J. L. Crawford
C. D. Elzinga
R. Yudico

Print Quality Measurements for High-Speed Electrophotographic Printers

Described here are some of the characteristics that make electrophotographic printing esthetically pleasing, and the use of a recently developed computer-controlled scanner for measuring those characteristics. New print quality measurements are described (for example, measurements of modulation, image gray-scale fidelity, and tangential-edge roughness) that allow the monitoring of the advanced printing functions made possible by all-point addressability. The requirements for and implementation of the scanner are discussed. Also discussed are the effects and limitations on print quality measurement resolution imposed by the algorithms used and the scanner; the effect of light scatter by the paper; and the usefulness of the print quality measurements as an aid in making design trade-off decisions and in manufacturing control.

Introduction

In the early years of data processing, the requirements for good print quality were to meet two needs: legibility and character placement on a page. Today, high-speed printers not only are used for traditional data-processing applications but for correspondence and graphics as well. Many users want print of high esthetic quality. To meet this demand for improved print quality, IBM introduced the 3800 Models 1 and 2 (hereafter designated as Model 1) high-speed electrophotographic printers [1].

The subsequent introduction, in the 3800 Models 3 and 8 (hereafter designated as Model 3), of all-point addressability and higher pel density has allowed the inclusion of a combination of text and images (noncoded information) printing. A brief description of the latter models and an introduction to the other papers in this series of papers on those models may be found in [2]. This new function has led to the development of new print quality parameters which have become a vital part of the design, development, testing, and manufacturing process of this printer. Examples are given that emphasize the usefulness of associated print quality (PQ) measurements.

In this paper, a brief description is given of the relationship between subjective judgments and objective measurements of print quality. The latter consist of the measurement of "basic" and "advanced-function" parameters. Associated measuring algorithms and instrumentation which are used are discussed. Designated as the Pictorial Information Dissector and Analyzer System (PIDAS), the instrumentation presents a digitized image of a document to IBM System/370 software for the extraction of PQ parameters using the measuring algorithms. We also discuss the factors that affect PQ measurements as they relate to reflectance resolution, spatial resolution, and light scatter by the paper. The examples used in this paper are intended to demonstrate the measurement techniques and do not necessarily represent any particular printer product.

Subjective judgments vs. objective measurements

Subjective judgments of print quality are usually made in such terms as "light," "dark," "fuzzy," or "rough." Research has shown that these subjective terms are not always directly relatable to objective measurements, such as stroke width, reflectance, or tangential-edge roughness [3]. This lack of a one-to-one relationship is demonstrated by the fact that apparent darkness is a function of both stroke width and reflectance and that apparent blur is a function of changes in stroke width and loss of detail. It is important to distinguish these two concepts to avoid confusion when objective measurements are related to the esthetic acceptability of printed documents [4].

- *Edge characteristics*

Degradation of edges can occur in two ways, generally referred to as edge roughness and edge blur. Edge roughness is the variation of edges from some nominal position. Our objective measure of this concept is called tangential-edge roughness and is defined later. For printers which form images from individual dots, the edge roughness is usually dominated by the dot size, which is more noticeable on diagonals or curved strokes. **Figure 1(a)** contains examples of diagonals having different amounts of edge roughness. (See the section on tangential-edge roughness for a further discussion of this figure.)

Edge blur occurs when there is poor toner-placement control, as shown in **Figure 1(b).** The distribution of toner particles away from the stroke edge causes a reflectance gradient at the edge. The width of this transition is an objective measure of this blur effect. Another source of edge blur is the shadow effect at the stroke edge, as discussed later under "Effect of light scatter by the paper." An apparent edge blur can be caused by loss of the capability to reproduce the fine details of a font [3]. Our objective measure of the loss of detail is designated as "modulation" and is defined later. It is significant that the eye is an order of magnitude more sensitive to roughness than to blur [5]. Because of this, the Model 3 has been designed to reduce edge roughness through use of an increased pel size (see discussion under "Modulation").

- *Background noise*

Background noise occurs when toner particles accumulate on unprinted areas of a page. This noise detracts from the desired contrast difference between paper and print, and whether it is on an isolated area of a page or is uniform throughout, it degrades print quality. Our objective measurement of this effect involves measuring the change in reflectance of the paper upon subjecting it to the electrophotographic process. Our studies show that a change in reflectance by more than 1.5% is not desirable.

- *Darkness*

Maintaining consistent darkness for characters and images throughout a page is important to subjective judgments of print quality. Variations in the electrophotographic process can cause objectionable variations in darkness if not controlled within acceptable levels. Examples of darkness uniformity that are within and beyond acceptable levels are shown in **Figure 2.** Our objective measurement of this effect is designated as "process uniformity," which is defined as the range and standard deviation of the reflectance of characters across the page. In our context, reflectance is related to optical density and contrast density, as follows:

$$D = \log_{10} \frac{1}{R_{\mathrm{PT}}} \quad \text{and} \quad D_c = \frac{R_{\mathrm{PR}}}{R_{\mathrm{PT}}},$$

where D = optical density, R_{PT} = reflectance at point of

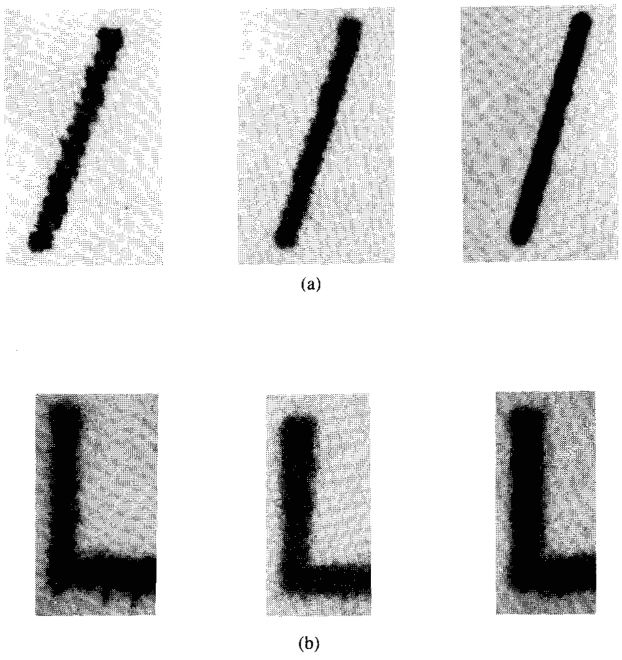


Figure 1 Examples of high, medium, and minimal edge roughness (a) and edge blur (b).

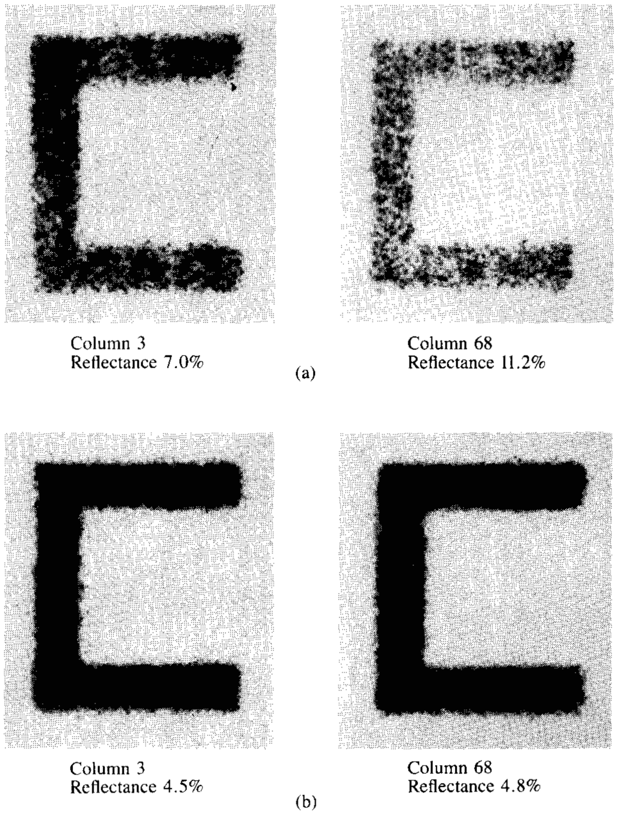


Figure 2 Peak character reflectance for Columns 3 and 68 showing (a) unacceptable and (b) acceptable variations within a page.

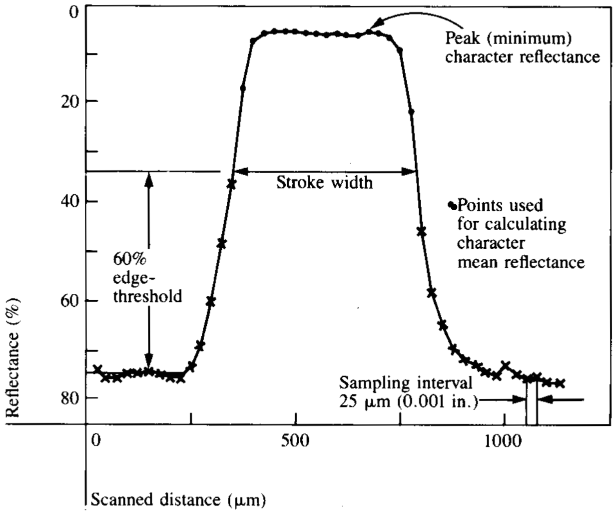


Figure 3 Digitized stroke-crossing profile as detected by the PIDAS scanner.

measurement, D_c = contrast density, and R_{PR} = reflectance of paper.

Objective print quality measurements

The capability to quantify print quality in objective and repeatable terms is essential in the printer development process. The objective measurements of PQ have traditionally been carried out with eye-loupes and comparators. These methods have been enhanced by the use of reflectance-measuring devices and scanning reflection microdensitometers. PIDAS was developed to provide further capabilities [6]. As indicated above, it is used for the objective measurements of basic and advanced-function parameters. The basic parameters are stroke width, character reflectance, process uniformity, and print registration, and they are mainly associated with the Model 1. The advanced-function parameters, added for the Model 3, are modulation, tangential-edge roughness, and image gray-scale fidelity. The latter were added to meet the increased need for fine-line resolution brought about by image printing, which may consist of logos, signatures, graphs, charts, schematics, and continuous-tone photographs.

- *Description of computer-controlled scanner*

The physical characteristics of the PIDAS scanner are as follows:

- Drum circumference: 450 mm (18 in.).
- Vacuum document hold.
- Encoder resolution of 25 μm (0.001 in.) for sampling around the drum.
- Stepper motor for camera motion along the drum in 12.5-μm (0.0005-in.) steps.
- Selectable apertures from 50 × 50 μm (0.002 × 0.002 in.) to 50 × 500 μm (0.002 × 0.020 in.).
- 256 levels of reflectance.
- Illumination:
  - Angle of 45°.
  - Four fiber-optic bundles located diagonally to document motion.
- Sensor-photomultiplier perpendicular to the document.

Use of PIDAS as a means for measuring PQ in manufacturing as well as development imposes some secondary but practical requirements, e.g., ease-of-use, measurement throughput, and serviceability. Flexibility is enhanced by its range of aperture sizes, sampling intervals, software measurements, and microprocessor control of the scanner. Measurement throughput is typically one minute per document (1500-character sample) for basic measurements such as stroke width and character reflectance. The gray-scale fidelity measurement, which requires the greatest amount of time, requires up to five minutes. Because of the simplicity of its mechanical design, the drum scanner requires only minimal preventive maintenance. The nonmechanical portions of PIDAS such as its optics, sensor, analog-to-digital conversion, and microprocessor portions are modularized for easy replacement when service is needed.

The use of a computer and scanner combination for PQ measurements provides many advantages, such as power to handle complex algorithms, tireless handling of operations with speed, and the data base and information handling that are needed when PQ measurements are broadly applied. Perhaps a less evident benefit of such a system is the ease of data logging and the utility afforded by the programmed access to the PQ data base. This data base, in conjunction with a machine-condition data base and operations log, allows extensive tracking and reporting of the printer's performance throughout development, testing, and manufacturing.

- *Stroke width, character reflectance, and process uniformity*

The stroke width, character reflectance, and process uniformity parameters are measured in a single operation, using a single program. They are measured for each character in a row or column, and 12 rows or columns per page are summarized to provide a page average. The measurements are extracted from the digitized signal from a scan with a slit aperture [50 × 500 μm (0.002 × 0.020 in.)] having the long direction perpendicular to the scan direction across a printed line of four-pel letter Cs.

Figure 3 shows the profile of a single vertical stroke crossing, as detected by the scanner. The +s represent the points at which the profile is sampled and digitized; the stroke width is the distance between the edge-threshold-crossing locations (i.e., the horizontal locations where the edge profile is equal to the edge threshold). The edge threshold is calculated at 60% of the transition from the paper (white) to the character peak (black). When the threshold does not occur at a digitized point, a straight-line interpolation is made to more closely approximate the actual threshold location. This interpolation improves the spatial resolution of the edge measurement over the base of a 0.025-mm (0.001-in.) sampling interval (see the discussion on spatial resolution). The edge threshold is set at 60% of the transition rather than at the 50% point in order to compensate for the change in the edge profile caused by light scattering by the paper. Light scatter is covered later in this paper, but, briefly, it has the effect of widening the edge profile at the base, which requires that stroke widths be measured higher up the profile. Although the reason is not explained, Engeldrum [7] also uses the 60% threshold to obtain "the width perceived by the human observer."

The mean character reflectance is calculated by summing all of the digitized reflectance values between the edge-threshold points and dividing the result by the number of sample points (shown as the solid circles in Fig. 3). The peak character reflectance (actually, the minimum reflectance) is the darkest digitized point between edge-threshold points. The mean character reflectance is a useful estimate of character reflectance when the toner is not evenly deposited (usually resulting in light printing). The peak reflectance is smoothed by the 50 × 500-μm (0.002 × 0.020-in.) aperture of the optical scanner and provides a good general measure of the reflectance of characters. The peak reflectance is also detected electronically and is controlled by the reflectance control servo of the Model 3; thus it is an important PQ measurement for the Model 3.

For the purpose of measuring process uniformity across a page, the peak character reflectance values of adjacent pairs of character columns (odd and even) are averaged and a limit is placed on the range and standard deviation of this column-pair average. Fig. 2 shows acceptable and unacceptable variations in peak character reflectance across the page. Process uniformity is acceptable when all column-pair deviations are at or below a maximum allowable deviation.

- *Print registration*

The deviation of rows from the horizontal is measured by use of a laser-printed test pattern that has a vertical bar along the left edge of the page and four horizontal bars evenly distributed throughout the page. When that deviation is out of specification, there is a skewing of the print on the page. PIDAS measures it by first scanning the centerline of all printed lines, fitting straight lines to each centerline, and then measuring the angle between the horizontal and vertical lines. Use is made of deviation from a straight, horizontal line in order to obtain the vertical misregistration or distortion of a character in a graph or image.

- *Modulation*

The Model 3 has a pel-placement addressability of 240 pels/in. with a nominal spot size of 104 μm (0.00417 in.). However, the resolution has been intentionally reduced (by increasing the spot size) to provide smoothing of diagonal lines. Resolution, in general, is a measure of the capability of the printer to print fine details; it can, in effect, be regarded as the smallest equal-width line pair that can be printed. To monitor and control the degree of change in the laser-print resolution, we have used "modulation." The latter is measured using a pattern of three frequencies of lines and gaps: one pel on, one pel off; one pel on, two pels off; two pels on, two pels off. (Note that for the 3800, a pel on results in black and a pel off in white; other printers, such as the IBM 6670, operate in reverse fashion.) PIDAS scans the pattern and provides a profile such as that shown in **Figure 4.** Modulation is calculated from this profile by the conventional electrical or optical expression for modulation, viz., one-half the signal variation divided by the average signal:

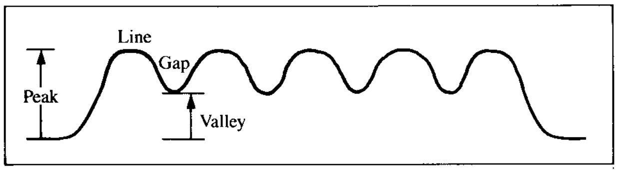


Figure 4 Typical modulation profile for a one-pel-on, one-pel-off test pattern.

$$\text{Modulation} = \frac{1/2\ (\text{peak} - \text{valley})}{1/2\ (\text{peak} + \text{valley})}.$$

Because of the increased spot size, the lines of the modulation pattern are wider than the gaps. This filling of the gaps causes the valley signal to rise and the modulation to decrease. By specifying a lower limit on the modulation, we can control the loss of the gaps and thereby the loss of the capability to resolve or distinguish the lines and gaps. Modulation measurements are made for an entire row or column of print, and with the modulation pattern oriented in both the horizontal and the vertical positions. Modulation measurements are affected by the shadows at stroke edges, as discussed later in the section on the effect of light scatter by the paper. Modulation is measured in manufacturing and has been effective in discovering print head problems which were not detected by component testing, or which occurred during the assembly of the print head.

- *Tangential-edge roughness*

The smoothing of stroke edges is measured by the tangential-edge roughness parameter. It is measured by making 22 scans across the vertical strokes of a row of four-pel Cs with a 50 × 50-μm (0.002 × 0.002-in.) scanning aperture. The scans are separated vertically by 50 μm (0.002 in.). The leading and trailing stroke edges are located as described for the stroke-width measurements. For each edge, a straight line is fitted

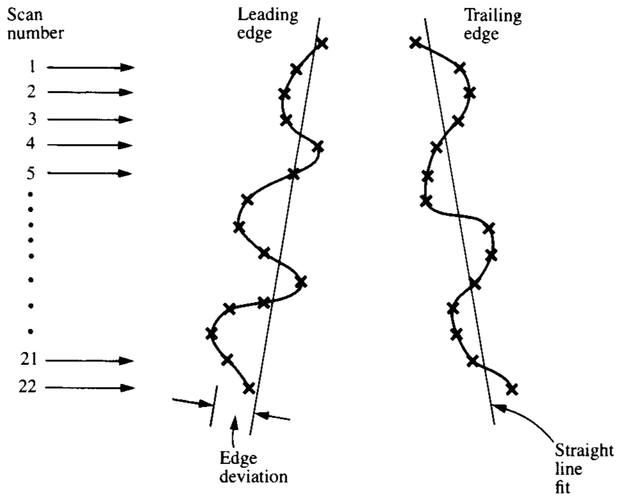


Figure 5 Illustration of means for calculation of tangential-edge roughness.

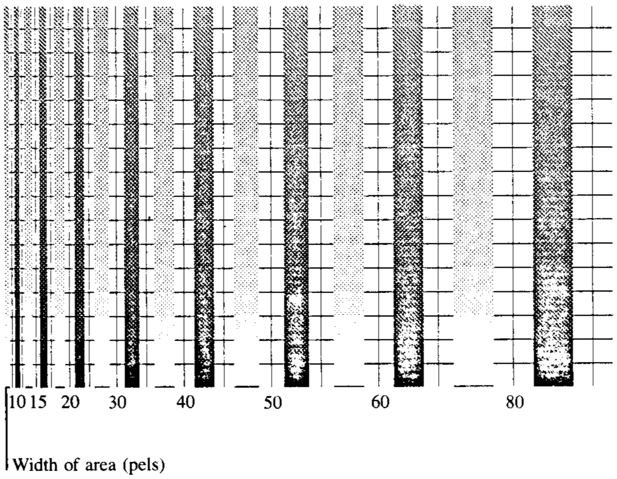


Figure 6 Lower half of 32-step gray scale, showing light-to-dark and dark-to-light pairs for each pel width.

Table 1 Tangential-edge roughness measurements for the characters shown in Figure 1(a).

Tangential-edge roughness level	*rms deviation* [μm (in.)]	*Peak-to-peak range* [μm (in.)]
High	25 (0.00099)	93 (0.00372)
Medium	17 (0.00068)	63 (0.00252)
Minimal	10 (0.00039)	36 (0.00146)

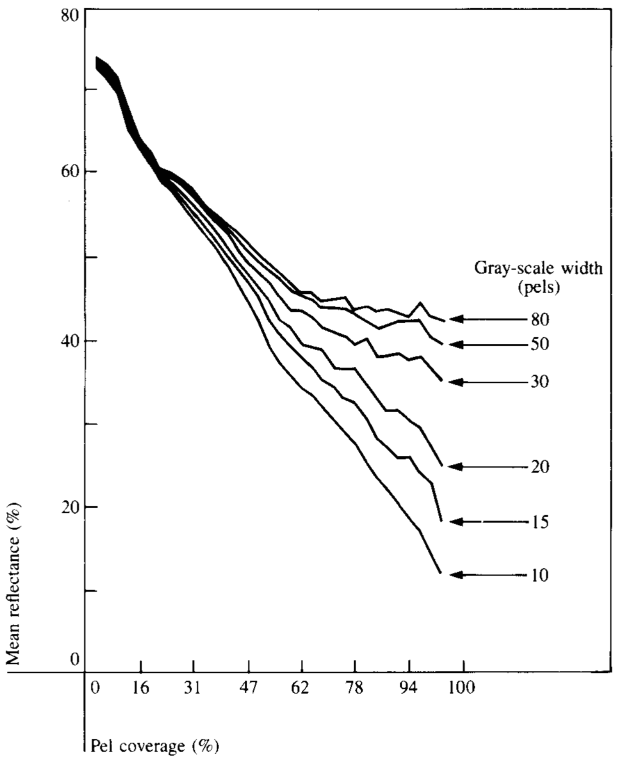


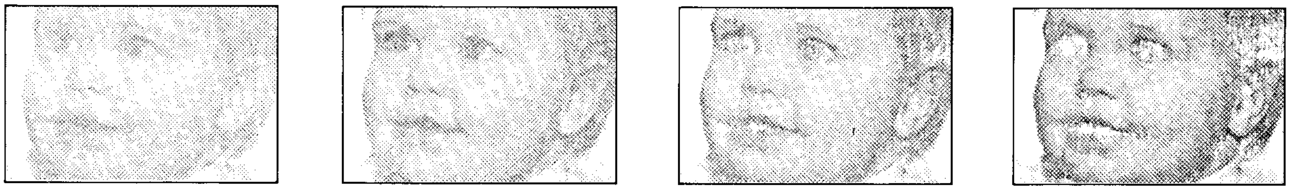
Figure 7 Reflectance vs. pel coverage corresponding to one level of gray-scale fidelity.

Table 2 Illustrative measurements of tangential-edge roughness.

Printer type	*Density* (pels/in.)	*Tangential-edge roughness*	
		rms [μm (in.)]	*Range* [μm (in.)]
Printer 1/paper 1	180	26.5 (0.00106)	96.8 (0.00387)
Printer 1/paper 2	180	21.3 (0.00085)	78.0 (0.00312)
Printer 2	240	18.5 (0.00074)	71.6 (0.00287)
Printer 3	300	15.8 (0.00063)	59.6 (0.00239)
®SELECTRIC	N/A	8.0 (0.00032)	29.3 (0.00117)

through the 22 edge points **(Figure 5).** The measures of tangential-edge roughness are the rms deviation about this line and the peak-to-peak range of this deviation. To provide a visual calibration of these measures, the values for the characters in Fig. 1(a) are given in **Table 1.**

The tangential-edge roughness parameter is applied to diagonal lines to measure the stair-step caused by the finite pel density. This and the modulation measurement are useful in establishing the amount of pel overlap for the desired compromise between resolution and smoothing of diagonal and curved lines. **Table 2** contains typical measurements of tangential-edge roughness. The measurements were obtained using three printers having different pel densities, and an IBM ®SELECTRIC. Such information is useful in assessing the



(a) Maximum pel coverage = 40% (b) Maximum pel coverage = 60% (c) Maximum pel coverage = 80% (d) Maximum pel coverage = 100%

(e) Maximum pel coverage = 40% (f) Maximum pel coverage = 60% (g) Maximum pel coverage = 80% (h) Maximum pel coverage = 100%

Figure 8 Halftone images with two levels of gray-scale fidelity: (a–d), faded at >60% pel coverage; (e–h), less fading at pel coverage of 40–100%.

smoothing effect of increasing pel density and provides an objective method of quantifying the effect of other printer parameters. Measurement of tangential-edge roughness is also used to check the operation of the laser-scanning mirror and print head electronics.

- *Image gray-scale fidelity*

Image gray-scale fidelity is a measure of the printer's capability to faithfully reproduce the gray levels of a continuous-tone image. Electrophotographic printers that are binary devices can print only black or white pels; therefore, halftoning is used to reproduce continuous-tone images, such as photographs. The perceived gray levels are obtained by controlling (through the software) the percentage of pels turned on in an area [8, 9]. For example, in an area 8 pels by 8 pels in dimension with 32 pels on and 32 pels off, the apparent reflectance would be approximately the mean of the reflectance of the paper and that of a solid black area.

Some electrophotographic printers and copiers exhibit fading of solid black areas; that is, attempts to print solid black areas result in an image that is dark around the edges and faded towards the center. Fading is a limiting factor in the accurate reproduction of images because as the percentage of pel coverage of the darker areas increases, the areas approach a solid black area and the fading effect begins to appear. The magnitude of the fading is also a function of the size of the area being halftoned; that is, it is determined by both the size and the pel coverage.

To measure the capability of the printer to print halftoned images, use is made of a test pattern consisting of a 32-step gray scale. This gray scale is printed in eight different widths to provide a range of area widths from 10 to 80 pels. **Figure 6** shows the lower half of the scale. The printed gray scales are scanned by PIDAS to measure the reflectance of each area. A plot is made of reflectance vs. the percentage of pel coverage for each width in the gray scale **(Figure 7).** Note that the expected near-linear relationship is lost for widths greater than 10 pels and, as the pel coverage exceeds 60%, the effect becomes more pronounced as the widths increase. It is for this reason that better image quality (for the printer used for Fig. 7) is obtained if solid black lines or areas are limited to 10 pels and also if halftoned images (logos, graphs, or continuous-tone photos) are limited to 60% coverage. This result is verified by visual inspection of actual halftoned images that have their maximum pel coverage limited to 40, 60, 80, and 100%, as illustrated in portions a, b, c, and d of **Figure 8** by the fading that occurs in the pupils of the eyes and the dark area around the lips for maximum pel coverage greater than 60%. The images in portions e, f, g, and h of Fig. 8 and the measurements in **Figure 9** were obtained from a printer with less fading.

Because it is cumbersome to retain these graphical results in machine-readable form (for data base and processing), a set of statistics has been defined that quantify their important characteristics. One of these is the range of reflectance values for a constant pel coverage, i.e., the vertical spread in the family of curves shown in Fig. 7. Spread values taken at 40, 60, 80, and 100% coverage are a measure of the variation in halftone reflectance for a constant pel coverage.

Factors that affect print quality measurements

When objective PQ measurements are carried out, it is important that the specific measurement algorithm used and the characteristics of the measuring instrument be well under-

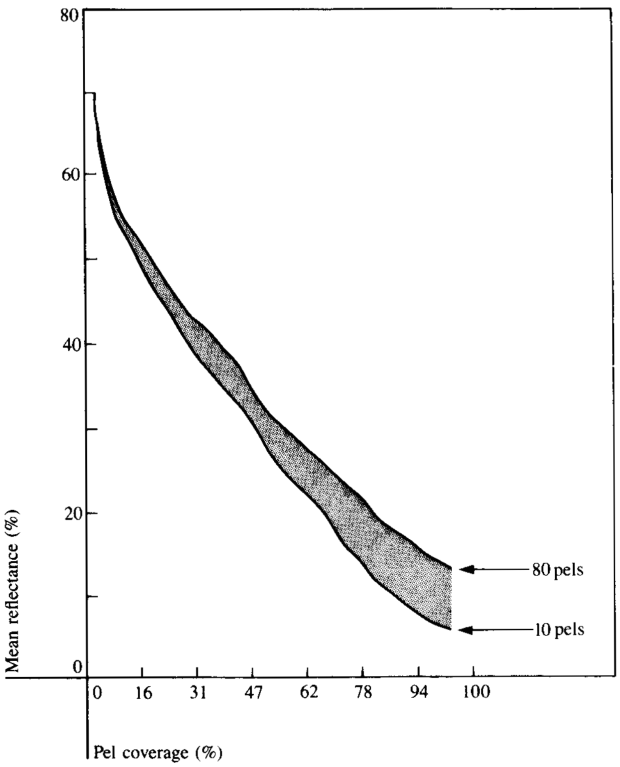


Figure 9 Reflectance vs. pel coverage showing gray-scale fidelity improvement over that shown in Fig. 7. This figure depicts the envelope of reflectance values for a range of gray-scale widths from 10 to 80 pels.

stood. This is especially true for PQ measurements, because such measurements involve reflection microdensitometry and the use of a paper substrate that contributes its own spread function to the measurements. The combined effect of algorithm, instrument, and paper results in measurements that are relative and not absolute. This lack of absoluteness does not reduce the validity and utility of the measurements in a practical application, if certain conditions are met. The measurements need not be absolute, but to be useful they must be 1) repeatable with time and repeatable from instrument to instrument, and 2) sensitive to a level of change that is appropriate to the application. The main factors that affect PQ measurements are reflectance resolution, spatial resolution, and light scatter by the paper.

- *Reflectance resolution*

The resolution of a measurement is limited by, but not necessarily limited to, the quantization increment (e.g., for PIDAS, 256 reflectance levels or 25-μm (0.001-in.) intervals between samples). When the peak reflectance of a single character is measured (a single extreme value), the resolution can be no better than approximately 0.4% reflectance (100%/256 = 0.391%). The single measurement can be less valid if the instrumentation noise is higher than the quantization level (for PIDAS, the three-sigma noise limit, when characters are measured, is approximately 1/10 of the quantization level). But, when the mean peak-character reflectance is estimated for 1500 characters on a page, the estimate can be closer to the actual mean than 0.4% reflectance, 1) if the underlying stability of the instrument is better than the quantization interval, and 2) if the sample size is sufficient. For example, the peak character reflectance of a set of printed documents has been measured repeatedly using two scanners over a period of four years with a measurement standard deviation of 0.1% reflectance.

- *Spatial resolution*

Spatial resolution is a measure of how well we can locate the edge of a stroke on paper. When the stroke-edge location is being measured using the data from a scan perpendicular to the stroke edge (see Fig. 3), this edge can be located to within one sampling interval of 25 μm (0.001 in.), using just the quantization of the encoder. The resolution of locating this edge can be improved by using the information contained in the reflectance values of the sample points on either side of the threshold to interpolate between the sample points. The improvement in spatial resolution depends on the repeatability and the number of reflectance levels between the adjacent points; e.g., the improvement is greater on near-vertical transitions than on near-horizontal transitions. Typically, near the 60% threshold point, there are at least 30 reflectance quantization levels available to resolve the edge location within the 25-μm (0.001-in.) sampling interval. This improvement in resolution is also dependent on the validity of the assumption of linearity between the sample points. If the measuring aperture were much smaller than the sampling interval (presumably because the fine details of an edge were desired), this could be a poor assumption, which would lead to an unwanted loss of detail in the measurement. But if we want to find the smoothed-edge location [e.g., edge integrated by a 50 × 50-μm (0.002 × 0.002-in.) or 50 × 500-μm (0.002 × 0.020-in.) aperture], the assumption is entirely valid and the resolution of the edge location is greatly enhanced by using the reflectance information. The smoothed edge is applicable to the stroke-width and tangential-edge roughness measurements, and the assumption of linearity applies to both.

In the case of tangential-edge roughness, our measurements show that rms tangential-edge roughness (as smoothed by a 50 × 50-μm aperture) has a one-sigma noise limit in the measurement of approximately 0.5 μm (0.00002 in.). In addition, there is an offset between our two laboratory scanners of 0.6 μm (0.000025 in.), which must be corrected for comparison of measurements between the scanners. Table 2 contains data which illustrate a practical range of these measurements from about 26.5 μm (0.00106 in.) for EP printing at a density of 180 pels/in. to 8.0 μm (0.00032 in.) for typewriter printing. This range represents 36 standard deviations (of the measurement uncertainty), which is a sufficient resolution to characterize the tangential-edge roughness differences between these technologies. To be able to discriminate between tangential-edge roughness differences of 1 to 2 μm, as suggested by references [3, 10], it would be necessary to make multiple measurements on the same scanner to reduce the measurement uncertainty; i.e., the standard deviation of the mean estimate should decrease as the square root of the number of measurement repetitions becomes larger.

Care should be taken when comparing our measurements to the tangential-edge profile measurements carried out by Hamerly [10], because his measurements were made with a different aperture [20 × 400 μm (0.0008 × 0.016 in.)] a different algorithm (scanned along the stroke edge with the aperture perpendicular to the stroke edge), and a different illumination geometry.

- *The effect of light scatter by the paper*

It is well known that incident light entering the paper structure is internally reflected by the paper fibers and a portion is reemitted through the paper surface, contributing to the reflectance of the paper. The spatial distribution of this re-emitted energy, designated as the paper-spread function, has been experimentally determined for typical papers used in printing [11, 12]. It thus appears that energy can be internally spread over an area 250 μm (0.010 in.) in radius, with 50% of the energy within a radius of approximately 50 μm (0.002 in.). The reflected light from paper, as seen by a scanner or the eye, is made up of contributions from the light reflected directly from the surface at the measurement point and internally scattered light from the surrounding illuminated area. If reflectance measurements are to be representative of human vision, they should include both contributions. This implies that the illumination footprint should be at least 500 μm (0.020 in.) in diameter [11]. Although such a large illumination area provides realistic reflectance measurements on toned and untoned areas of the paper, it introduces a spreading or blurring of the stroke edges. This effect is explained by the attenuation of the scattered-light contribution near the edges caused by the illumination striking the toned characters and being absorbed rather than scattered. The results of this edge blurring can be seen in Fig. 3, where the edge transition is broader than the slightly more than 50 μm (0.002 in.) expected from the 50-μm aperture width, plus lens flare. Note that for characters like those shown in Fig. 1(b), toner scatter also contributes to the apparent edge spread.

It is significant that the edge transition due to paper is asymmetrical. This is because the transition is dominated by the broad paper spread away from the edge (a slow rise). Subsequently it approaches the slope of the aperture function (faster rise) as the aperture moves onto the character. The significance of this change in slope is that the edge-resolving sensitivity in the presence of paper spread improves when a higher edge threshold is used. We use a 60% threshold in our stroke-width and tangential-edge roughness measurements because of the good correlation between visual and scanner measurements and because use of such a threshold allows better detection of edge variations.

The modulation measurement is also affected by the paper spread. Any white gaps less than 500 μm wide appear gray due to the light shadow effect. Although the measurements are relative and not absolute, they are sensitive to changes in modulation of the printer and are representative of what the eye sees. Typical modulation values are 65% for the one-pel-on, two-pels-off pattern, and 30% for the one-pel-on, one-pel-off pattern. Because the spatial and reflectance measurements are sensitive to the effect of paper spread, probably the most important factor in obtaining repeatable PQ measurements is the illumination geometry. Therefore, after much experimentation, we have settled on a simple 45° source, 90° detector arrangement with four fiber-optic bundles spaced on the diagonals to the document motion. It is important to duplicate carefully the selected geometry for each instrument to avoid differences in paper spread.

Concluding remarks

In the development of electrophotographic printers, the need has arisen for improved measurements of print quality, such as modulation, tangential-edge roughness, and image grayscale fidelity. A computer-controlled reflectance measuring system has recently been developed which satisfies that need. By designing suitable test patterns, by programming associated reflectance measurements, and by analyzing and presenting the reflectance data in a form that effectively indicates image quality, measurements could be made which proved useful in the development of the 3800 Models 3 and 8—and which now are used in the manufacture of those printers.

Acknowledgment

Much of the early print-quality-analysis of software and measurement algorithms were developed by Ron Harrison, currently of the IBM Boulder Laboratory

References

1. U. Vahtra and R. F. Wolter, "Electrophotographic Process in a High Speed Printer," *IBM J. Res. Develop.* **22,** 34–39 (1978).
2. R. C. Miller, Jr., "Introduction to the IBM 3800 Printing Subsystem Models 3 and 8," *IBM J. Res. Develop.* **28,** 252–256 (1984, this issue).
3. C. A. Dvorak, "Text Sharpness, Its Components and Text Quality," *J. Appl. Photog. Eng.* **9,** 109–111 (1983).
4. J. R. Hamerly, "A Method of Assessing Image Quality," *Proc. Second National Print Quality Seminar,* May 9–11, 1982, pp. 57–69.
5. C. A. Dvorak and J. R. Hamerly, "Just-Noticeable Differences for Text Quality Components," *J. Appl. Photog. Eng.* **9,** 97–100 (1983).
6. J. L. Crawford, "The Development and Application of a Digitizing System to Implement a Print Quality Standard," *Proc. Second National Print Quality Seminar,* May 9–11, 1982, pp. 91–102.

7. P. G. Engeldrum, "Quality of Dot Formed Images," *SPIE Image Quality* **310**, 118–124 (1981).
8. Dimitris Anastassiou and Keith S. Pennington, "Digital Halftoning of Images," *IBM J. Res. Develop.* **26**, 687–697 (1982).
9. P. Stucki, "Image Processing for Document Reproduction," *Advanced Digital Image Processing,* P. Stucki, Ed., Plenum Press, New York, 1979, pp. 210–217.
10. J. R. Hamerly, "An Analysis of Edge Roughness," *J. Appl. Photog. Eng.* **7**, 148–151 (1981).
11. D. R. Lehmbeck and J. J. Jakubowski, "Optical Principles and Practical Consideration for Reflection Microdensitrometry," *J. Appl. Photog. Eng.* **5**, 63–77 (1979).
12. M. Maltz, "Light Scattering in Xerographic Images," *J. Appl. Photog. Eng.* **9**, 83–89 (1983).

Received October 14, 1983; revised December 16, 1983

J. L. Crawford *IBM General Products Division, Tucson, Arizona 85744.* Mr. Crawford is presently an advisory engineer in the Future Print/Technology Evaluation Department at Tucson. He is currently involved in the development and testing of non-impact printers. Previous assignments include the development of storage systems and optical character readers. Working through the American National Standards Institute, he has been active in the development of print quality standards for optical character recognition. He received a B.S. in electrical engineering from the University of Missouri School of Mines and Metallurgy in 1963 and an M.S. in electrical engineering from the University of Missouri at Rolla in 1964. He joined IBM in 1964. Mr. Crawford has received an IBM Outstanding Contribution Award for his pioneering work in the definition and measuring of objective print quality.

C. Dennis Elzinga *IBM General Products Division, Tucson, Arizona 85744.* Mr. Elzinga received his B.S. in physics and mathematics from Utah State University in 1964. He obtained the M.S. in engineering economic systems at Stanford University in 1978 and has completed course work for his engineer's degree there. Upon joining IBM in 1964, he had the responsibility for an electron beam controller and then for cathode ray tube development for a high-resolution photocomposer. He began work on electrophotographic printers in 1967 and was the manager of the development of the IBM 3800 laser printer head, forms overlay, print reflectance control, and print quality. He was granted a one-year sabbatical for graduate study at Stanford University in 1976. Mr. Elzinga is currently a senior engineer in advanced printer technology development at the Tucson laboratory.

Ricardo Yudico *IBM General Products Division, Tucson, Arizona 85744.* Mr. Yudico is a staff engineer, currently responsible for future printer print quality requirements. He joined IBM at Boulder, Colorado, in 1971. Since then, he has worked on Capstan motor development design for MSS and product test on the Series III copier. Mr. Yudico transferred to Tucson in 1978 to work in the tribology area, and became involved with printer technology in 1980. He received a B.S. in mechanical engineering from the University of Texas, El Paso, in 1971.