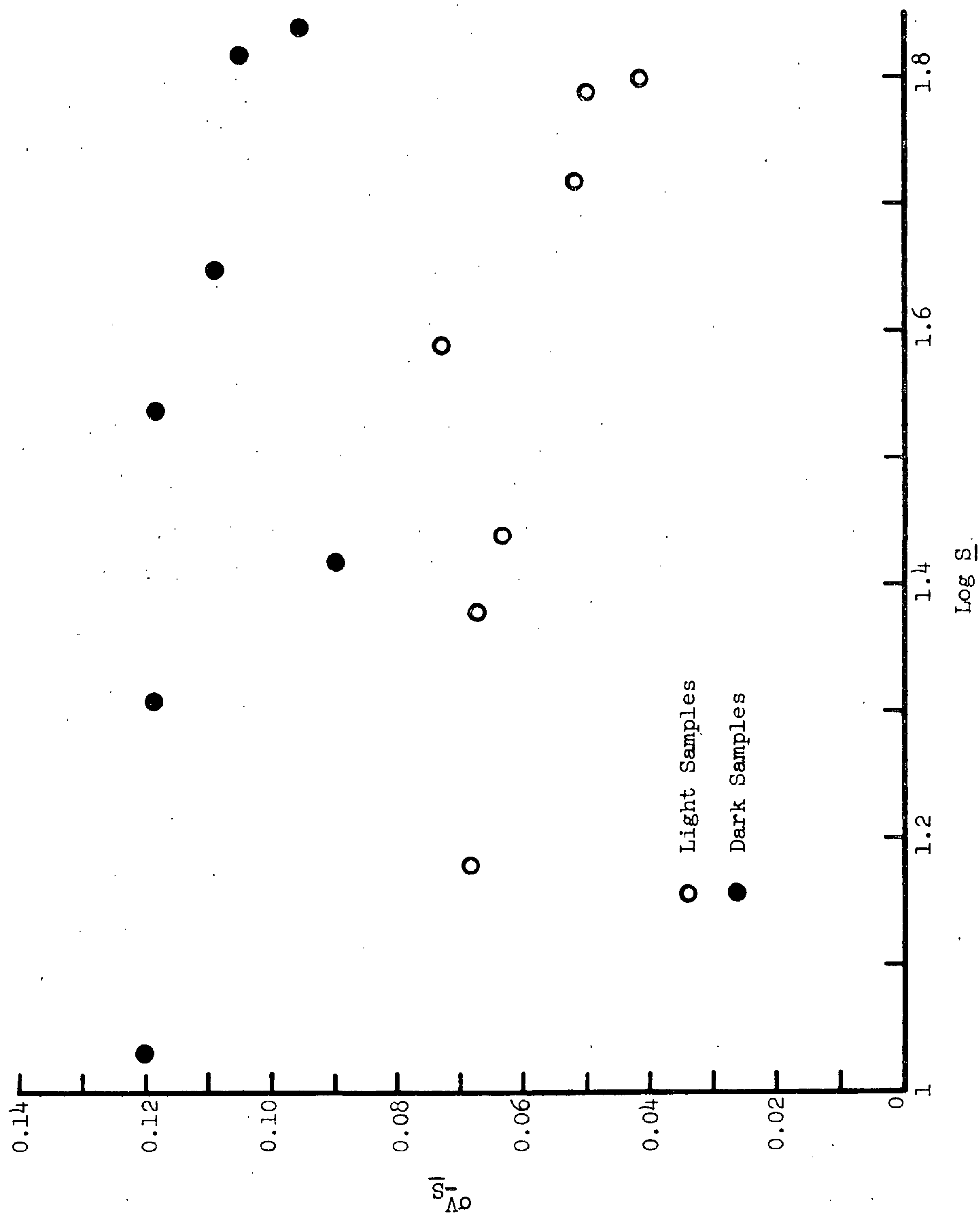


Figure 3. The Standard Deviation of Munsell Value (V) vs. the Logarithm of Subjective Evenness for the 14 Letterpress Halftones of Mixed Darkness

samples as much too uneven. Plots for σW_S and $\sigma Y_S \cdot (\log \bar{Y})/\bar{Y}$, which have not been included in this report, are similar to that for σV_S. The reason that σV_S, σW_S and $\sigma Y_S \cdot (\log \bar{Y})/\bar{Y}$ fail to properly correlate with the subjective evenness of these samples is not known. It was for such mixed sets that it had been expected that they would be required. It should be noted, however, that present evidence is restricted to sample sets of halftone prints and a set of solid letterpress prints (LPS No. 1 of Report Two) in which unevenness was largely the result of print break-up. In both cases the unevenness is of the type which Poulter (3) has called "speckle" for the variation is due to irregularity of the high contrast image elements of ink and paper. It is possible that a different result would be obtained with "mottled" samples such as unprinted papers or continuous tone prints in which variation is at low contrast over even small distances. The previous results reported by Parsons and Abson (2) for gloss mottle suggests that this may be the case.

Even though σV_S, σW_S and $\sigma Y_S \cdot (\log \bar{Y})/\bar{Y}$ fail to properly predict the subjective unevenness of these halftone samples, it is of interest to note that these measures of variation are essentially equivalent. The correlation coefficient between any two of these measures is in excess of 0.999. This provides strong evidence that multiplication of luminous reflectance variation by $(\log \bar{Y})/\bar{Y}$, as recommended by Makkonen and Nordman (1), is equivalent to expressing the variation as value (V) or lightness (W). Therefore, it is possible to design an unevenness instrument to provide the standard deviation of $Y_S - Y_L$, which has been shown to be useful for halftone prints, and for samples of a different type, be able to convert this number to one equivalent to the standard deviation of Munsell value, V, provided that the average reflectance of the sample is known.

It should be noted that, although $\sigma(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$ is the preferred unevenness number, $\sigma\underline{Y}_{\underline{S}}$ is next best, particularly with the sample set of mixed darkness considered. If $\underline{Y}_{\underline{L}}$ were constant, $\sigma\underline{Y}_{\underline{S}}$ would equal $\sigma(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$. Therefore, it is appropriate to consider whether higher $\underline{r}^2$ for $\sigma\underline{Y}_{\underline{S}}$ would be obtained if $\underline{Y}_{\underline{S}}$ were determined directly rather than by adding an independently determined $\underline{Y}_{\underline{L}}$ to $\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}}$. If $\underline{Y}_{\underline{S}}$ is in error due to the indirect method of determination the same errors would be included in $\sigma\underline{V}_{\underline{S}}$, $\sigma\underline{W}_{\underline{S}}$, $\sigma\underline{Y}_{\underline{S}}\cdot(\log \overline{\underline{Y}})/\overline{\underline{Y}}$, $|\overline{\underline{S\Delta D}}|$ and $(|\overline{\underline{S\Delta D}}|)$ which are all calculated from $\underline{Y}_{\underline{S}}$. Therefore, the same set of 14 mixed samples was scanned using only the small aperture detector to determine $\underline{Y}_{\underline{S}}$ directly. The $\underline{r}^2$ for $\sigma\underline{Y}_{\underline{S}}$ as well as the other statistics which can be calculated from $\underline{Y}_{\underline{S}}$ are included as the last two columns of Tables Ia and Ib. There is clearly no advantage to the direct determination of $\underline{Y}_{\underline{S}}$ with only the small aperture.

The superiority of $\sigma(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$ over $\sigma\underline{Y}_{\underline{S}}$ indicated by the $\underline{r}^2$ values shown in Tables Ia and Ib is probably due to the fact that $\underline{Y}_{\underline{L}}$ is not constant. Gradual changes in reflectance which are visually unimportant are minimized as $\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}}$ but are fully included as $\underline{Y}_{\underline{S}}$. These subjectively unimportant variations are also included in all the statistics which are calculated from $\underline{Y}_{\underline{S}}$.

Report One discussed the manner in which the square small aperture of the instrument can be adjusted to include a constant integrated dot area. A square with side equal to the screen unit diagonal when properly oriented always includes dot area equivalent to two dots; a square with twice this length of side always includes area equivalent to 8 dots. These have been designated as 2-dot and 8-dot apertures. Comparison of the $\underline{r}^2$ values for the 2-dot and 8-dot apertures of Tables Ia and Ib shows that within this range the size of the small aperture does not significantly affect the correlation of $\sigma(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$ with subjective unevenness. The actual magnitude of $\sigma(\underline{Y}_{\underline{S}}-\underline{Y}_{\underline{L}})$ is reduced as the aperture size is increased because the effects of printing defects are integrated over larger areas but the sensitivity to defects is adequate to maintain substantially equivalent correlation. However, for the scans made with only the small aperture, correlation with subjective evaluation did decrease upon changing to the larger aperture. This result is in agreement with the report of Makkonen and Nordman (1) concerning the effect of aperture size with their single aperture instrument. This difference in the effect of aperture size upon correlation of $\sigma(Y_S - Y_L)$, for the two aperture instrument, and σY_S, for the single aperture instrument, may be due to the differences in sensitivity to variation. The total range of the two aperture instrument is devoted to recording the variation in reflectance from the local average. When operated as a single aperture instrument this same range must be used to measure the actual reflectance. The variation in reflectance is small in comparison to the reflectance and becomes smaller with increasing aperture size.

MODIFICATION OF THE SUBJECTIVE EVALUATION METHOD

The method of subjective evenness evaluation which was described in Report Two was fashioned after the magnitude estimation methods described by Woodworth and Schlosberg (4). The judge estimates the magnitude of sensation due to each sample on a ratio scale relative to a standard or another sample. By making the judgments between adjacent samples in the series he never has to make such a judgment between samples which are very different. It may be expected that the judge will be most successful if there are no large quality gaps in the series which require applying a large ratio between adjacent samples. Upon further thought it seems clear that evenness is just the lack of unevenness and that unevenness is the characteristic which is being judged. To ask the judges to score increasing unevenness on a descending evenness scale is a confusing and unnecessary complication which may affect the scale but not the order of the samples in the set. Consequently, in recent evaluations a subjective unevenness scale has been used. The instructions given to the judges are included in the appendix.

It has been noted that judges differ considerably in the numerical scale they use. A ratio scale of 1 to 10 is, of course, equivalent to one from 10 to 100. When the geometric mean is computed the scores of judges using these two numerical scales is given equal weight. However, scale differences such as 10 to 27 and 10 to 500 have been noted within a single judging panel. In this case the geometric mean gives greater weight to the scores of the judge using the steeper numerical scale. To avoid such unequal weighting, raw scores (S) are now being converted to equal weight scores (S') by the expression,

$$S' = aS^b,$$

where a and b are calculated for each judge. The exponent b adjusts the ratio (highest score)/(lowest score) to be equal for all judges. This adjusted ratio could be any arbitrary value but at present the geometric mean of the ratios for all judges is being used. The coefficient a adjusts all scores so that the geometric mean of all sample scores for each judge is the same. At present this adjustment is to the grand geometric mean of S^b (all judgments of all judges). The subjective unevenness, U_S, of each sample is then the geometric mean of aS^b values for all the judges.

The U_S of a sample has meaning only with relation to the other samples in the sample set that was judged. However, this mathematical treatment suggests a means, as yet not evaluated, for developing unevenness scores which could be used in interset comparisons. Two standard samples, one considerably more uneven than the other, could be included in every set to be judged. The raw scores for each judge would then be adjusted by an exponent, b, and a coefficient, a, which would provide predetermined scores for the two standard samples. Since all samples in all sample sets would be judged relative to the same standard samples, the subjective unevenness values should be comparable from set to set.

MODIFICATION OF THE UNEVENNESS INSTRUMENT

When it had been demonstrated that $\sigma(Y_S - Y_L)$ was the most satisfactory unevenness number of the many which had been tried for expressing the unevenness of halftone prints, it was desirable to eliminate the data logging on magnetic tape, the subsequent digitizing, and the analysis by computer and to develop an instrument which would provide this unevenness number directly or with minimum computation. This number could easily be multiplied by $(\log \bar{Y})/\bar{Y}$ if for other types of sample it should prove desirable to use a visually uniform tone scale. In order to facilitate the conversion to a new computation method and, at the same time, reduce scanning time some changes were made in the mechanical scanning equipment. The optical system of the previous instrument was used without change but the flat scanning mechanism was replaced by a scanning drum 10 inches in diameter and 2 inches wide. The drum rotates at 30 rpm which corresponds to a scanning speed of 15.7 inches/second. The drum advances 0.05 inch/revolution on its lead screw but an auxiliary motor which can turn the lead screw in either direction provides the option of 0.0407, 0.05, or 0.0593 inch between scanning lines. Usually four replicate determinations are made, changing the relative position between the drum and lead screw at the start of each scan in a manner that interlaces the new scanning paths between those of previous scans to more completely cover the specimen area. A small magnet rotates with the drum and closes a reed switch momentarily upon each revolution to signal the start of a scanning line.

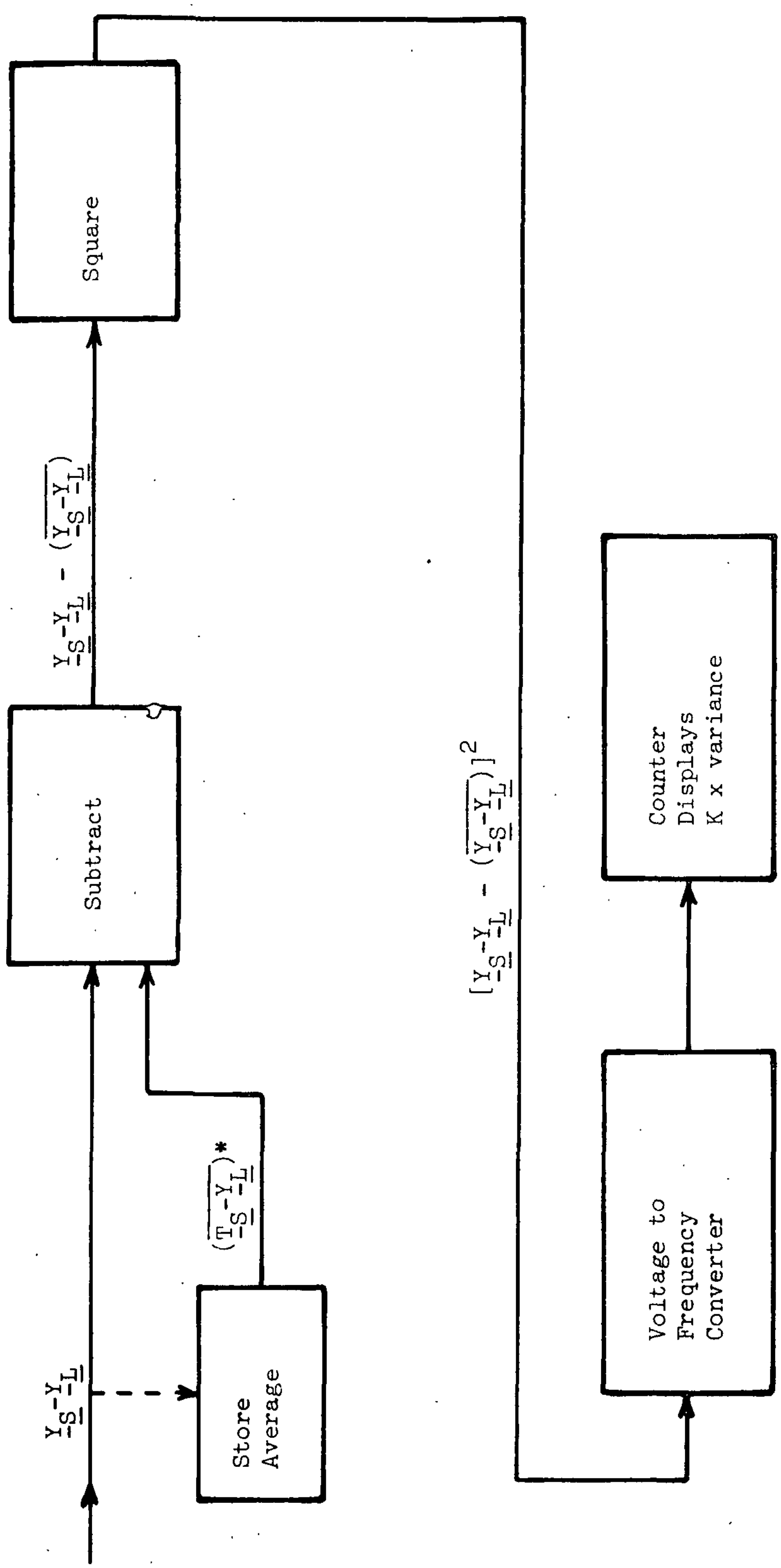
The projection lamp is operated with direct current because during the initial evaluation of the instrument it was found that the results were affected by the 120 cycle light variation due to operation on alternating current. Such light variations affect both the small and large aperture responses. At balance, when $\underline{Y}_S-\underline{Y}_L = 0$, these variations in the responses cancel but at sample points where $\underline{Y}_S \neq \underline{Y}_L$ they do not cancel and do contribute to the detected variation.

The equipment for analog computation and digital output was designed and constructed by Mr. Keith Hardacker of the Institute staff. Mr. Hardacker expects that if a group of several instruments is to be built it will be more economical to use digital computation with a minicomputer. The present system of computation is illustrated schematically by Fig. 4. The $\underline{Y}_S-\underline{Y}_L$ analog voltage is compared with the stored average voltage of the previous scanning line and the difference is squared. A frequency proportional to this squared voltage signal is generated by the voltage to frequency converter and the peaks of this signal are counted to provide the digital output. The count for 10 or 20 scanning lines is accumulated and displayed. The reed switch signals the start of a scanning line and the length of the line is controlled by a timer which limits each line to approximately 3 inches. A 10 or 20 line scan requires 11 or 21 drum revolutions, respectively, because during the first revolution only the initial average, for use in the first scanning line is determined. Even in the absence of unevenness, a count of one is recorded for each time the magnet closes the reed switch and these counts must be subtracted from the accumulated total. The objective unevenness number, $\underline{U}_0$, is based on the average count per line and is proportional to $\sigma(\underline{Y}_S-\underline{Y}_L)$. It is given by the equation,

$$U_0 = k\,\sigma(Y_S-Y_L) = \left(\frac{\text{count}-(n+1)}{n}\right)^{1/2}$$

where $\underline{n}$ is the number of scanning lines, which can be set at 10 or 20.

The complete instrument, including digital voltmeter for use in calibration, is shown in Fig. 5.



*The $(\overline{Y_S-Y_L})$ used is always that of the immediately preceding scanning path.

Figure 4. Schematic Diagram of Instrument Computation System

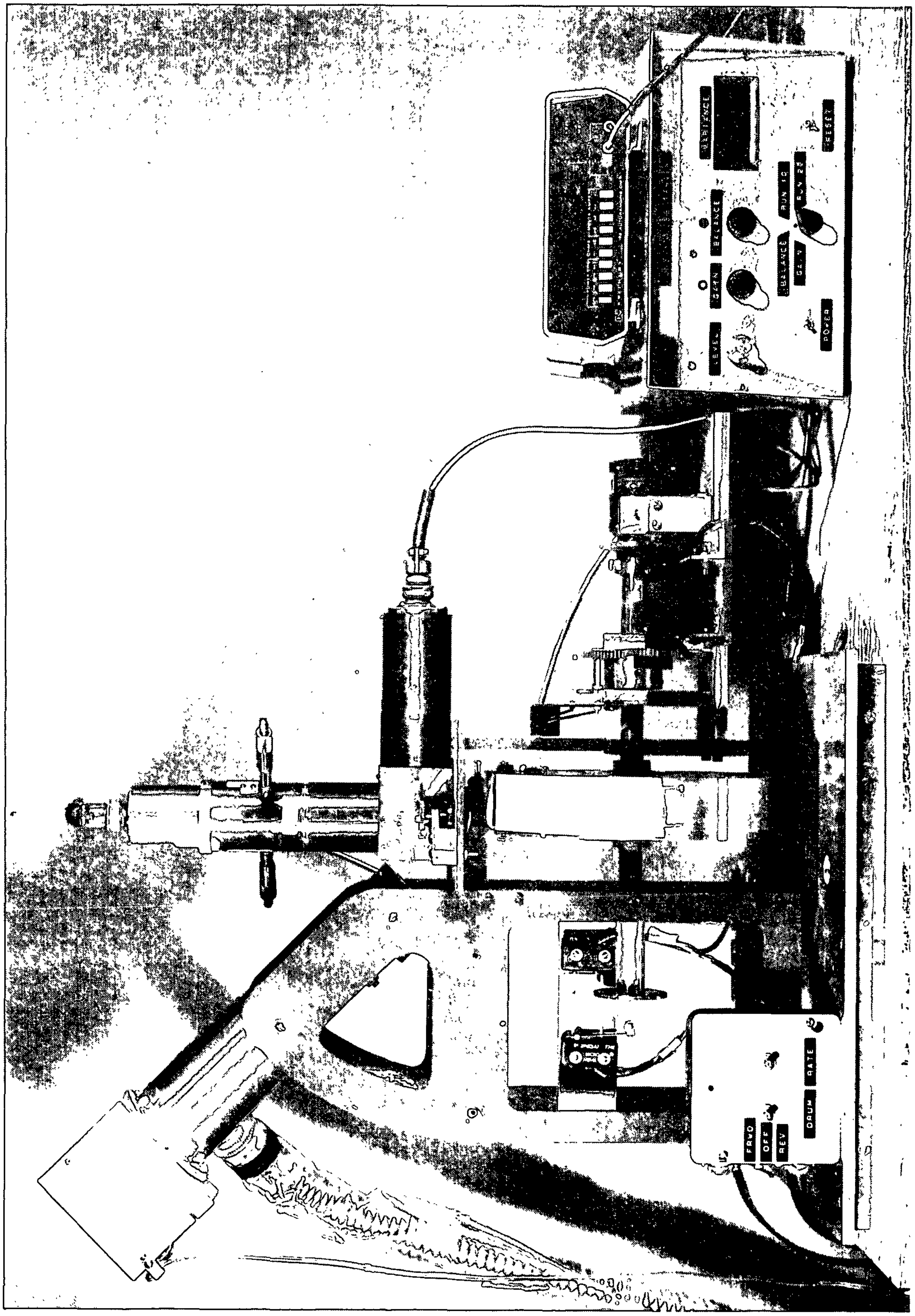


Figure 5. The IPC Unevenness Tester

MEASUREMENTS WITH THE MODIFIED INSTRUMENT

In order to compare unevenness numbers obtained with the new instrument with $\sigma(Y_S-Y_L)$ values previously obtained, the light and dark halftone letterpress prints were reexamined. Unfortunately, the original specimens could not be removed from the sample holders without some damage so it was necessary to cut new specimens from adjacent areas of the same prints. The poorer of these samples had been printed at scant impression and they varied in unevenness from area to area so these samples were rejected from the comparison. Figure 6 is a plot of the objective unevenness numbers (U_{02} and U_{08} for the 2-dot and the 8-dot apertures, respectively) *vs.* the corresponding $\sigma(Y_S-Y_L)$ values obtained previously. Linear regression indicated that

$$U_0 = \sigma(Y_S-Y_L)/0.07$$

when the new instrument is set up at 1 volt per 1% Y.

The new specimens of the 14 mixed light and dark samples were then evaluated subjectively by the modified procedure described above. This not only provided subjective unevenness numbers which applied to the specimens actually scanned, but these numbers should be free of any distortion of scale that might be caused by the previous method of grading increasing unevenness on a decreasing evenness scale. These new subjective unevenness numbers, and their logarithms, were compared with objective unevenness numbers obtained with both 2-dot and 8-dot apertures with the new instrument. The suitability of these objective measures for predicting the subjective scores (or their logarithms) can be judged by the square of the correlation coefficients which are presented in Table II. It is evident that the most satisfactory relationship exists between the objective unevenness numbers and the subjective unevenness, U_S. There is no significant

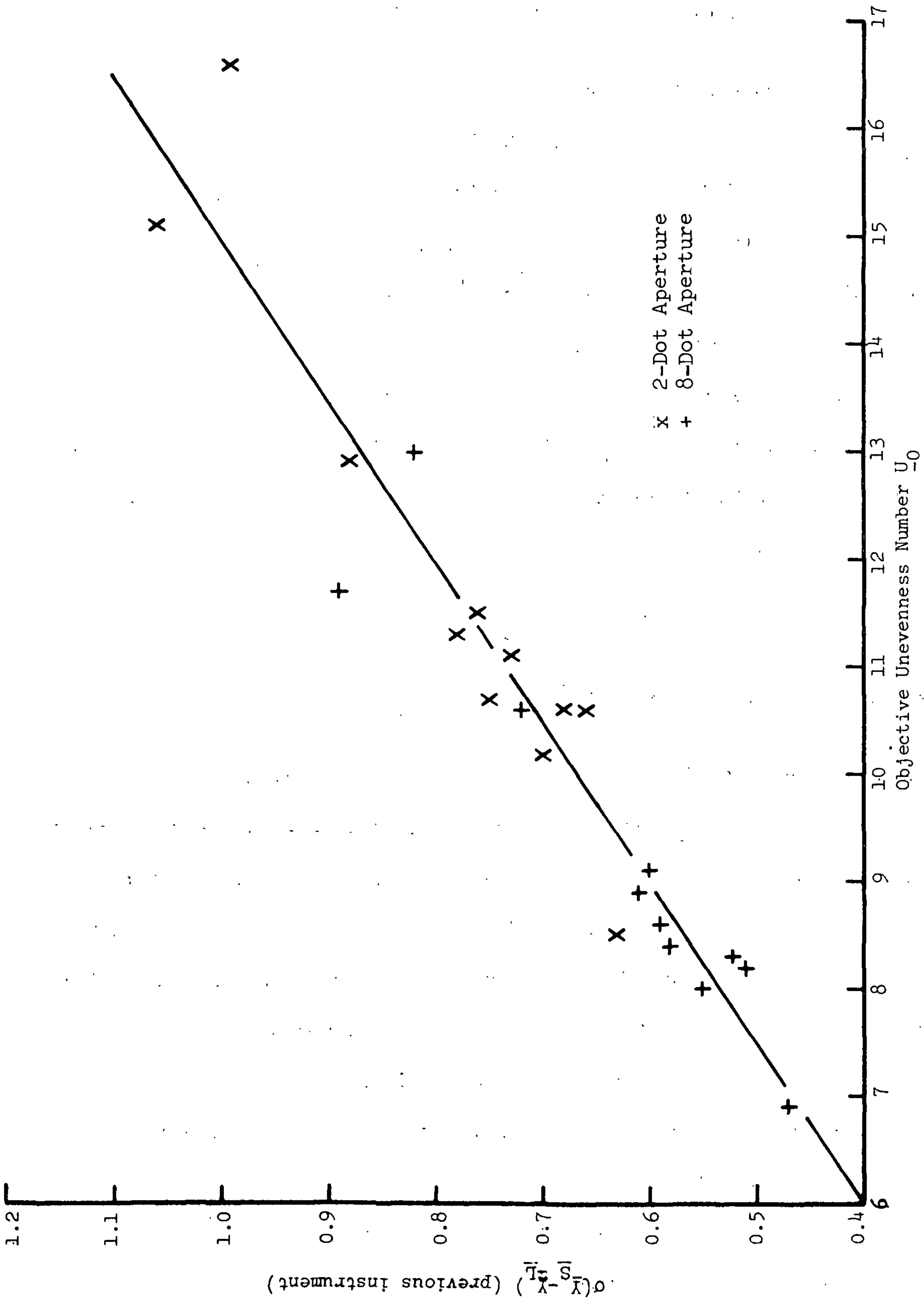


Figure 6. Objective Unevenness Numbers vs. $\sigma(Y_S - Y_L)$ as Previously Determined with Former Instrument for Both 2-Dot and 8-Dot Apertures

TABLE II

OBJECTIVE AND SUBJECTIVE UNEVENNESS OF HALFTONE PRINTS

Sample No.[a]	U_{02}[b]	U_{08}[b]	U_S	log U_S
40	18.7	14.5	13.4	2.13
44	8.5	6.9	20.4	1.31
47	15.1	11.7	70.5	1.85
49	11.5	9.0	37.7	1.58
51	16.6	13.0	109.0	2.04
56	12.9	10.6	47.9	1.68
58	10.2	8.0	19.9	1.30
60	16.5	13.1	96.1	1.98
63	22.1	17.5	17.1	2.23
65	18.2	14.9	12.9	2.11
67	10.6	8.3	26.8	1.43
68	24.5	19.1	19.2	2.28
71	10.6	8.2	23.1	1.36
77	14.6	11.2	83.4	1.92
	r^2	0.995	0.98	0.91
	--	r^2	0.98	0.91

[a]Samples 40-58 20% printing area; Samples 60-77 50% printing area.

[b]U_{02} and U_{08} — objective unevenness numbers determined with 2-dot and 8-dot small apertures.

difference between correlation using the 2-dot and the 8-dot aperture results. Somewhat poorer correlation is obtained when the logarithm of the subjective unevenness is used. Comparison of Fig. 7 and 8 reveals that use of the logarithm causes a distinct curvature of the plot.

There is considerable difference in both $\underline{U}_{02}$ and $\underline{U}_{08}$ for the two best (least uneven) samples, as is illustrated by Fig. 7 for $\underline{U}_{02}$, even though they received essentially the same subjective score. Examination of the individual judges' scores revealed generally good agreement concerning the superiority of the five best samples for no judge ranked any of these worse than sixth. However, there was little agreement concerning the relative unevenness among the best four, which contained two light and two dark samples. The judges seemed to show a preference for either the light or the dark samples, since the light samples tended to be ranked 1 and 2 or 3 and 4. Judges were apparently reluctant to place a sample of different lightness between two samples of equal lightness and very nearly equal unevenness. To provide further information concerning the visual unevenness, the best 5 samples were ranked by pair comparison, using the same 12 judges. Results of this ranking experiment are summarized in Table III. It is evident that these samples are very closely spaced because there is substantial disagreement among the judges. None of the individual judges ranked the samples in exactly the composite rank order. However, the composite rank order is in excellent agreement with the order provided by both the 2-dot and the 8-dot objective unevenness numbers.

These subjective evaluation experiments may raise some questions concerning the relative advantages and disadvantages of the two subjective evaluation methods. Pair comparison is probably less subject to errors caused by the tendency of judges to be consistent with respect to extraneous differences such as the darkness difference. However, pair comparison does not appear to be any more sensitive.

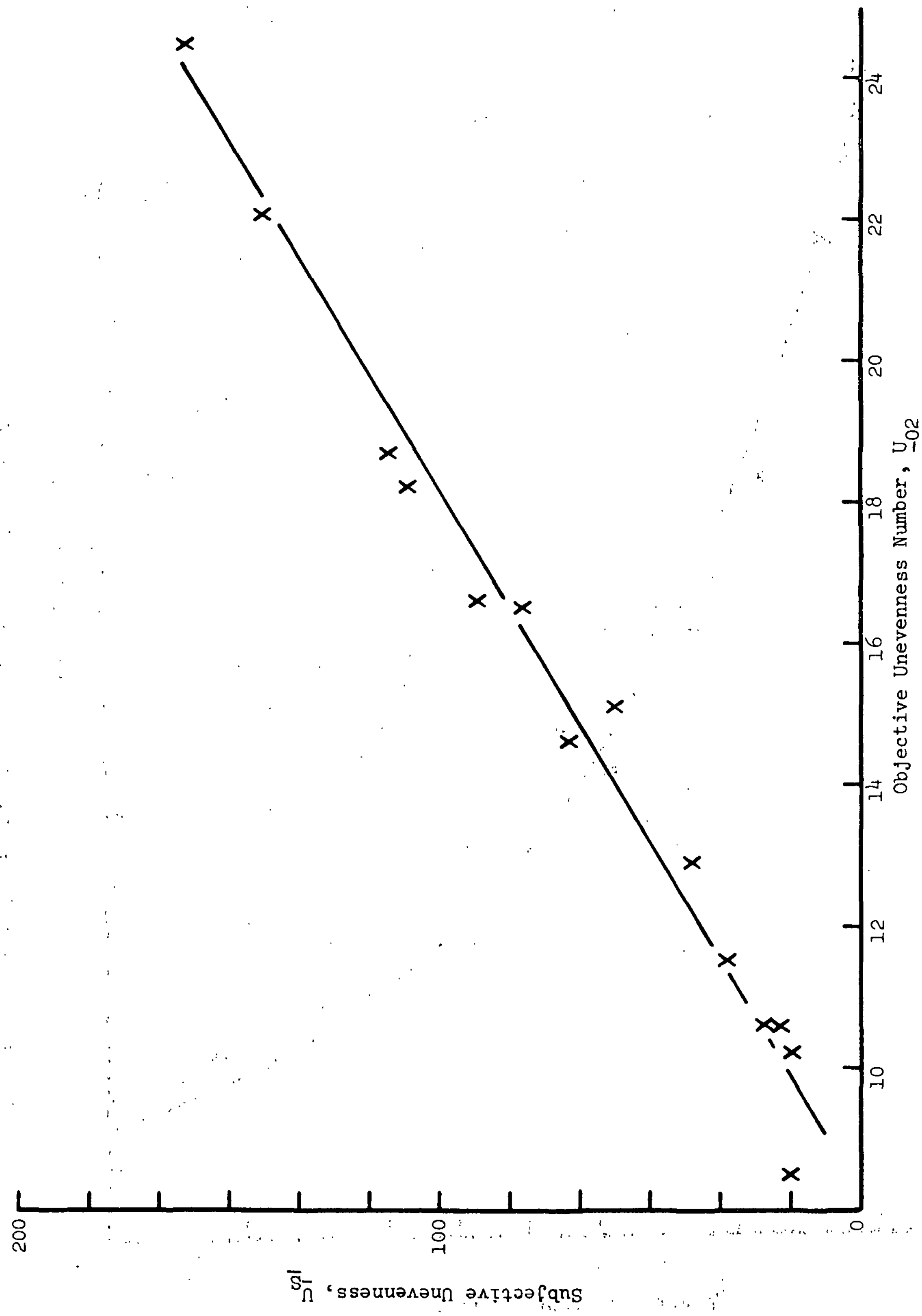


Figure 7. Objective unevenness for 2-Dot Aperture vs. Subjective Unevenness of 14 Letterpress Prints

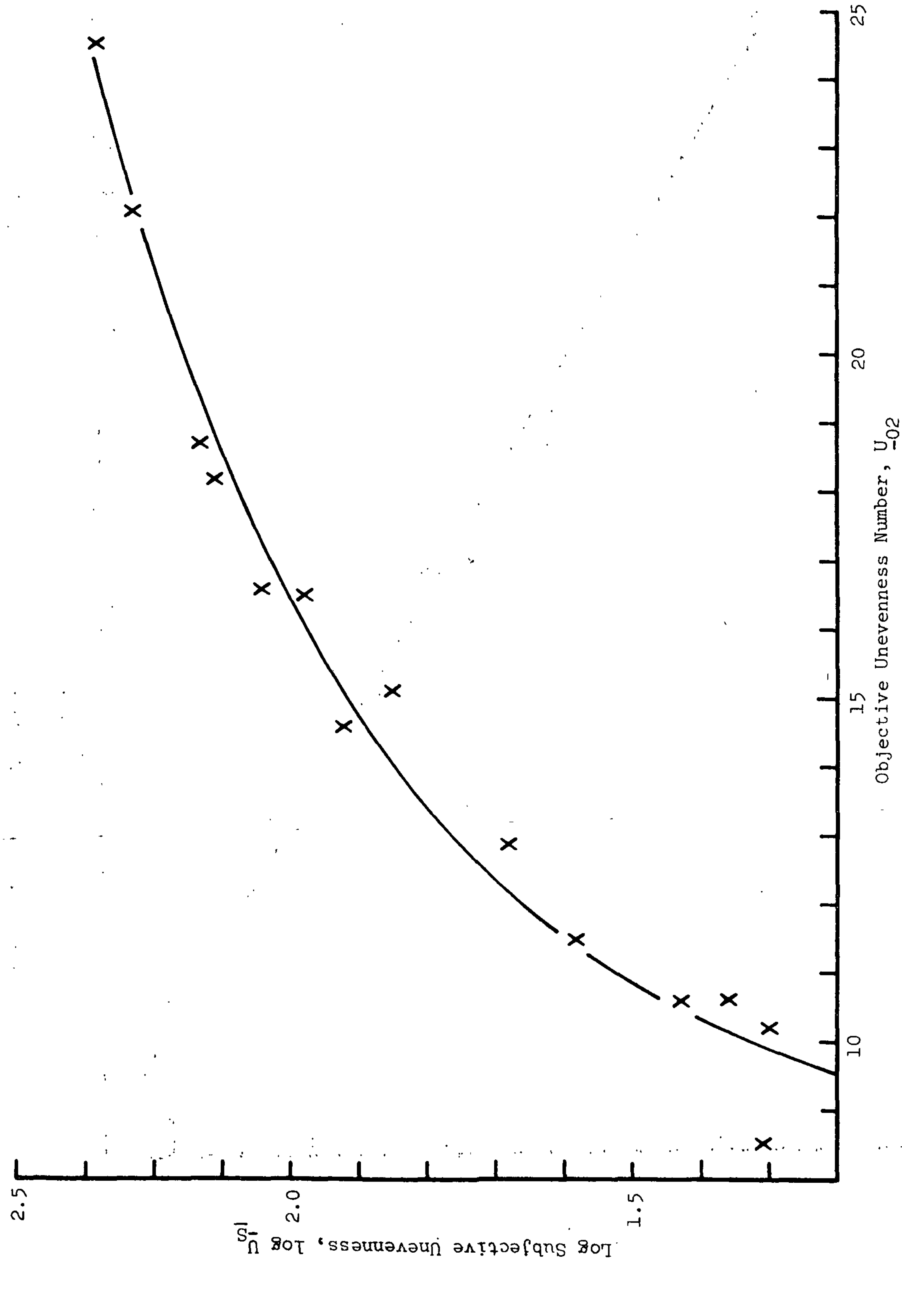


Figure 8. Objective Unevenness for 2-Dot Aperture vs. the Logarithm of Subjective Unevenness of 14 Letterpress Prints

The rank order of the original $\underline{U}_S$ values has only one adjacent inversion from the composite rank order by pair comparison. Although none of the individual judges ranked the samples in the composite rank order by pair comparison, four of the twelve judges scored these five samples in this order when evaluating $\underline{U}_S$.

TABLE III

RANK ORDER OF THE LEAST UNEVEN FIVE HALFTONE PRINTS

Sample No.	Pair Comparison Score[a]	Pair Comparison Rank[b]	Rank[b] by $\underline{U}_S$	Rank[b] by $\underline{U}_{02}$	Rank[b] by $\underline{U}_{08}$
44	10	1	2	1	1
49	43	5	5	5	5
58	17	2	1	2	2
67	30	4	4	3.5	4
71	20	3	3	3.5	3
		$\underline{r}_S$	0.900	0.975	1.00

[a]The score is the number of times the sample was judged the more uneven of a pair by a panel of 12 judges.
[b]Rank order from least uneven (1) to most uneven (5).

MOTTLE OF COATED BOARDS

A member company submitted a series of coated unbleached boards with their own rank order of subjective mottle. These samples were subjectively graded at the Institute and scanned with the new instrument. Because the manufacturer's evaluation was available only as a rank order, the Institute subjective unevenness score, U_S, the instrumental unevenness number, U_0, and the product $U_0 \cdot (\log \bar{Y})/\bar{Y}$ values were also converted to rank orders and are shown in Table IV together with the Spearman correlation of ranks coefficients, r_s. Correlation is better for $U_0 \cdot (\log \bar{Y})/\bar{Y}$ than for U_0 regardless of whether the manufacturer's or the Institute's subjective rank order is used. Agreement between $U_0 \cdot (\log \bar{Y})/\bar{Y}$ rank order and either of the subjective rank orders (r_s = 0.86 and 0.90) is about the same as the agreement between the two subjective judging panels (r_s = 0.88). In Table V the actual IPC subjective scores, U_S, are compared with the objective values U_0 and $U_0 \cdot (\log \bar{Y})/\bar{Y}$. Here, too, better correlation is obtained with the $U_0 \cdot (\log \bar{Y})/\bar{Y}$ values. These results provide evidence that unevenness numbers designed to present variation information on a visually uniform tone scale are superior to those based on the reflectance scale for mottled samples where variation is at low contrast. However, the results should be verified for a set of papers or continuous tone prints which have a wider range of average reflectance.

TABLE IV

SUBJECTIVE AND OBJECTIVE UNEVENNESS RANK ORDER[a]
OF COATED BOARDS

Sample No.	Subjective Rank Order: Manufacturer	Subjective Rank Order: IPC[b]	Objective Rank Order: $\underline{U}_0$	Objective Rank Order: $\underline{U}_0 \cdot (\log \bar{\underline{Y}})/\bar{\underline{Y}}$
1	7	11	9	10
2	6	5	4	7
3	5	4	2	2
4	4	6	3	4
5	3	3	7	5
6	2	1 1/2	5	3
7	1	1 1/2	1	1
8	8	7	6	6
9	9	8	10	8.5
10	10	9	8	8.5
11	11	10	11	11
	$\underline{r}_S$	0.88	0.76	0.86
	--	$\underline{r}_S$	0.76	0.90

[a]From least uneven (1) to most uneven (11).
[b]From $\underline{U}_S$ scores.

TABLE V

SUBJECTIVE AND OBJECTIVE UNEVENNESS OF COATED BOARDS

Sample No.	IPC Subjective Unevenness, U_S	Objective Unevenness	
		U_0	$U_0 \cdot (\log \bar{Y})/\bar{Y}$
1	38.3	6.56	0.164
2	22.3	5.91	0.151
3	21.8	5.56	0.139
4	26.4	5.73	0.143
5	16.5	6.17	0.146
6	15.6	5.96	0.141
7	15.6	5.27	0.121
8	27.3	6.04	0.148
9	30.0	6.59	0.163
10	32.0	6.51	0.163
11	32.4	6.64	0.166
	r	0.739	0.831
	r^2	0.541	0.691

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The contribution of Mr. Keith Hardacker to this work is gratefully acknowledged. He designed and constructed the equipment for analog computation and digital read-out of the variance. Thanks are also due to the members of the Institute staff who have served as judges in the subjective evaluations.

LITERATURE CITED

1. Makkonen, T., and Nordman, L., Paper and Timber 50:509-16(1968).

2. Parsons, C. L., and Abson, P. L., TAPPI Conference Papers, Printing and Reprography-Testing 1977:25-8.

3. Poulter, S. R. C., Tappi 51(8):87A-91A(1968).

4. Woodworth, R. S., and Schlosberg, H. Experimental Psychology. 3rd Edition. Holt Rinehart and Winston Inc., 1971. pp. 73-9.

THE INSTITUTE OF PAPER CHEMISTRY

Russell F. Tyler
Research Fellow

Jack D. Hultman
Research Fellow

Robert M. Leekley
Graphic Arts Consultant

Approved by:

John W. Swanson
Senior Scientist
Surface & Colloid
Science Center

APPENDIX

SUBJECTIVE UNEVENNESS METHOD — INSTRUCTIONS TO JUDGES

1. Arrange the samples in the order of increasing unevenness.
2. Assign a value of 10 to the best sample, i.e., the one with the least mottle.
3. Compare the second sample in the series to the one already assigned the score of 10 and assign a score which indicates how much more uneven it is. For example, if the second sample is twice as mottled as the first, assign a score of 20. If it is three times as mottled assign a score of 30. If it is only 10% more mottled assign a score of 11.
4. Next compare the third sample with the second. For example, if you have already assigned a score of 20 to the second sample and the third sample is three times as uneven as the second, the third sample would receive a score of 60. However, if it is only 1 1/2 times as uneven it would receive a score of 30.
5. Continue until all the samples have been scored. In each case the sample is given a score based on how much more uneven it appears than the next lower member of the series. Do not be concerned by the total range of your scores.