Fast Gray Calibration for Digital Photographic Printers

P. Zolliker
GRETAG IMAGING AG
Regensdorf, Switzerland

Abstract

Gray calibration of a photographic printer is usually an iterative process of printing and measuring test prints with the goal to produce a gray wedge from paper white (D_{min}) to the maximal reachable dark gray (D_{max}). The iterative nature is due to the lack of an appropriate color reproduction model, in particular for colors not on the gray axis. A calibration method is presented based on two main elements. One element is a color reproduction model using the spectral properties of the color dyes of the photographic paper. This model was originally developed to facilitate color management for photographic printing but turned out to be very useful also for paper calibration. The other element is an analytical model for the saturation curves of the three dyes. Special attention is paid to the handling of the colors close to D_{max} and D_{min}. The presented method drastically reduces the number of iterations needed for the calibration process and even allows one step calibrations in many cases. A first successful implementation of this method was realized in GRETAG's CYRA FastPrint.

Introduction

Gray calibration of a photographic printer is commonly an iterative process of printing and measuring test prints with the goal to produce a gray wedge from paper white (D_{min}) to the maximal reachable dark gray (D_{max}). The iterative nature is due to the lack of an appropriate color reproduction model, in particular for colors off the gray axis.

A calibration method is presented based on two main elements. One element is a model for the saturation curves of photographic paper and the other is a color reproduction model based on the spectral reflection properties of photographic paper.

The task of paper linearization consists of finding three one-dimensional functions to describe the relation between RGB values and the intensities of the exposure system. In this paper we call the device dependent color space p_{RGB}. Another task is to find the relation between p_{RGB} and a device independent color description (e.g. CIE-Lab). In color management terms this task can be described by a profile. For calibration purposes, where only gray wedges are involved, this task simplifies to a one-dimensional relation between the measured paper densities (measured as CMY or CIE-Lab) and the p_{RGB}. Test prints are interpreting sRGB values as p_{RGB}. This way calibration forces the gray axis of the p_{RGB} color space to be the same as sRGB. However the relation between CMY densities and p_{RGB} is not linear and depends on the spectral reflection properties of the paper. We call this relation aims curve. Empirically this aim curve can be approximated by a curve of the form $(1-x)^{\gamma}$ with a parameter γ of approximately 1.5. Below we will show that this function can be derived from the spectral paper model.

Paper Linearization

Here the first element of our calibration method is described. A common way to handle paper calibration is to set up a table for all measured gray patches. A suitable (mostly linear) interpolation determines the grays in between. In the presented the paper saturation curve is described with an analytical function with as few parameters as possible. In a very first approximation the paper saturation curves resemble a *tanh*-function, if we use a logarithmic scale for the exposure values. This is a good base to start with. Instead of modeling the saturation curve $y = f(x)$ itself we use the first derivative of it as function of y: $y' = g(y)$, which will be called 'paper slope function'. The saturation curve can be reconstructed by integration.

For our base model we have

$$g(y) = (1-y^2) \quad (1)$$

which after integration results in the saturation curve

$$y = tanh(x-x0) \quad (2)$$

For our actual model a forth order polynome is used for the paper slope function:

$$g(y) = \Gamma_{max} \cdot (1 - s(y)^2) \cdot (1+p1 \cdot s(y) + p2 \cdot s(y)^2) \quad (3)$$

where

$$s(y) = (2 \cdot y - D_{min} + D_{max})/(D_{max} - D_{min}) \quad (4)$$

The paper slope function crosses zero at D_{min} and D_{max}. The maximum value Γ_{max} of the polynome corresponds to the maximum slope of the saturation curve. The 6 free parameters (D_{min}, D_{max}, Γ_{max}, two higher order coefficients p1, p2, and x0) are fitted to the measured data.

The parameter p1 describes the asymmetry of the paper slope function and the parameter p2 describes the linearity of the paper curve for intermediate densities.

Both parameters have a range of [-1,1]. Independent of D_{max}, D_{min} and Γ_{max} they describe the form of the paper saturation curve.

The inverse of the saturation curve is set up by numerical integration

$$logE(y) = \int 1/g(y) * dy \qquad (5)$$

from which the saturation curve can be derived by numerical inversion of the function. The sixth parameter x0 corresponds to the shift in exposure density and can be determined with the integration.

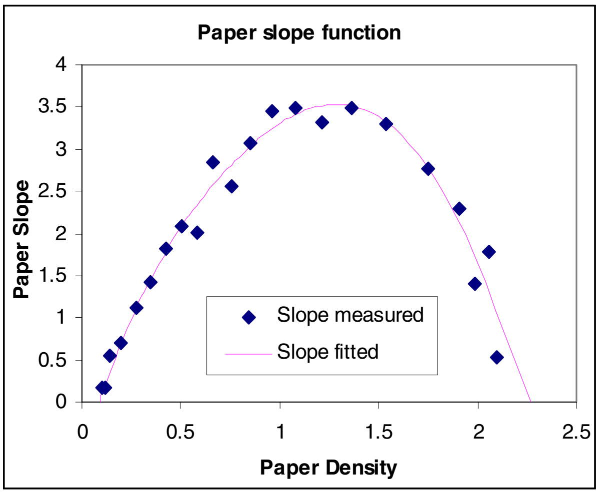

Figure 1. Paper slope as a function of Paper density (measurement data and fitted data)

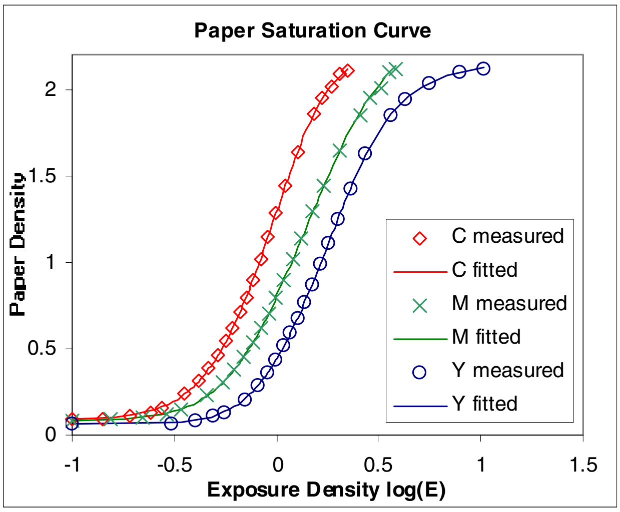

Figure 2. Paper curves of a typical paper

Tests were made for commonly used photographic papers of the major paper manufactures with a digital printer using DMD-technology (Digital Mirror Device). Within the used density range from paper white to D_{max} (typically 2.0 – 2.2). The saturation curve could be fitted better than an average of 0.02 paper density differences with maximum deviations of 0.05 in the dark grays (see Fig. 1 and 2). For all investigated papers we found no need to add further higher order terms to Eq. (3).

Spectral Paper Model

The second element in our calibration model is a color reproduction model using the spectral properties of the dyes built up in photographic paper. This model was originally developed to facilitate color management for digital photographic printing.[1] The spectra of any combination of dye concentrations can be modeled based on the measured spectra of pure dye colors, using a one parameter Kubelka-Munk[2] model for color mixing. Paper densities and CIE-Lab values can be computed from the modeled spectra using the appropriate filters. We need measured reflection spectra of the three saturation colors C, M, and Y $R_i(\lambda)$ (i=1,2,3) and the reflection spectrum of the paper base $R_0(\lambda)$.

Given three dye concentrations c_i in the range [0,1], the reflected intensity can be computed for every wavelength λ. First we use a transformation to bring the spectra into a form that they are additive. Then we use the inverse transform to get back the modeled reflection spectra.

$$K(\lambda) = -0.5 \cdot ln(R(\lambda)/[(1-f_{int})+f_{int} \cdot R(\lambda)]) \qquad (6)$$

The parameter f_{int} is used to compensate for internal reflections for which Williams et.al. [3] report a value of $f_{int} = 0.614$. In our model spectral absorptions $K_i(\lambda)$ for the three dye colors and the paper base are assumed to be additive.

$$K(\lambda) = K_0(\lambda)+\sum_i C_i(K_i(\lambda) - K_0(\lambda)) \qquad (7)$$

Inverting Eq. (6) we get back the reflection spectra:

$$R(\lambda) = e^{-2 \cdot K(\lambda)} \cdot (1-f_{int})/(1-f_{int} \cdot e^{-2 \cdot K(\lambda)}) \qquad (8)$$

CMY densities can now be computed by convoluting with the appropriate filter curves. For paper calibration purposes ANSI Status A paper densities are used. Using standard filter curves f^{ANSI}_i and standard light source $\Sigma(\lambda)$ (e.g. D65) we get

$$CMY_i = N^{-1} \cdot \int \Sigma(\lambda) \cdot f^{ANSI}_i(\lambda) \cdot R_i(\lambda) d\lambda \qquad (9)$$

with norm

$$N = \cdot \int \Sigma(\lambda) \cdot f^{ANSI}_i(\lambda) \qquad (10)$$

CIE-Lab values can be calculated in the same way by convoluting with the filter curves of a standard observer to obtain XYZ.

Now we have established a model, which allows the computation of paper densities CMY for every triple of concentration c_i. Within the gamut of all paper densities the model can also be inverted. For every measured CMY triple a concentration triple c_i can be found. For practical purposes a three-dimensional lookup table using interpolation approximates the inverse model.

The link from concentrations c_i to p_{RGB} is done by a one-dimensional function to ensure that p_{RGB} is linear to sRGB for the gray axis. The following one-parameter function allows a good approximation:

$$c_i = (255-p_{RGBi})/(255+d_i*p_{RGBi}) \qquad (11)$$

The parameter d_i is chosen in a way that the reference gray of p_{RGB} is equal to its sRGB value. Applying this model to a gray wedge allows to compute the aims curve.

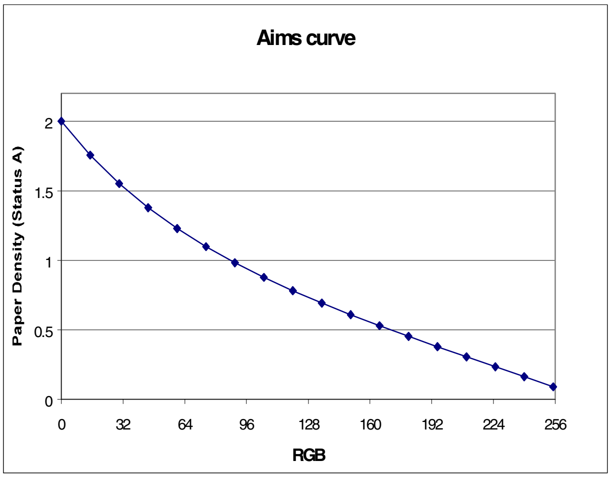

Figure 3. Paper Density as a function of pRGB

Discussion

Speed Up Iteration Process

If the paper saturation curves are set up using the relation of log(E) versus paper densities the calibration process is iterative. This is due to the spectral distribution of the color dyes. The paper model now allows to transform the measured paper densities to p_{RGB} values. The three color channels are independent of each other. The paper saturation curve can be set up using log(E) versus p_{RGB}. If the paper model is accurate enough, the calibration process can be done in just one step. This requires the spectral measurement of the test patches. In practice a model for an average photographic paper already brings a big improvement, even if only CMY paper densities (and not spectra) are available.

Insensitivity to Errors in the Measurements

In contrast to a calibration using an interpolated linear lookup table, the model based paper saturation curve is insensitive to measuring errors of single patches. It is also easier to identify measurements of patches that are clearly out of range.

D_{min}-D_{max} Considerations

Special attention has to be given to the handling of the colors close to D_{max} and D_{min}, because no photographic paper can achieve pure white and pure black. For the reproduction of light grays it is important to have a smooth transition to paper white. The analytical model allows a more accurate description for paper densities close to paper white as compared to a linear interpolation (e.g. using equally distributed gray patches).

To get the most out of a photographic paper it is the goal to use a D_{max} as high as possible. But there are several reasons to restrict the D_{max} to a lower value than the photographic paper could deliver. Flaring effects (producing colored text borders) and inter-color activation (e.g. yellow turning to orange at high exposure intensities) are not acceptable. Conserving gray up to D_{max} also has to be considered. Exposing devices may not deliver enough light to reach the maximal density for one ore more colors.

The saturation model allows an estimate of the maximum reachable paper density; even if it is past the maximum measured density (see Fig. 4). This approximation may not be very accurate, but it still can give an indication whether a D_{max}-restriction is due to the paper or due to the exposing device.

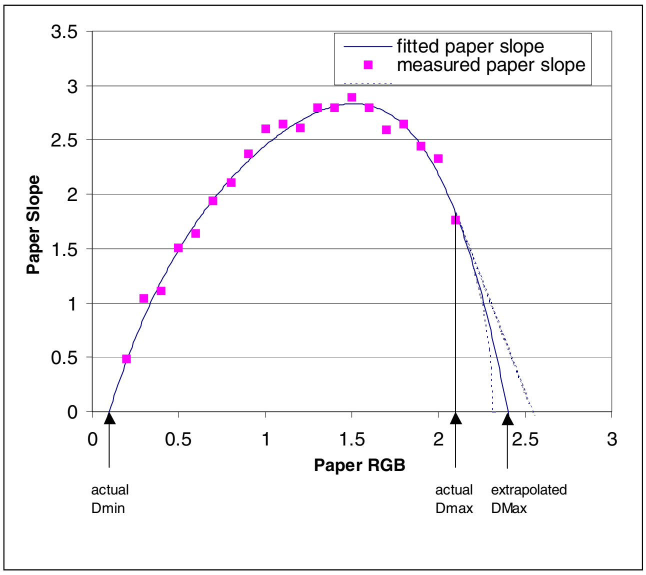

Figure 4. D_{max}-estimation

We can interpret the aim curve as a one-dimensional model of the color management. If the printer is used together with a color management profile, the aims curve must reflect the perceptual rendering properties of the profile on the gray axis. The selection of D_{max} and D_{min} are then given by the profile. In this way paper calibration and profiling are consistent, even if the two steps are done independently.

Conclusion

The presented method reduces the number of iterations needed for the calibration process. It is even possible to achieve a calibration in one step. Furthermore this method delivers more stable results, because it is not sensitive to small errors of single measurements and since it has an excellent behavior close to D_{min}.

If spectra of a few additional color patches (3 - 24) are considered not only a one-iteration paper calibration can be achieved, but it is also possible to get a full color management profile, which otherwise would require 200 or more patches, if commercial color management programs are used.

A first successful implementation of this method was realized in the CYRA printer of GRETAG Imaging.

References

1. R. Meier, and P. Zolliker, "A Color Model for Digital Photo Printing on Silver Halide Paper", paper presented at CGIV'2002 (2002).
2. H. R. Kang, in "Color Technology for Electronic Imaging Devices", SPIE Optical Engineering Press (Washington, USA), pg.48ff. (1997).
3. F. C. Williams and F. R. Clapper, J. Opt. Soc. Am., 43, p. 595ff (1953).

Biography

Peter Zolliker has a degree in Physics from the Swiss Federal Institute of Technology and received a Ph.D. in Crystallography from the University of Geneva in 1987. From 1987 to 1988 he was a post-doctoral fellow at the Brookhaven National Laboratory, New York. In 1989 he joined the R&D team at Gretag Imaging. His work is mainly focussed on image analysis, image quality and setup and color management procedures for digital printers.