*Evaluating Tone Reproduction in Input to Output Digital Systems**

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Abstract The system level details of full digital imaging systems tone reproduction starting with camera or scanner input and finishing with the printed or displayed reproduction are reviewed. Responsivity of digital sensors, camera and scanner effects such as flare light, integrating cavity effect, test patterns for scanners and cameras including the ISO Opto Electronic Conversion Function (OECF) pattern are briefly discussed along with references to explore each further. A four quadrant Jones plot including the camera, image processing, the printer and the final reproduction is illustrated and discussed as a useful engineering tool. Examples of test patterns are shown. Concepts of offset, gain and linear response are reviewed as well as various units for measuring input to the capture device. The role of image processing for tone control and the use of gamma for displays is also discussed.

* *Much of this material is taken with permission of the publishers from D. Lehmbeck and J. Urbach, Image Quality for Scanning and Digital Imaging Systems, Chapter 3, pp133-246, in Handbook of Optical and Laser Scanning, 2nd Edition, Ed by G.F. Marshall and G.E. Stutz (CRC Press, Taylor & Francis Group, Boca Raton, FL, 2012)*

3.4.0. Introduction: Evaluating Digital Imaging Systems Response Involves Cameras and/or Scanners as well as Printers

In recent years, the advent of digital cameras, cell phone cameras and the plethora of office, home, and professional scanners have promoted wide interest in the subject of characterizing devices and systems that produce or capture digital images. Also, several commercially available image analysis packages have been developed for general image analysis, many using scanners or digital cameras, and many often attached to microscopes or other optical image magniication systems. Components of these packages and the associated technical literature speciically address scanner analysis or calibration.[87–89] A variety of standards activities have evolved in this area.[90–93] Additional related information is suggested by the literature on evaluating microdensitometers.[94,95] These systems are a special form of scanners in which the sensor has a single aperture of variable shape. Much of this work relates to transmitted light scanners but reflection systems have also been studied.[96] Methods for evaluating digital cameras and commercially available scanners for specific applications have been described by many authors.[77,93,97]

3.4.1 Digital System Responses for Tone Reproduction

Unlike many other imaging systems, where a logarithmic response (e.g., optical density) is commonly used, the tonal rendition characteristics of input scanners are most often described by the relationship between the output signal (gray) level and the input reflectance or brightness. This is because most electronic imaging systems respond linearly to intensity and therefore to reflectance. Three such relationships are shown in Figure 3.23. In general these curves can be described by two parameters, the **offset,** ***O,*** against the output gray level axis and the **gain** of the system **Γ**, which is defined in the equation in Figure 3.23. Here ***g*** is the **output gray level**, and ***R*** is the **relative reflectance factor**. If there is any offset, then the system is not truly linear despite the fact that the relationship between reflectance and gray level may follow a straight-line relationship. This line must go through the origin to make the system truly linear.

Often the maximum reflectance of a document will be far less than the 1.0 (100%) shown here. Furthermore, the lowest signal may be significantly higher than 1% or 2% and may frequently reach as much as 10% reflectance. In order to have the maximum number of gray levels available for each image, some scanners offer an option of performing a histogram analysis of the image of the reflectances of the input document on a pixel-by-pixel or or other sampled basis. The distribution is then examined to find its upper and lower limits. Some appropriate safety factor is provided, and new offset and gain factors are computed. These are applied to stretch out the response to cover as many of the total (256 here) output levels as possible with the information contained between the maximum and minimum reflectances of the document.

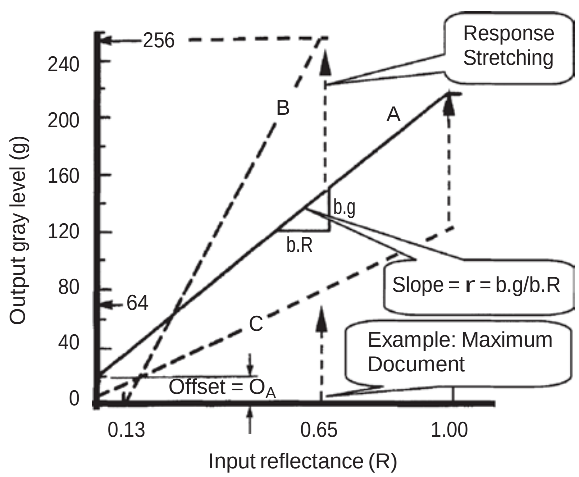

FIGURE 3.23
Typical types of scanner input responses, illustrating the deinitions of "gain" (i.e., slope), "offset," and "response stretching."

Other scanners may have a full gray-scale capability from 4 to 12 bits (16–4096 levels). In the igure, curve C is linear, that is, no offset and a straight-line response up to a reflectance of 1.0 (100%), in this case yielding 128 gray levels. Curve A would represent a more typical general purpose gray response for a scanner while curve B represents a curve adjusted to handle a speciic input document whose minimum reflectance was 0.13 and whose maximum reflectance was 0.65. Observe that neither of these curves is linear. This becomes very important for the subsequent forms of analysis in which the nonlinear response must be linearized before the other measurement methods can be applied properly. This is accomplished by converting the output units back to input units via the response function.

In a digital scanner the sensors themselves are fairly linear as can be seen in Figure 3.24 which plots exposure in linear units (lux-s) versus output in millivolts (mV). The response is strictly linear from 0 to 2.2 lux-sec and then begins to roll over as it saturates. Notice the difference between the “linear saturation exposure” and the “saturation exposure” which is a graphical construct projecting the linear part of the curve to the maximum signal. It is often observed that digital sensors are linear but it can be seen from the igure that this is only true for most but not all of the response curve. The scanner or camera designer is free to use as much or as little of the nonlinear high end of the curve as he desires. For digital cameras the indicated standard exposure differs by camera specifications but is usually in the linear region

It is also possible to arrange the electronics in the video processing circuit so that equal steps in exposure do not generate equal steps in electronic or digital response, but rather are appropriately spaced steps in some units that are more significant, either visually or in terms of materials properties. A logarithmic A/D converter is sometimes used to create a signal proportional to the logarithm of the reflectance or to the logarithm of the reciprocal reflectance (which is the same as “density”). Some scanners for graphic arts applications function in this manner. Another common conversion is making the signal proportional to *L**, both of these require a larger number of levels to start with than what is output. These systems are highly nonlinear, but may work well with a limited number of gray levels, for example with 8 bits (256 levels) rather than the 10 or 12 bits as discussed earlier.

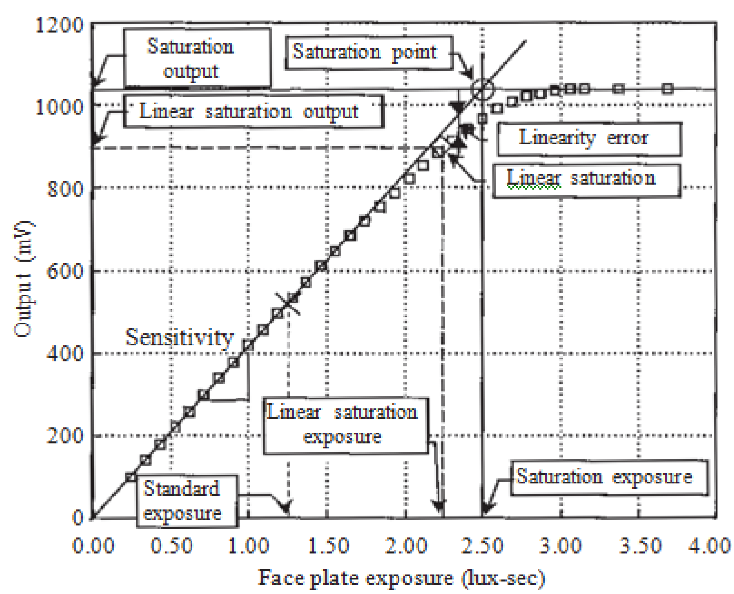

FIGURE 3.24
Fundamental electronic response to light of a sensor used in scanners and cameras showing the linear and nonlinear regions. (Reproduced with permission of the publisher from Nakamura, *J. Image Sensors and Signal Processing for Digital Still Cameras;* Taylor and Francis: Boca Raton, FL, 2006; Mizoguchi, T. Ch 6: Evaluation of image sensors, 179–203; Yoshida, H. Ch 10: Evaluation of image quality, 277–303, p. 189.)

Many input scanners operate with a built-in calibration system that functions on a pixel-by-pixel basis. In such a system, for example, a particular sensor element that has greater responsivity than others may be attenuated or amplified by adjusting either the gain or the offset of the system or both. This would ensure that all photosites (individual sensor elements) respond equally to some particular calibrated input, often, as is common with most light measuring devices such as photometers and densitometers, using both a light and dark reflectance reference (e.g., a white and black strip of paint).

It is possible in many systems for the sensor to be significantly lower or higher in responsivity in one place than another. As an example, a maximum responsivity sensor may perform as shown in curve A while a less sensitive photosite may have the response shown in curve C. If curve C was captured with the same A/D converter at the same settings (as is often the case in high-speed integrated circuits), the maximum signal range it contains has only 120 gray levels. A digital multiplier can operate upon this to effectively double each gray level, thereby increasing the magnitude of the scale to 220 or 240, depending upon how it handles the offset. Note that if some of the elements of a one-dimensional sensor responded as curve C, others as A, with the rest in between, then this system would exhibit a kind of one-dimensional granularity or non-uniformity, whose pattern depends upon the frequency of occurrence of each sensor type. This introduces a quantization error varying spatially in one-pixel-wide strips, and ranging, for this example, from strips with only 120 steps to others with 240 steps, yet covering the same distribution of output tones.

An ideal method for measuring tone reproduction is to scan an original whose reflectance varies smoothly and continuously (See Figure 3.50 at the top) from near 0% to near 100%, or at least to the lightest “white” that one expects the system to encounter. The reflectance is evaluated as a function of position, and the gray value from the scanner is measured at every position where it changes. Then the output of the system can be paired with the input reflectance at every location and a map drawn to relate each gray response value to its associated input reflectance. A curve like Figure 3.23 can then be drawn for each photosite and for various statistical distributions across many photosites.

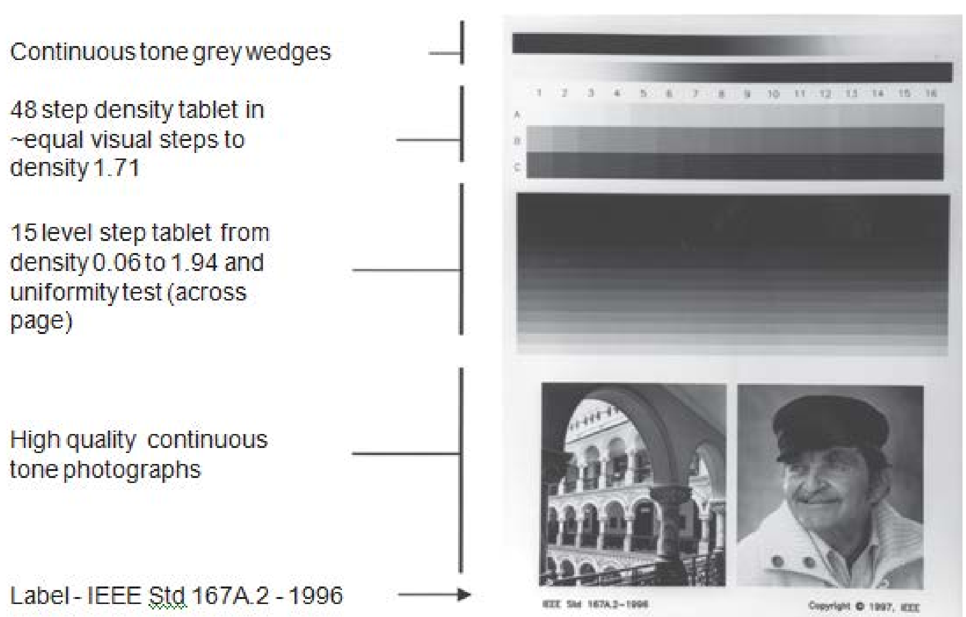

Figure 3.50A
Image of an IEEE Standard Facsimile Test Chart found in IEEE Std. 167A.2-1996, High Contrast (gray scale) chart printed on glossy photographic paper. It contains many elements valuable in assessing tone reproduction performance of scanning systems. To identify what test pattern element each annotation refers to, project the relative vertical position of the bar in the specific annotation horizontally across the image of the test pattern. A full explanation of each is available on the IEEE web site which, at the time of this writing, was http://standard.ieee. org/catalog/167A.l-1995.htm.

(*Note:* Do not attempt to use reproductions of this figure as test patterns, they are highly degraded .)

It is difficult to fabricate continuous grey wedges, so, many test patterns used for such evaluations are created as steps of different greys as seen in the next two sets of patterns in Figure 3.50. The page wide steps in the 15 step array enable testing for non-uniformity as described earlier Often such testing needs some context using a real picture to evaluate human reaction to tonal reproduction, so, a landscape and a portrait have been included at the bottom of the test chart. In a camera situation testing is often done using a large step tablet situated in the middle of an actual scene, often a table top set up.

3.4.2 The Digital System Jones Plot

The classic concepts of quality in tone reproduction generally extend to processes and devices beyond the capture device. Hence the idea of quality for a scanner involves how well it integrates into an overall system that would include a printer or display. This integration is facilitated by image processing, both hardwired in the scanner and through off-line software systems. The graphical construction of a multi quadrant “Jones Plot” has often been used in photography to characterize how a film integrates with camera/optics, ilm processing, an enlarger and printing paper and even the visual system.[60,61] Similar systems plots can be constructed for the digital system starting either with the camera or the scanner. One such example, using representative system data is shown in Figure 3.25. Starting at the axis labeled “original density” one creates four quadrants in a clockwise progression starting with Quadrant 1 (lower right) as a plot of digital output level (DOL) versus input Density (or equivalent Log Exposure) for the scanner or camera in question. This is a type of OECF (Optoelectronic Conversion Function) Curve.[65] In this illustration Density of the original target is plotted increasing to the left (Log exposure would increase to the right) and DOL (some call this value digital count or gray value) increases toward the top. A dashed line indicates a linear response that follows the actual curve down to the dark region where it begins to flatten out due largely to flare light. The fact that the log values of density in the bolder solid curve agree so well with the linear values of electronic digital output (DOLs) suggests that the on-board image processing in this scanner is creating a nonlinear response (for the linear sensors as noted above) in order to better fit some output needs of printing or viewing. This would be typical of some digital cameras as well as some scanners where off-line image processing was expected. The lighter dotted line represents the output of a typical scanner integrated with the printer shown in Quadrant 3, a so-called all-in-one system or a digital copier.

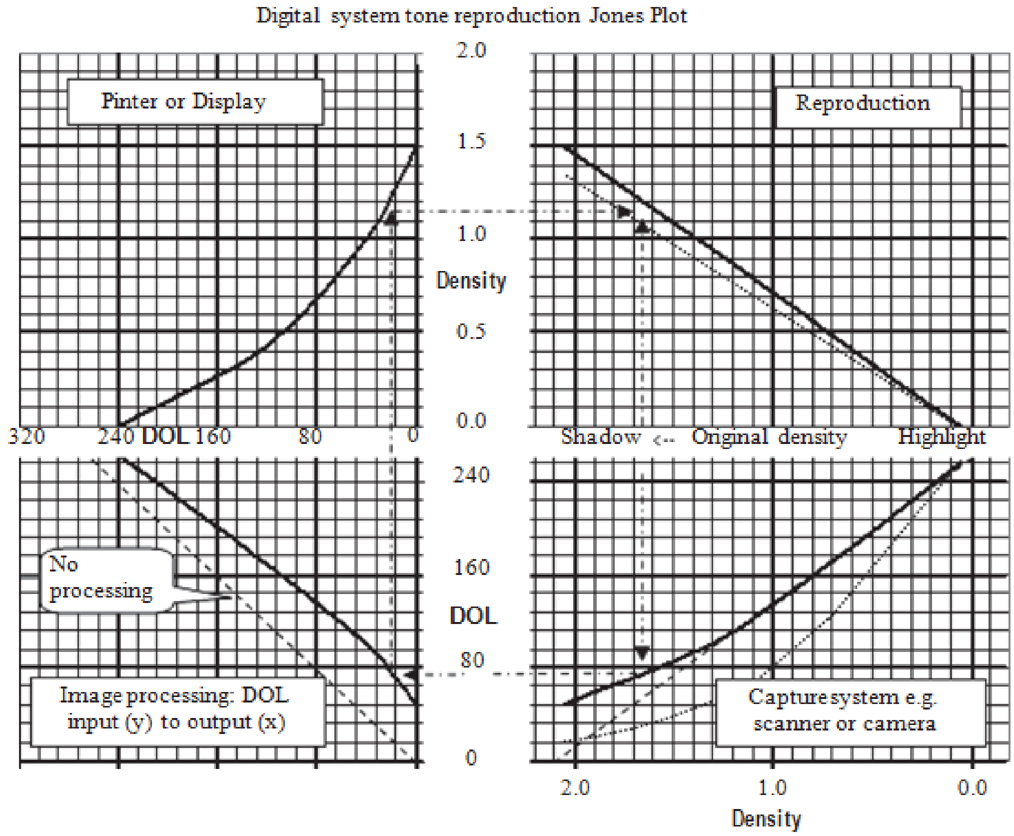

FIGURE 3.25
Jones plot for tonal response in a digital imaging system showing the cascade of components using four quadrants, Q1–Q4: Q1 (lower right) is for digital capture system (scanner or camera) showing density of the original test object (x-axis) mapped to digital output level (i.e., DOLs on y-axis), Q2 (lower left) is the image processing which maps the same DOLs on y-axis to image processing digital output levels (DOLs on x-axis) The latter are also digital input levels in Q3 (upper left) for either a printer or display. Here printer input levels map to output printed density (x-axis). In Q4 (upper right) the resulting solid curve (follow the dashed arrow through all four quadrants to see the cascading) gives printed density (y-axis) compared to original test object's density (x-axis). This is the scanning (or photographic) system's overall tone reproduction.

In many such evaluations two of the other three quadrants are specified and the goal is to derive the missing curve. Consider that the rendering device (Quadrant 3 clockwise) is a printer with a fixed density response to a given array of input DOLs. Assume that the it is desired that reproduction (Quadrant 4) be a linear relationship between density of the original and that of the print, even though the maximum densities do not match. This leaves the image processing (Quadrant 2) to be determined. A linear, one for one, image processing between input from the first scanner and output DOLs (dashed curve) would result in a very light print with a somewhat curved density reproduction relationship. The solid curve in Quadrant 2 (Image Processing) results in the desired linear density relationship in Q4.

The second scanner curve (dotted) is less linear but includes on-board image processing which predistorts the output to compensate for the highly curved printer density response curve. This scanner response directly provides another linear inal tone reproduction in Quadrant 4, although with slightly lower maximum density. In the Jones Plot this result uses the dashed "no image processing" curve in Quadrant 2 since off-line image processing is not possible in an all-in-one (copier) system. This scanner curve is the same one used in Figure 3.26 later.

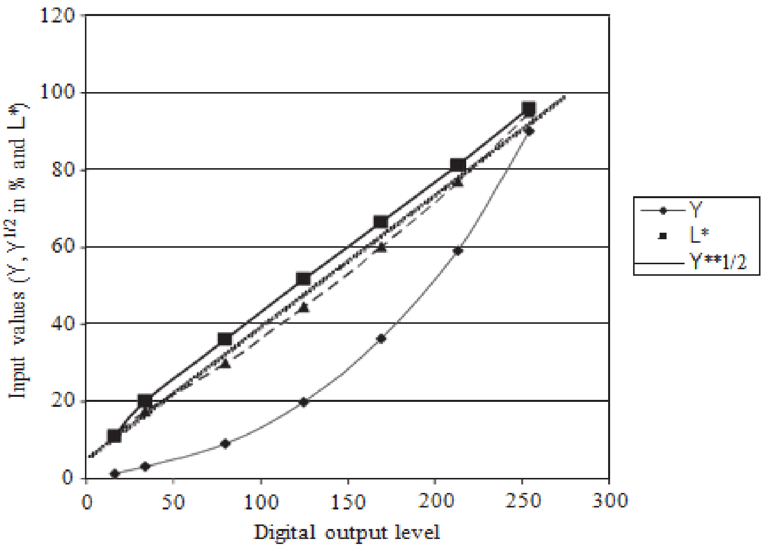

FIGURE 3.26
Scanner output digital levels (x-axis) as predicted by the input test target reflectance values or CIE *Y* (diamonds), *L** (large squares), $Y^{1/2}$ (small triangles), and a straight dotted line visually **it** to the last two. The ordinate is the input value plotted on a relative scale of 0–100. Therefore *Y* (which ≈ reflectance) is given in %.

Most scanners operate with sufficiently small detector sites or sensor areas that they respond to input granularity. Thus, a single pixel or single photosite measurement will not suffice to get a solid area response to a so-called uniform input. Some degree of averaging across pixels is required, depending upon the granularity and noise levels of the input test document and the electronic system.

The use of a conventional step tablet or a collection of gray patches, where there are several discrete density levels, provides an approximation to this analysis but does not allow the study of every one of the discrete output gray levels. For a typical step tablet with approximately 20 steps changing by 0.10 reflection density, half of the gray values are measured by only 4 steps, 0, 0.1, 0.2 and 0.3 density (D=.3 is 50% reflectance). Thus a smoothly varying density wedge is more appropriate for the technical evaluation of an electronic input scanner or camera.

However, since suitable wedges are difficult to fabricate repeatably as noted earlier, the use of uniform patches of several discrete densities is much more common in many operations. See, for example, Reference 106 for many commercial test targets. In fact the ISO standard target for camera testing in Figures 3.51 is only composed of 12 steps but has been specified in several contrasts extending the precision of the standard Nonetheless, wedges are available (see the IEEE target in the top of Figure 3.50 as explained above, or the Kodak Q60 target[106]), and are essential to accurately evaluate certain scanning effects.

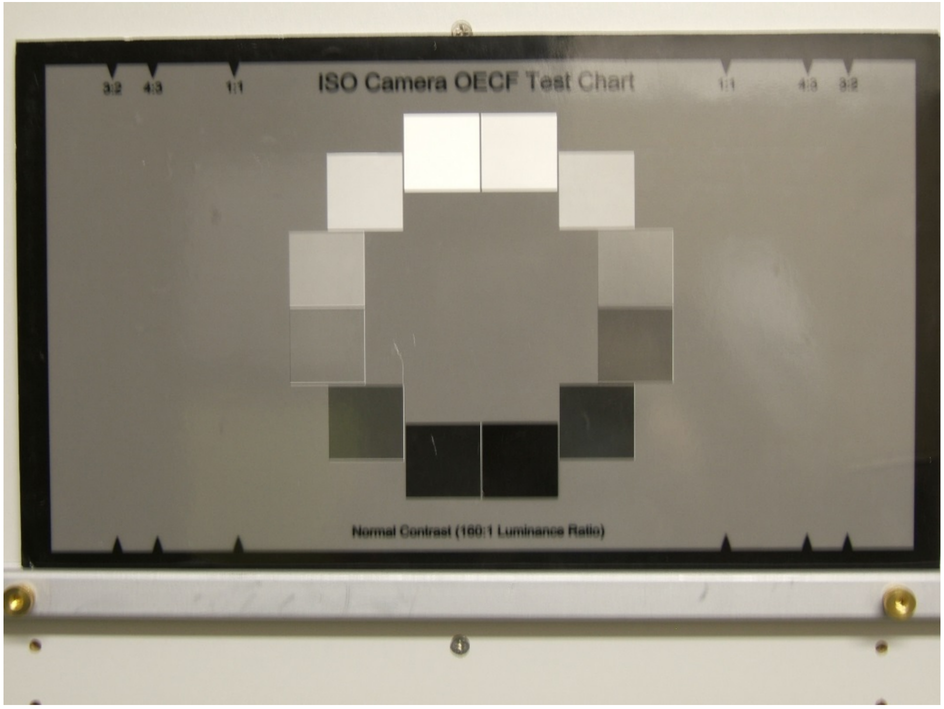

Figure 3.51
A picture of the ISO Camera OECF Test Chart for measuring tonal response where the steps are arranged in a circle to compensate for a well known digital camera effect in which response varies with the radius from the center of the image. In this arrangement the camera respons is a constant (but not the maximum) and only the tonal response variation is captured by the steps. OECF means Opto-Electronic Conversion Function which is the digital camera characteristic curve terminology. These charts have differing reflectance or luminance ranges. This one is for 160:1, the average outdoor scene luminance range.

Returning to the large area tonal response of the scanner itself, it is tempting to describe it as the linear equation for the sensor itself but the fact is that most scanners today have some built-in image processing associated with them and it is more practical to use a curve. To compensate for some common printer and display response, scanner's tone response neglecting flare can often be mapped as

$$DOL = Hr^{1/\gamma} \qquad (3.11)$$

where Hr is the relative exposure from the input and ș (gamma) is a constant designed to compensate for the exponential-shaped curves often found in output printers or displays. Values of 1.8, 2.2 are examples for Mac and PC monitors and 3 to emulate L* but a general purpose scanner may desire to satisfy all these conditions with some hybrid and a few other terms. Results for a recent desktop scanner are shown in Figure 3.26—an x versus y inverted type of OECF21 curve—using the resulting digital output levels as the x-axis and various characterizations of the input as the y-axis to deduce the vendors image process- ing. The system is not linear in reflectance but is approximately linear in either L* or ș = 2 Note ș = 2 is halfway between the Mac and PC standards.

Setting the maximum point equal to 100% input reflecSetting the maximum point equal to 100% input reflectance is often a waste of gray levels since there are no documents whose real reflectance is 100%. A value somewhere between 70% and 90% would be more representative of the upper end of the range of real docu- ments. Some systems adjust automatically to the input target and are therefore dificult to evaluate. They are highly nonlinear in a way that is dificult to compensate. See Gonzalez and Wintz98 for an early discussion of automatic threshold or gray scale adjustment and Hubel93 for more recent comments on this subject as it relates to color image quality in dig- ital cameras. Most amateur and some professional digital cameras fall into this automatic domain93 as do many scanners. A system that finds this point automatically is optimized for each input differently and is therefore difficult to evaluate in a general sense.

An offset in the positive direction can be caused either by an electronic shift or by stray optical energy in the system (as shown in Q1 of Figure 3.25). If the electronic offset has been set equal to zero with all light blocked from the sensor, then any offset measured from an image can be attributed to optical energy. Typical values for flare light, the stray light coming through the lens, would range from just under 1% to >5% of full scale.96 While offset from uniform stray light can be adjusted out electronically, signals from flare light are document dependent, showing up as errors in a dark region only when it is surrounded by a large field of white on the document. Therefore, correction for this measured effect in the particular case of an analytical measurement with a gray wedge or a step tablet surrounded by a white field may produce a negative offset for black regions of the document that are surrounded by grays or dark colors. If, however, the source of stray light is from the illumination system, the optical cavity, or some other means that does not involve the document, then electronic correction is more appropriate. Methods for measuring the document-dependent contribution of flare have been suggested in the literature.96,97,99 Some involve procedures that vary the surround ield from black to white while measuring targets of different widths;96 others use white surround with different density patches.97

A major point of confusion can occur in the testing of input scanners and many other opti- cal systems that operate with a relatively confined space for the illumination system, docu- ment platen, and recording lens. This can be thought of as a type of integrating cavity effect. In this situation, the document itself becomes an integral part of the illumination system, redirecting light back into the lamp, reflectors, and other pieces of that system. The document's contribution to the energy in the illumination depends on its relative reflectance and on optical geometry effects relating to lamp placement, document scattering properties, and lens size and location. In effect the document acts like a position-dependent and nonlinear amplifier affecting the overall response of the system. One is likely to get different results if the size of the step tablet or gray wedge used to measure it changes or if the surround of the step tablet or gray wedge changes between two different measurements. It is best, therefore, to make a variety of measurements to find the range of responses for a given system. These effects can be anywhere from a few percent to perhaps as much as 20%, and the extent of the interacting distances on the document can be anywhere from a few millimeters to a few centimeters (fraction of an inch to somewhat over one inch). Relatively little has been published on this effect because it is so design specific, but it is a recognized practical matter for measurement and performance of input scanners. An electronic correction method exists.[100,101]

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