# Characterization of an eight colorant inkjet system for spectral color reproduction

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## Abstract

The experimental setup of a 8-channel inkjet printing system intended for spectral color reproduction is proposed. A spectral model of the printer based on the Yule-Nielsen modified spectral Neugebauer equation is presented, discussed, and evaluated experimentally. Although the spectral and colorimetric precision of the printer model leaves room for improvement, the presented research forms an interesting foundation for further research in the field of spectral color reproduction.

## Introduction

Even though Professor Hunt pinned down the concept of *spectral color reproduction* some time back, [1] the idea of creating a reflective physical image, in which the spectral reflectance of the original scene is reproduced, have not been much explored. Besides a few early photographic techniques, it is only recently that this idea has been taken up again in color imaging research. [2–5]

We suggest that it is possible to reproduce multispectral color images faithfully on printed media, using a multichannel image reproduction system. The goal is to reproduce images with a spectral match to an original scene, or a reference image, in order to eliminate the problems of the conventional metameric matches that can be achieved with four-color printing processes. A metameric match is only correct under a given viewing illuminant, while a spectral match is correct under any illuminant.

This spectral match can only be achieved through careful selection of colorants and an innovative separation algorithm. One possible strategy for this would be to first make a colorimetric match through conventional four-color separation techniques, and then add the extra channels in order to reduce metamerism. Another strategy is to use spectral printer models for the separation, for example the Yule-Nielsen modified spectral Neugebauer equations. [6,7]

The current paper describes our recent results with spectral color reproduction using an off-the-shelf ink-jet printer with exchangeable ink cartridges. The sheet is passed through the printer several times, and ink cartridges are exchanged between the passes. While this is obviously not a very practical solution – the eight-channel printing process is indeed quite cumbersome and time consuming, and alignment problems do occur – it is adequate for research purposes, and allows to demonstrate the concept of spectral printing. Once the different research tasks have been solved, there should be no fundamental obstacles to realizing a multi-head ink-jet printer.

First, we describe the equipment and experimental setup, followed by a presentation of our approach to spectral modeling, i.e. characterization, of the 8-channel printer. Then, we present and discuss our experimental results, before concluding and giving directions for further research.

## Equipment and experimental setup

We have used the Hewlett Packard Deskjet 1220c inkjet printer for our experiments. The main reason for choosing this printer was the availability of replacement ink cartridges with custom inks of different colors. The printer was connected to a personal computer running Microsoft Windows 2000 operating system. Matlab was used for implementing the spectral model.

A set of 8 custom ink cartridges manufactured by Collins Ink Corporation was made available to us. Their spectral reflectances, when applied to regular copy paper were measured by GretagMacbeth's Spectrolino spectrophotometer, with data from 380nm to 730nm with 10nm intervals, see Figure 1.

In order to enable direct control over the K channel of the printer, Ghostscript was used with the Uniprint driver "HP Deskjet 690 Normal gamma 2.0," which provide Floyd-Steinberg Error Diffusion halftoning. The standard Windows printer driver interface could not be used, since it is only working in RGB mode. It was shown [8] that with the aperiodic error diffusion halftoning the problems with overprint moiré was reduced drastically compared to when using regular AM halftoning, see Figure 2.

## Spectral modeling

In accordance with the work of Taplin and Berns [4] and several others, we decided to use the Yule-Nielsen modified spectral Neugebauer model (YNSN), [6,7] to model the spec-

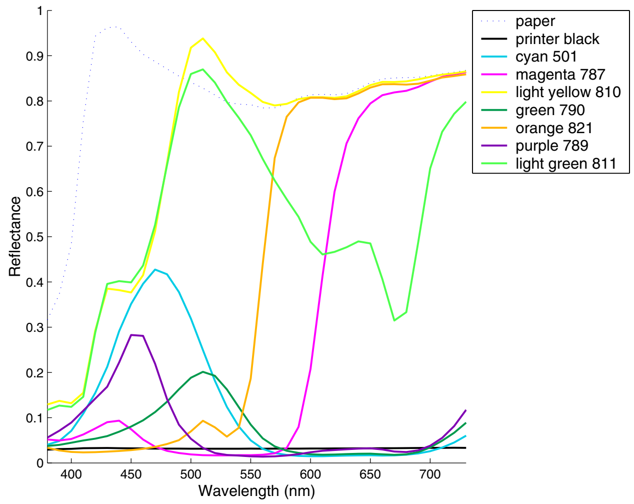


Figure 1: Spectral reflectances of the 8 inks on paper.

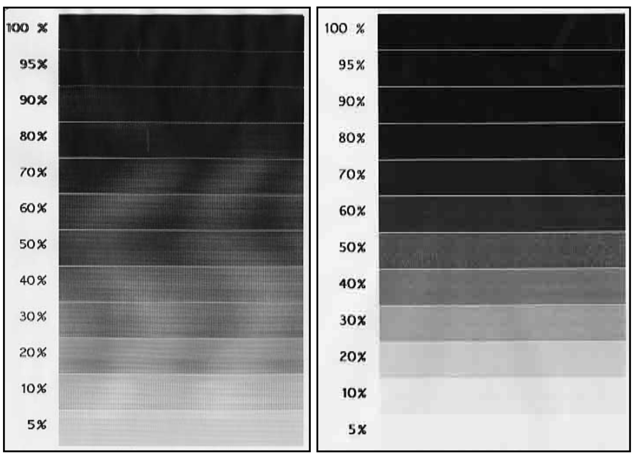


Figure 2: Overprints of two identical halftoning patterns by two passes using AM halftoning (left) and stochastic FM halftoning (right).

tral behavior of the printing system. In this model, the spectral reflectance $\hat{r}(\lambda)$ for a given combination of ink coverages is predicted as

$$\hat{r}(\lambda) = \left( \sum_{i=1}^{2^K} w_i r_{i,\max}(\lambda)^{1/n} \right)^n , \tag{1}$$

where $n$ is an empirical factor accounting for ink-paper interactions, $r_{i,\max}(\lambda)$ is the spectral reflectance of the $i$th Neugebauer primary, and $w_i$ is a weighting factor related to the effective area coverage of each ink.

If $n$ is set to 1, Equation 1 reverts to Neugebauer's original equation. Generally, $n$ is optimized empirically. It has also been proposed to optimize $n$ for different wavelengths. [9]

In order to establish the parameters of this model with our eight-color printing system, we need to print linearization ramps for each primary, as well as all the $2^8 = 256$ Neugebauer primaries, that is, all combinations of one, two, three, and so on, up to eight primaries. We designed a color target specifically for this purpose, see Figure 3. The lower part of the target contain a set of 351 random patches used for evaluation purposes – the test set.

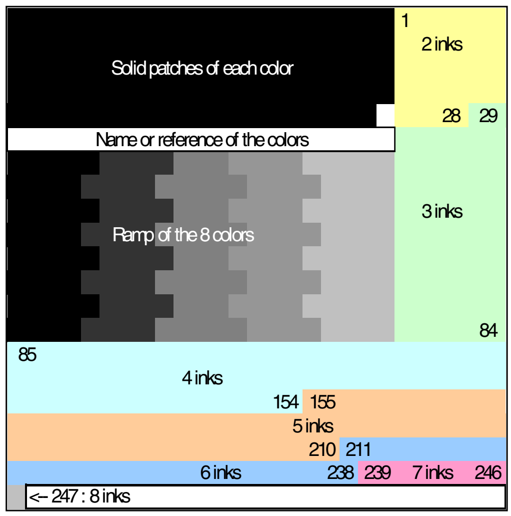


Figure 3: Layout of the 8-overprint target which constitutes the training set.

The printing results with this target is shown in the upper part of Figure 4. We note, not surprisingly, that the amount of ink coverage required for creating the Neugebauer primaries, poses severe problems, as the paper is completely soaked. To evaluate possible solutions to this problem, we devised to modify the target to use 50% coverage instead of 100% as primaries, giving the printed results shown in the lower part of Figure 4. We will refer to these two cases as the 100% and 50% printers.

## Results and discussion

In order to evaluate the accuracy of the spectral model of the printing system, we compare the measured and predicted reflectances of the test target. A multitude of metrics for comparing different spectra exist. [10] We decided here to base our evaluation on the root-mean square (RMS) spectral difference, the relative RMS spectral difference and CIELAB $\Delta E^*_{ab}$ under D65 illuminant.

The results using a plain spectral Neugebauer model ($n = 1$), the YNSN model with $n$ optimized to minimize the RMS spectral error, and with $n$ optimized for minimum spectral error for each sampled wavelength (Figure 5), are shown in Table 1 for the 100% printer, and in Table 2 for the 50% printer. In accordance with the previous results of Wyble and Berns [11] we see that the Yule-Nielsen modified spectral Neugebauer model with spectrally optimized n-values has superior performance for both printers, both in


Figure 4: Printing results of the 8-overprint target using 100% coverage (above) and 50% coverage (below) per primary.

terms of spectral and colorimetric precision. Therefore we retain this model for our further analysis. In Figure 6 we show a few examples of spectral reflectances predicted by the model, compared to the measured ones. The results are clearly better for the 50% printer than for the 100% printer, as was expected mainly due to the obvious ink problems in the high-coverage areas.

Table 1: Performance of the different versions of the model for the 100% printer.

| | Spectral RMS | | Rel. RMS (%) | | $\Delta E^*_{ab}$ | |
|---|---|---|---|---|---|---|
| $n$ | Ave. | Max. | Ave. | Max. | Ave. | Max. |
| 1 | 0.038 | 0.161 | 35.2 | 69.2 | 12.7 | 50.8 |
| 0.9 | 0.037 | 0.141 | 35.1 | 79.8 | 13.0 | 53.6 |
| $n(\lambda)$ | 0.034 | 0.127 | 33.2 | 58.7 | 11.7 | 49.0 |

Table 2: Performance of the different versions of the model for the 50% printer

| | Spectral RMS | | Rel. RMS (%) | | $\Delta E^*_{ab}$ | |
|---|---|---|---|---|---|---|
| $n$ | Ave. | Max. | Ave. | Max. | Ave. | Max. |
| 1 | 0.041 | 0.128 | 17.0 | 48.0 | 7.29 | 20.0 |
| 0.7 | 0.036 | 0.100 | 14.7 | 46.1 | 7.38 | 24.6 |
| $n(\lambda)$ | 0.034 | 0.098 | 14.1 | 45.3 | 6.78 | 20.1 |

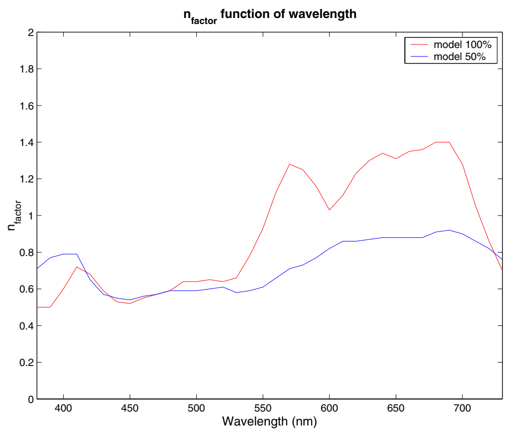


Figure 5: Variation of $n$ with wavelength.

By comparing with results obtained by other researchers, we see that there is indeed room for improvement, e.g. Taplin and Berns[4] obtain an average spectral RMS modeling error of 0.012 with a 6-color inkjet printer using the YNSN model, while Wyble and Berns[11] obtain a spectral RMS of 0.053 with a YNSN model with wavelength-dependent $n$. We therefore proceed to a discussion of the potential sources of the prediction errors.

By plotting the different error metrics versus the total ink coverage (Figure 7) we see a clear tendency of increased relative spectral errors for higher ink coverages, as expected.

Table 3: Ink coverages and prediction errors for the patches of Figure 6.

| Ink coverages | Spectral RMS | Rel. RMS | $\Delta E^*_{ab}$ |
|---|---|---|---|
| Best, 100% printer | | | |
| 0 0 0 0 15 0 0 0 | 0.063 | 5.13 | 3.15 |
| 0 0 0 0 0 0 5 15 | 0.058 | 5.18 | 1.91 |
| 10 15 0 0 0 0 10 35 | 0.051 | 5.55 | 0.57 |
| Worst, 100% printer | | | |
| 0 0 65 0 40 15 85 0 | 0.041 | 58.1 | 12.3 |
| 0 0 100 0 55 0 80 10 | 0.036 | 58.5 | 12.0 |
| 15 0 50 0 60 0 100 10 | 0.037 | 58.7 | 13.0 |
| Best, 50% printer | | | |
| 0 0 10 0 35 0 5 15 | 0.010 | 6.53 | 2.50 |
| 0 40 0 10 0 20 0 12.5 | 0.003 | 6.70 | 4.14 |
| 0 45 12.5 37.5 5 10 0 12.5 | 0.004 | 7.23 | 2.09 |
| Worst, 50% printer | | | |
| 47.5 0 35 0 15 0 0 0 | 0.033 | 43.0 | 12.5 |
| 45 0 7.5 0 50 35 27.5 2.5 | 0.025 | 43.5 | 9.83 |
| 47.5 50 0 0 12.5 17.5 12.5 0 | 0.028 | 45.3 | 12.9 |

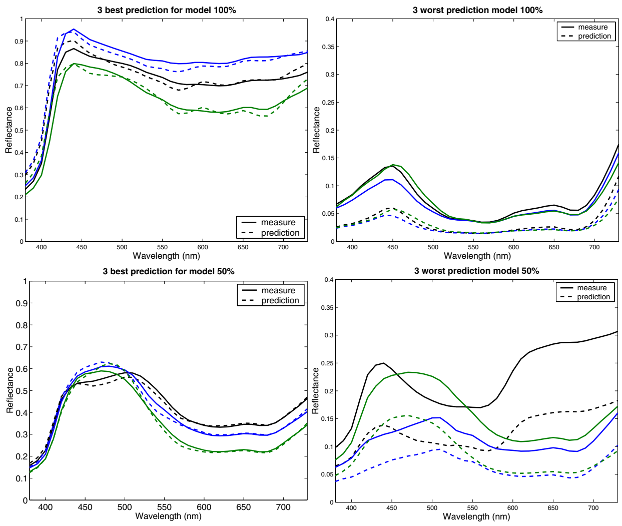


Figure 6: The three best (left) and worst (right) spectral prediction results with regards to relative RMS error, with the 100% printer (above), and the 50% printer (below).

However, it is not evident to observe a significant trend for spectral RMS or $\Delta E^*_{ab}$. Another way of rearranging the results is according to the number of inks used, see Tables 4 and 5. We see that the relative RMS error increases when more inks are used.

Other possible sources of errors include measurement and printing variability. Due to the multi-pass approach there are issues with alignment, and also, especially for light patches the actual dot distribution might be a problem, since the print resolution is rather low. Another problem could originate from the use of inks and paper with fluorescent agents, e.g. the light yellow and light green inks (Figure 1).

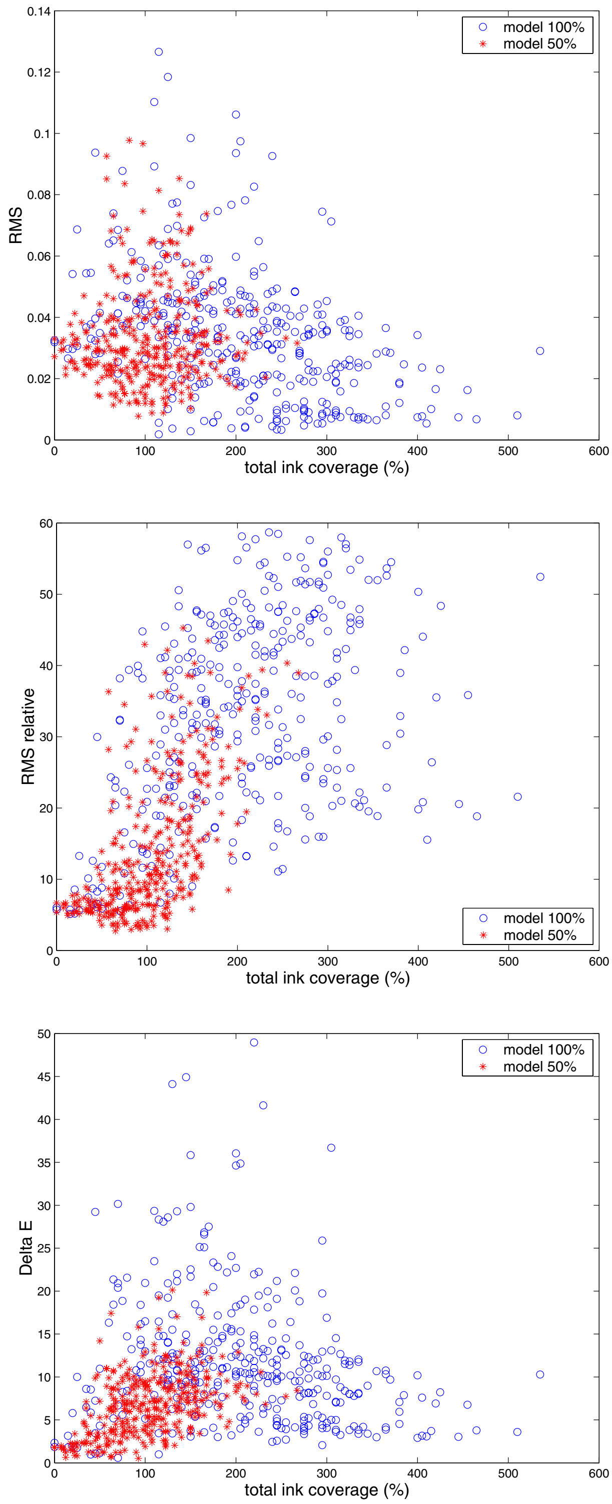


Figure 7: Spectral RMS error (upper), relative spectral RMS error (middle), and $\Delta E^*_{ab}$ (lower) versus total ink coverage.

Table 4: Prediction errors for the 100% printer, sorted according to number of inks.

| | Spectral RMS | | Relative RMS (%) | | $\Delta E^*_{ab}$ | |
|---|---|---|---|---|---|---|
| #inks | Ave. | Max. | Ave. | Max. | Ave. | Max. |
| 1 | 0.047 | 0.094 | 20.9 | 44.8 | 11.4 | 29.2 |
| 2 | 0.039 | 0.078 | 24.0 | 56.1 | 10.9 | 44.1 |
| 3 | 0.040 | 0.127 | 31.9 | 57.0 | 14.1 | 44.9 |
| 4 | 0.035 | 0.106 | 35.3 | 58.5 | 12.1 | 41.6 |
| 5 | 0.028 | 0.118 | 36.7 | 58.7 | 10.6 | 29.8 |
| 6 | 0.025 | 0.083 | 36.7 | 58.0 | 10.0 | 49.0 |

Table 5: Prediction errors for the 50% printer, sorted according to number of inks.

| | Spectral RMS | | Relative RMS (%) | | $\Delta E^*_{ab}$ | |
|---|---|---|---|---|---|---|
| #inks | Ave. | Max. | Ave. | Max. | Ave. | Max. |
| 1 | 0.028 | 0.041 | 6.73 | 13.9 | 3.76 | 14.2 |
| 2 | 0.035 | 0.093 | 10.4 | 34.5 | 5.43 | 11.8 |
| 3 | 0.035 | 0.097 | 12.1 | 43.0 | 6.48 | 17.4 |
| 4 | 0.034 | 0.098 | 13.5 | 42.1 | 6.84 | 20.1 |
| 5 | 0.034 | 0.085 | 17.0 | 45.3 | 7.89 | 19.8 |
| 6 | 0.031 | 0.067 | 17.7 | 43.5 | 7.26 | 12.3 |

## Conclusions and Perspectives

The experimental setup of a 8-channel inkjet printing system intended for spectral color reproduction was proposed. A spectral model of the printer based on the Yule-Nielsen modified spectral Neugebauer equation was presented, discussed, and evaluated experimentally. Although the spectral and colorimetric precision of the printer model leaves room for improvement, the presented research forms an interesting foundation for further research in the field of spectral color reproduction.

There is a huge potential for further research in this area, e.g. devising a more practical setup for multi-channel printing, improving the precision of the spectral model, inverting the model so as to be able to reproduce multispectral color images faithfully, considering spectral gamut limitations, selecting an optimal set of inks, analyzing the tradeoffs involved concerning the number of inks to use, etc.

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## Biography

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