Simulation Experiments in Turbid Media – The Effect of Inhomogeneous Layers

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Abstract: The optical property of the substrate governs the reproduction characteristics and quality of printed paper. Paper is a very complex substrate that is designed for different application areas. In the simplest case it is a one-layer structure of fibers. In more complex structures the substrate may be build from several layers with different properties. In both situations it is vital to be able to control the manufacturing in order to achieve the desired product. This paper deals with simulation of differently composed structures that is difficult to accomplish in complex cases that goes beyond the Kubelka-Munk original theory. The paper describes qualitative results concerning the reproduction due to inhomogeneities in the layers themselves and the layer structures. More specifically we will study two simple structures, a one-layer substrate with inclusions (for example recycled paper) and a two-layer substrate in which the coating layer thickness varies. In the second example the optical properties for the coating layer are supposed to be different from the base. The qualitative results show the degradations that can be expected due to inhomogeneities. The simulations will also allow for computation of the tone value increase in the simulated instances.

Introduction

The modeling of paper and ink interaction and its influence on print quality has attracted a lot of interest in the literature lately. In the Graphics Arts and Paper manufacturing literature it started in 1931 with a new approach to these problems written by Kubelka and Munk, (Kubelka, 31). In a follow up paper (Kubelka, 48) the approach got a wider dissemination. Kubelka and Munk accomplished a description of the phenomena as the result of a two flux light radiation (up and down) in the substrate. Their theoretical formulation was in the form of two coupled partial differential equations, the so called Kubelka-Munk equations. In the paper industry much work and measurements have been based on these equations.

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The second paper of Kubelka (Kubelka, 48) focused on the light scattering in the substrate. The observation that, contrary to the Neugebauer assumptions, the tone value isn't a linear function of ink coverage on the substrate surface has been the subject of many papers. Modeling of the phenomenon based on the scattering of light inside the substrate gave rise to a new model that was proposed by Kruse and Gustavsson (Kruse, 96a, 96b, Gustavsson, 96). The model explained the dot gain and through simulation the tone value increase curves could be assessed for different types of halftoning method.

Further studies were made to solve some problems that were not explained by the Kubelka Munk equations. Granberg and Edström investigated deficiencies in the model under the condition of strong light absorbtion (Granberg, 03). Another effort to advance the knowledge was made by Yang, Kruse and Miklavcic (Yang, 04a, Yang, 04b). The modification of the original Kubelka Munk equations proved to better model reality as shown in extensive measurements. The approach has been criticized and a model based on more general radiative transfer theory has been proposed by Edström (Edström, 07a, Edström, 07b). In a response to the criticism Yang (Yang, 07) justifies the revised approach. The interest in modeling the complex interaction of light, ink and paper has also found interesting properties on the micro scale level.

The present paper is an effort to model the print on substrates (turbid media) that are not uniform. Experiments with halftoning, varying coating thickness, absorbent enclosures in the substrate and small diffusely spread absorbing particles are demonstrated.

Turbid media

In the following we will regard the substrates that we simulate as being constituted by turbid media. In some cases there are more than one type of layer and in others the media is disturbed by enclosures. As a first exercise we simulate how the radiation from a line-source inside a substrate spreads. This is a case that never will appear in reality but it is interesting because it shows the form of the "point spread function". Figure 1 shows a cut in an otherwise unlimited substrate. The radiation spreads outward from the central source. The form of the attenuation at a distance from the center is dependent on the distance itself but also on the absorption and scattering in the substrate. See for example Kruse 1996 b. The attenuation is shown explicitly in Figure 2. For the interested reader we also show the graph as a surface plot, Figure 3, and a contour plot, Figure 4.

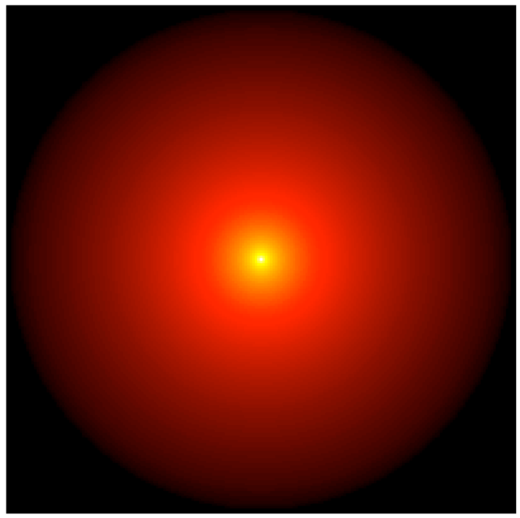

Figure 1. Light scattering from a singular line source.

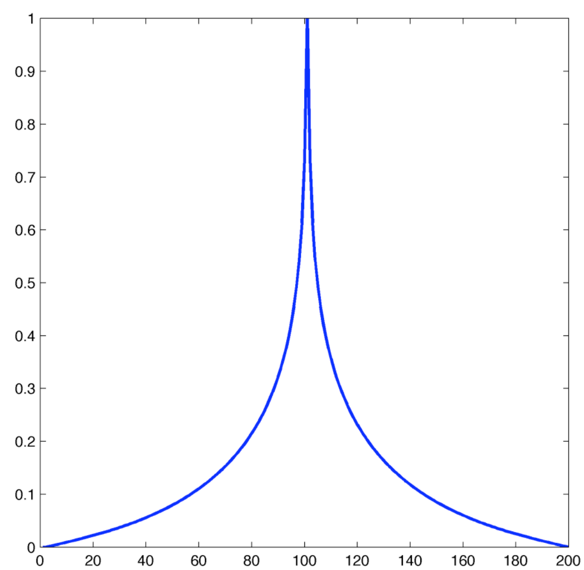

Figure 2. Plot through the center of Figure 1.

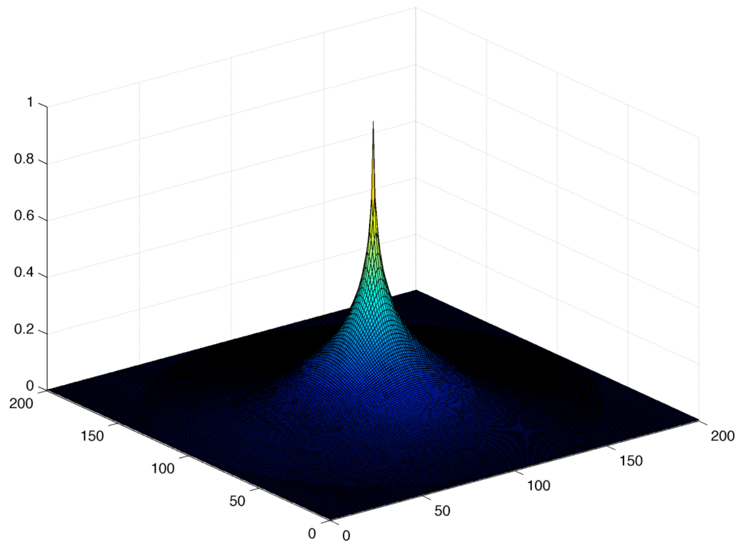

Figure 3. Surface generation of Figure 1.

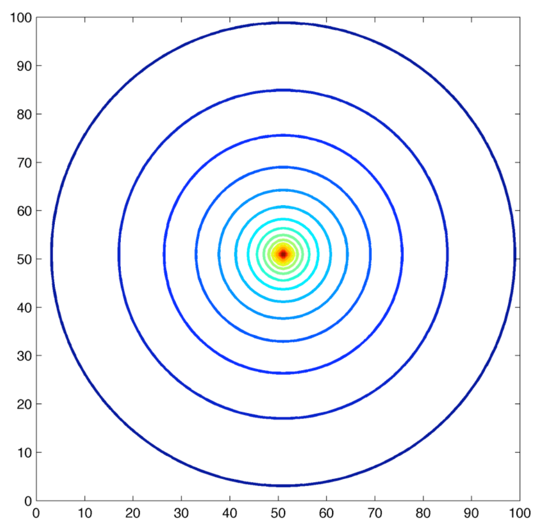

Figure 4. Contour plot of Figure 3.

In the simplest case a single substrate with homogeneous properties is studied for reference. The substrate consists of a homogeneous layer with infinite size in the plane perpendicular to the illustration in Figure 5. The light source illuminates only the middle and not the ends of the substrate. The experiment shows how the radiation density varies with the penetration depth. In the figure it can be observed how the omni directional radiation penetrates into the non illuminated areas on both sides of the substrate. In the middle of the sample the radiation is unperturbed and can be used as a reference for the "white point" for the simulated paper. In both ends where there is no light radiation emerges due to the internal scattering in the substrate. In the vicinity of the transition from illumination to no illumination there is a mixed situation. Some of the light emerges despite that the substrate isn't illuminated. Figure 6 shows clearly what happens in the transition areas. This effect is the prime reason for increased tonal density values close to transition areas.

The effect of half toning

In the preceding paragraphs it has been shown how the scattering in a substrate give rise to a tonal change in the vicinity of a transition from illumination to non-illumination. If we print on the surface of the substrate we get the same situation in principle. Where there is ink there is little light entering into the paper and where there is no ink there is free passage. If the screen ruling is high so the distance between the screen dots is comparable to the distance light is traveling in the substrate the transition areas merge resulting in a substantial tonal value increase. Furthermore in the areas covered by ink the light that emerges has to pass twice through the ink layer which attenuates the emerging light even more. In Figure 7 the effect of two different density values are shown. The ink coverage in the figure is 20 resp. 60 percent. The amount of light emerging from the surface is shown in Figure 8 and Figure 9. Due to the passage through the ink layer the curves are no longer symmetrical as in Figure 6.

Figure 5. Substrate with central illumination with no light falling on the end areas.

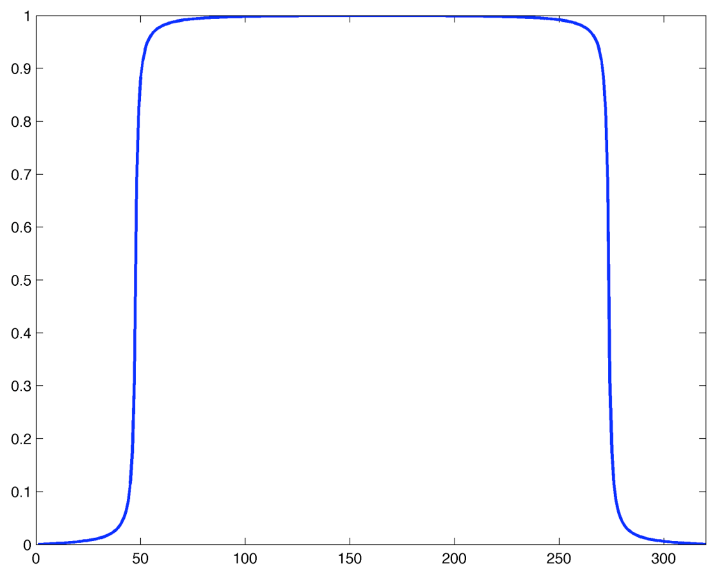

Figure 6. Plot of the normalized radiation leaving the surface.

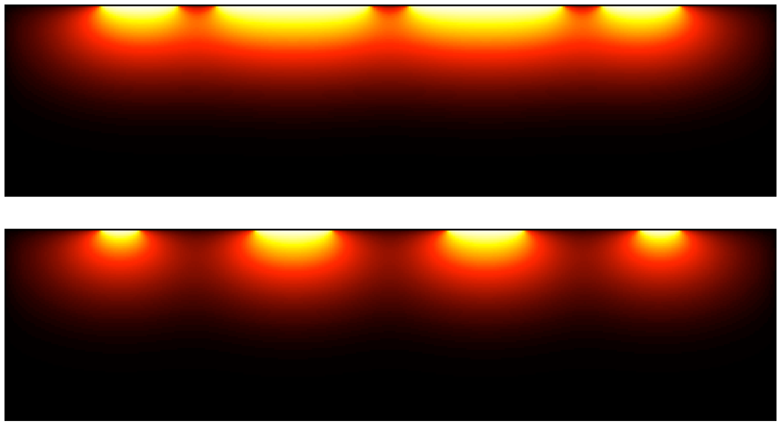

Figure 7. Scattering beneath halftone dots, 20 (upper) and
60 (lower) area coverage.

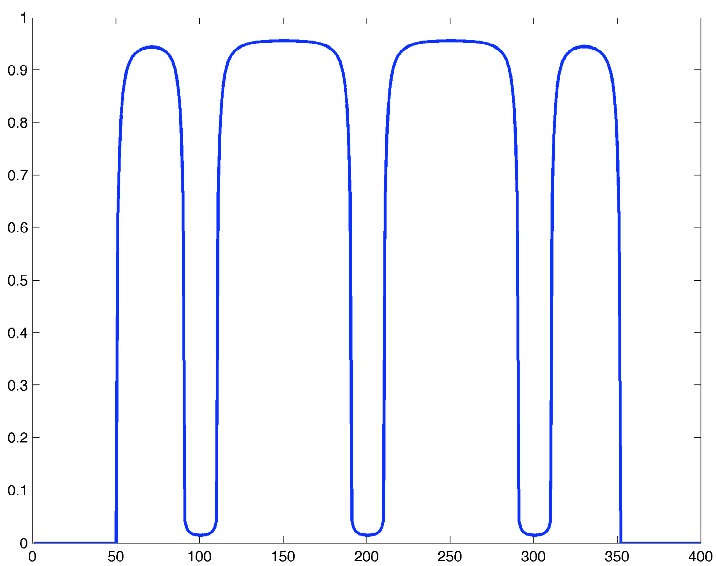

Figure 8. Plot from Figure 7, 20 (upper) , of the light leaving the surface,

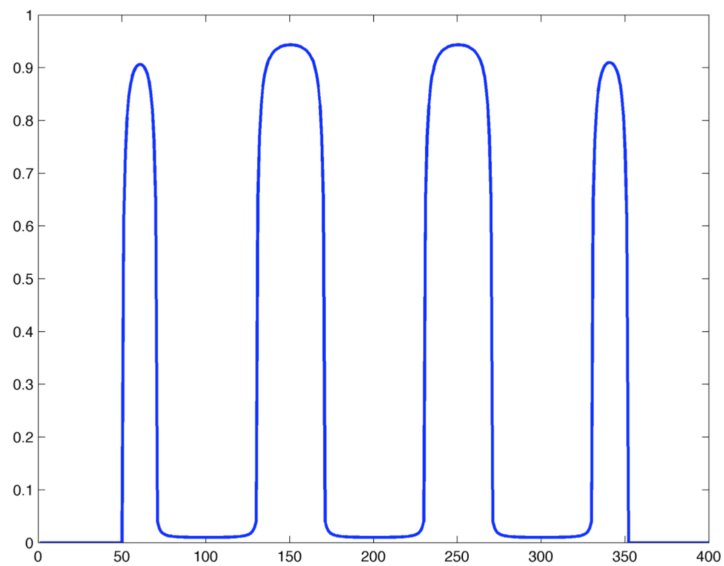

Figure 8. Plot from Figure 7, 60 (lower) of the light leaving the surface,

The effect of enclosed absorbing particles

The preceding experiments have shown the effect of illumination with absorbing ink on an otherwise homogeneous substrate. In the following experiment we will see how a buried absorbing particle will change the situation. Apart from the particle the substrate is still homogeneous. In Figure 9 two situations are shown. In the upper figure the absorbing particle is close to the surface whereas in the lower figure it is buried deeper in the substrate. The effect of the buried particles is shown in Figure 10. Due to the absorption the light penetrating the substrate is attenuated below the particle which is easily understood. However due to the diminished back scattering caused by the absorbing particle also the amount of light that emerges from the top surface is influenced. In Figure 11 it can be observed how the emerging light just above the particle has been dramatically reduced.

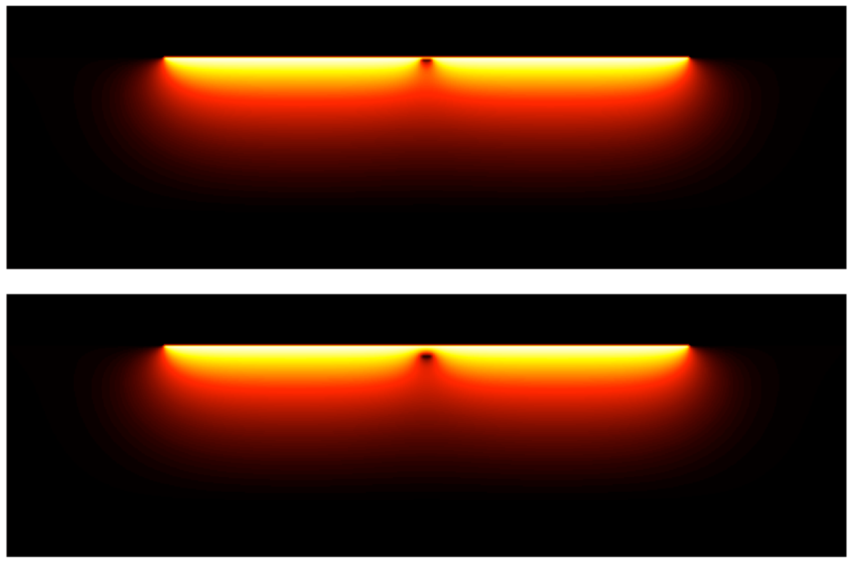

Figure 9. Two cases of particles are shown. In the upper figure the particle is closer to the surface as compared to the lower figure.

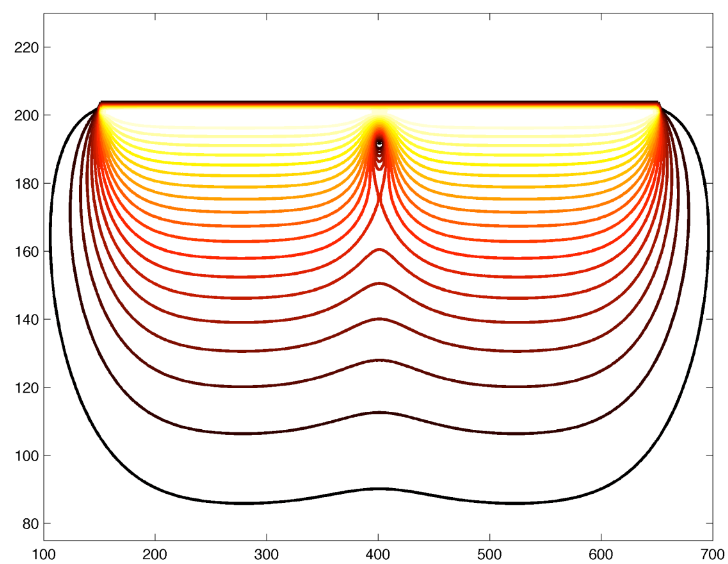

Figure 10. The contours of equal radiation from the lower of theexamples in Figure 9

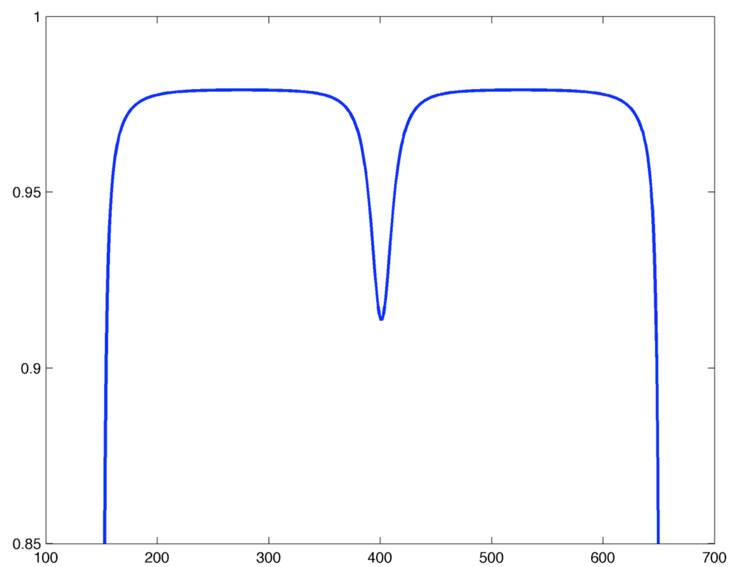

Figure 11. The buried absorbing particle is causing large variation of the emerging light on the surface.

The effect of diffusely spread particles

The effect of a single, rather large, absorbing particle, was demonstrated in Figure 11. In the situation where we have a large number of smaller absorbing particles the effect will increase. Figure 12 shows a situation where the right hand part of the substrate is contaminated with small randomly positioned particles. It can be clearly seen how they cooperate to reduce the emerging light. The reduced whiteness of recycled paper is caused by this effect. Both the contour map of Figure 13 and the plot of Figure 14 clearly shows the effect on an otherwise homogeneous substrate. The effect mottling can to some extent also be accounted for by varying absorption in the composition of normal paper substrates.

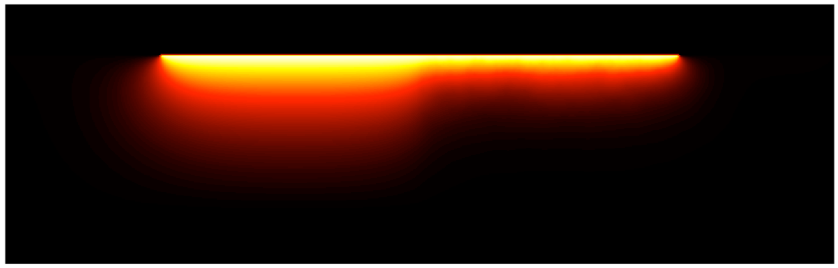

Figure12. The effect of diffusely spread particles buried in the substrate. The contaminated part is to the right.

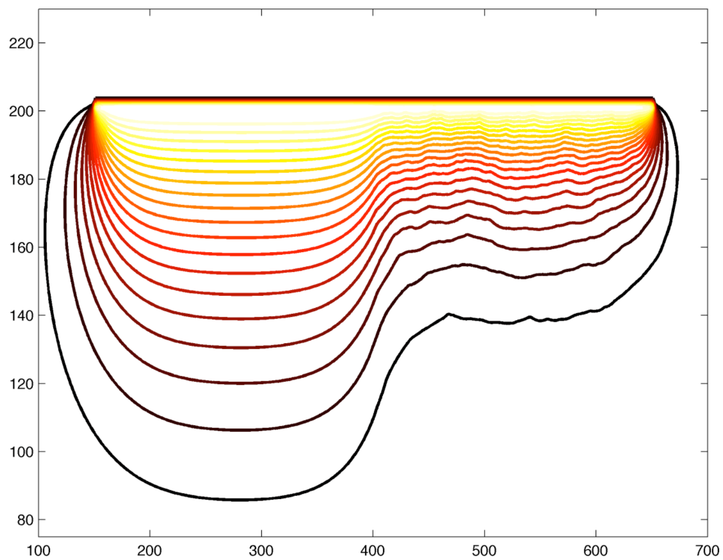

Figure 13. Contour map of the effect of contamination of absorbing particles.

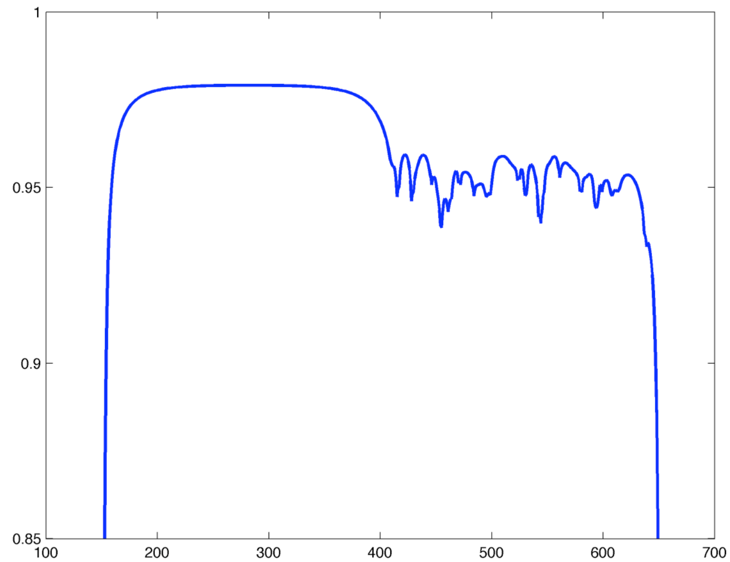

Figure 14. Plot of the emerging light from the contaminated Substrate. The irregularities and attenuation in general can easily be observed.

The effect of a varying coating layer

In the following we will run an experiment with a more complex situation. We assume that we have a homogeneous bulk and coating of the substrate. However we will assume that the interface between the coating and the bulk is varying. With similar optical properties of the bulk and the coating there would be no or little effect on the emerging light. Assuming different scattering properties the varying thickness of the coating layer will have a large impact. In Figure 15 is shown the composition of the substrate. The bulk is covered by a varying layer of coating material. We will assume that the absorption in the coating is higher than in the bulk. In order to complicate the situation further we will also assume that the substrate is printed. The screen ruling is supposed to be low in comparison to the variation of the coating thickness. The result of these assumptions are shown in Figure 16. Where there is ink there is virtually no trace of the varying substrate thickness. On the other hand in the areas that are not covered by ink the effect is clearly seen. It is especially clear from Figure 18 where the peaks in emerging light is caused by the thin layer of coating. Figure 17 shows the contour map of Figure 16.

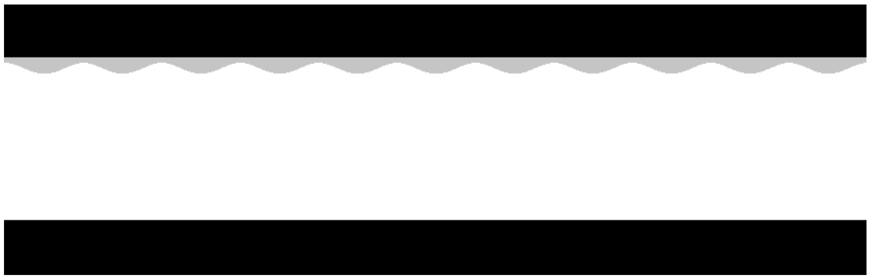

Figure15. The coating layer (gray) on top of the bulk (white)

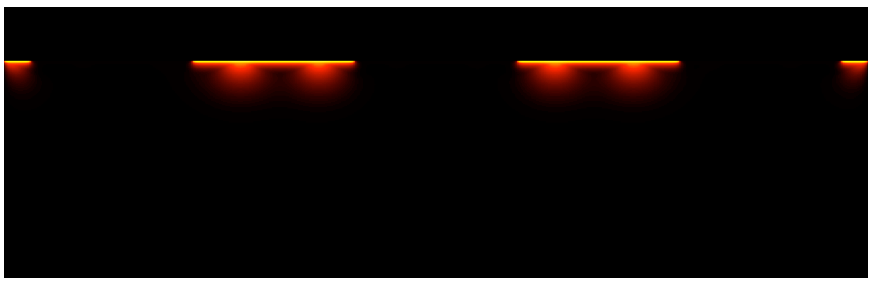

Figure 16. The scattered radiation with varying coating thickness.

Conclusions

The experiments reported in this paper illustrate the complexity of Graphic Arts from a somewhat unusual angle. It also has an impact on paper making. The ultimate goal is to achieve a parameter controlled model that allow us to compute the outcome of a printing operation given the characteristics of the paper, inks, prepress and the printing press. We are still far from having a model that allows simulation of the entire reproduction process. In fact we don't even know what the most relevant parameters should be. Some of the parameters for the effects that we have studied here are not even possible to measure in the print shop. For example, variations in the coating thickness can only be measured in special laboratories through destructive testing.

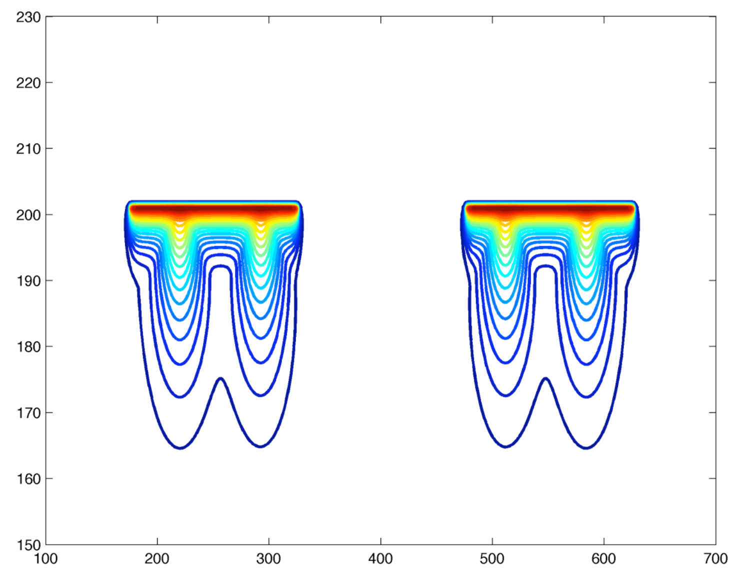

Figure 17. The iso contours of Figure 16.

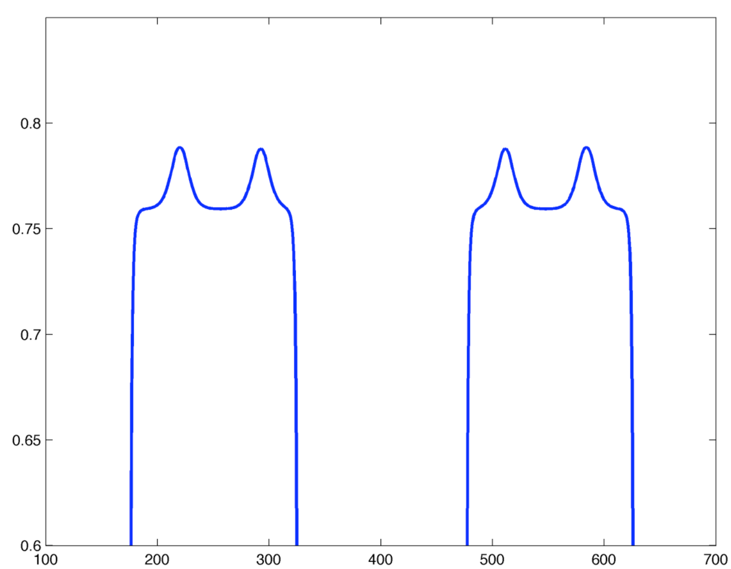

Figure 18. Plot of the emerging radiation from the surface.

Some results are obvious. Absorbing particles, even though they are buried inside the substrate, are clearly visible from the surface. The visibility is clearly reduced the deeper they are located in the substrate. The influence of contaminating small particles has a large influence on the characteristics of the paper and its whiteness. If the contamination can be kept well inside the substrate however, the effects can be reduced. The variation of the coating layer thickness can be as visible as buried particles. This requires of course that the optical properties of the coating and the bulk are quite different. If there are undulating thickness variations as in Figure 15 through 18 and the frequency coincides with the printed halftone very undesired results, with an emphasized beat frequency, will occur.

The reason for the importance of the optical properties of paper is twofold. For the paper making industry the paper whiteness is a question of price. The higher whiteness the higher price can usually be obtained. For the Graphic Arts industry it is important because the tone value increase is an determining factor for the rendering of images on the paper surface. In general the higher the scattering the larger tone value increase and the larger color gamut can be obtained. The results shown here are similar for typical illuminations such as D50 in the Graphic Arts and D65 in the paper industry. It goes without saying that the measurements can be made more narrow banded for the entire spectral region. Fluorescence whitening agents do have a large influence in different parts of the visible spectrum.

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