Optical Homogeneity of Prints

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Doctoral Thesis

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Abstract

This work deals with methods for characterizing one important aspect of print quality, namely the optical homogeneity of prints. By “optical homogeneity” we mean freedom from disturbing noise or patterns in optical density or in the gloss characteristics of the printed surface. These disturbances are often referred to as mottle, speckle, graininess or cloudiness.

Since the concept of print quality is based on the visual experience of human observers, any instrumental measure developed must be validated against subjective quality evaluations. The work therefore treats the problem of how to measure and represent inhomogeneities in prints in concordance with perceptual quality, but it is also concerned with comparisons with the underlying structure of the paper.

For the data treatment and presentation we have found the power spectrum with constant relative bandwidth (mainly octave bands) a useful tool in itself and as an input data set for different models. The parameter analyzed is in most cases the coefficient of variation of the reflectance but the same analytical approach can also be applied to other structural features of paper, like grammage, coating thickness or surface height profiles.

For the acquisition of image data, we emphasize the profound importance of the illumination and detection angles, the choice of which will influence the information gained in a radical way. Technical and psychometric studies have led us to the conclusion that by using a $45^{\circ}/0^{\circ}$ illumination/detection geometry and calculating the reflectance coefficient of variation (COV_R) within a 1-8 mm spatial wavelength range, we gain a valuable tool for estimating the perceptual severity of print mottle. It is however shown that ordered patterns have a stronger visual impact than their COV_R indicates.

The gloss character of prints was investigated in a similar approach but with a $20^{\circ}/20^{\circ}$ specular reflection geometry chosen on the basis of gonio-photometric variation analysis. A spatial band-pass analysis, this time with a 0.4-3.2 mm wavelength range, gave measures with a very good correlation to subjective quality ratings.

The final part of the work treats the relation between print reflectance and surface topography. Yet another illumination geometry is here utilized, namely grazing light at 72° to the normal. Through summation, subtraction and integration of image pairs with illumination from opposite directions, separate maps of reflectance and surface topography can be achieved. This in turn provides new opportunities to test different hypotheses relating to the influence of topography on ink transfer. The method has been applied on gravure and flexo prints, and indications of critical surface characteristics have been found.

Keywords: Print quality, Mottling, Gloss variations, Surface topography, Ink transfer, Image analysis.

List of papers:

Paper I — Johansson, P-Å. and Norman, B. (1996)
Methods for evaluating formation, print unevenness and gloss variations developed at STFI.
Proc. TAPPI 1996 Process and Product Quality Control Conference, Cincinnati, TAPPI Press, Atlanta, p. 139.

Paper II — Johansson, P-Å. (1993)
Print mottle evaluation by band-pass image analysis.
IARIGAI's 22nd International Research Conference, Munich.
Advances in Printing Science and Technology 22, Pentech Press, p. 403.

Paper III — Johansson, P-Å., Lundby, H., Lindberg, S. and Nyström, S. (1999)
Optical homogeneity of traditional and digital prints
IARIGAI's 26th International Research Conference, Munich. To be published in Advances in Printing Science and Technology 26, PIRA Int.

Paper IV — Johansson, P-Å. (1999)
Instrumental evaluation of gloss variation – Angular dependence
Unpublished.

Paper V — MacGregor, M. and Johansson, P-Å. (1991b)
Gloss uniformity in coated paper - Measurements of commercial papers
Proc. TAPPI 1991 Coating Conference, Montreal, TAPPI Press, Atlanta, p. 495.

Paper VI — Béland, M-C., Lindberg, S. and Johansson, P-Å. (1999)
Optical measurement and perception of gloss quality of printed matte-coated paper.
To be published in Journal of Pulp and Paper Science 26(3), March 2000.

Paper VII — Hansson, P. and Johansson, P-Å. (1999a)
A new method for the simultaneous measurement of surface topography and ink distribution on prints.
To be published in Nordic Pulp and Paper Research Journal 14(4), Dec. 1999.

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1 Introduction

1.1 Scope of the work

This work deals with methods for characterizing one aspect of print quality, namely the optical homogeneity of prints. Since the concept of print quality is based on the visual experience of human observers, any instrumental measure developed must be validated against subjective quality evaluations. This means that the search for suitable analysis methods should include:

- ways to detect the optical variations with an adequate resolution,
- suitable signal treatment to calculate relevant parameters,
- statistical treatment and presentation of the results in both a compact and a detailed way for different needs,
- establishment of the perceptual relevance of the measures, and
- if possible, the establishment of links between the quality measured and the underlying technical causes of the quality variations *e.g.* structural properties of contributing materials like paper.

1.2 Optical Homogeneity as a print quality factor

Optical Homogeneity is without doubt an important quality factor. By homogeneity we mean freedom from disturbing noise or patterns in solid tones or smooth image parts. Such disturbances, which are often referred to as print mottle, speckle, graininess or cloudiness, are feared by printers as well as by paper producers.

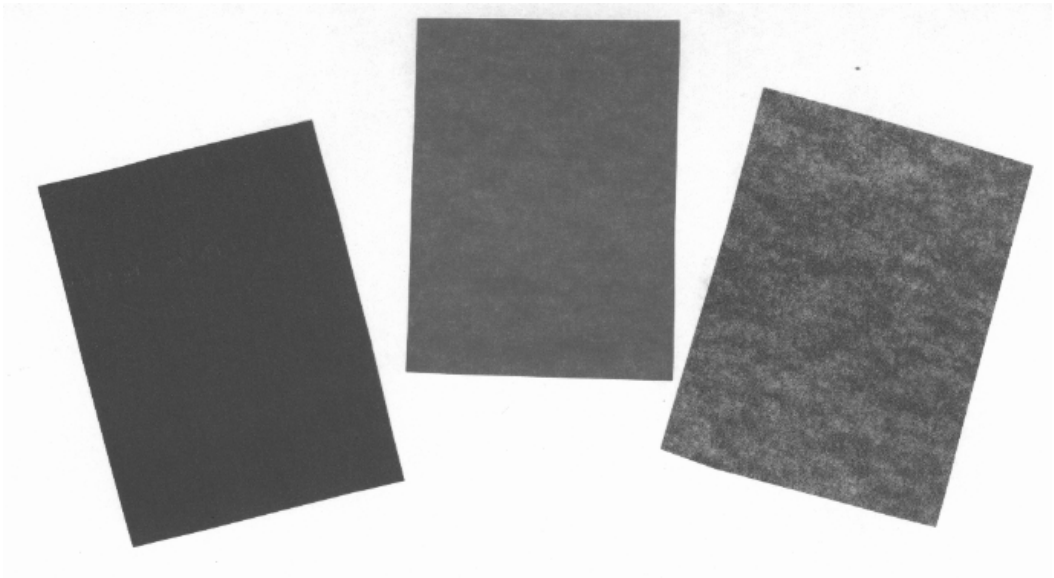

Figure 1.1. Three printed samples with different degrees of print mottle.

Although Optical Homogeneity is an important print quality factor, it is not the only one. Instead it can be fruitful to see different quality factors as possible axes in a multi-dimensional quality space. Some rather obvious factors can be deduced from the everyday experience of inspecting a set of newly processed photographs. A satisfying image quality must include reasonable levels for at least the following factors:

- Detail resolution enough to give a sharp impression
- Contrast range in black as well as in colors
- Tone rendering precision including color balance
- Optical Homogeneity meaning freedom from lateral variations (noise) in print density or in gloss characteristics

It is worth noticing that these factors are orthogonal in the sense that they can vary independently of each other. One can for instance easily imagine a print having a satisfying color contrast while at the same time lacking detail resolution, or a print having satisfactory data in most factors but having a disturbing color shift. The present work, however, is focussed on the optical homogeneity only.

The reason for visual small-scale lateral variations in print density is normally some kind of inhomogeneity of the print substrate or other material involved in the printing process. There is an obvious need for instrumental methods to assess these defects and if possible to point out the reason for a specific defect.

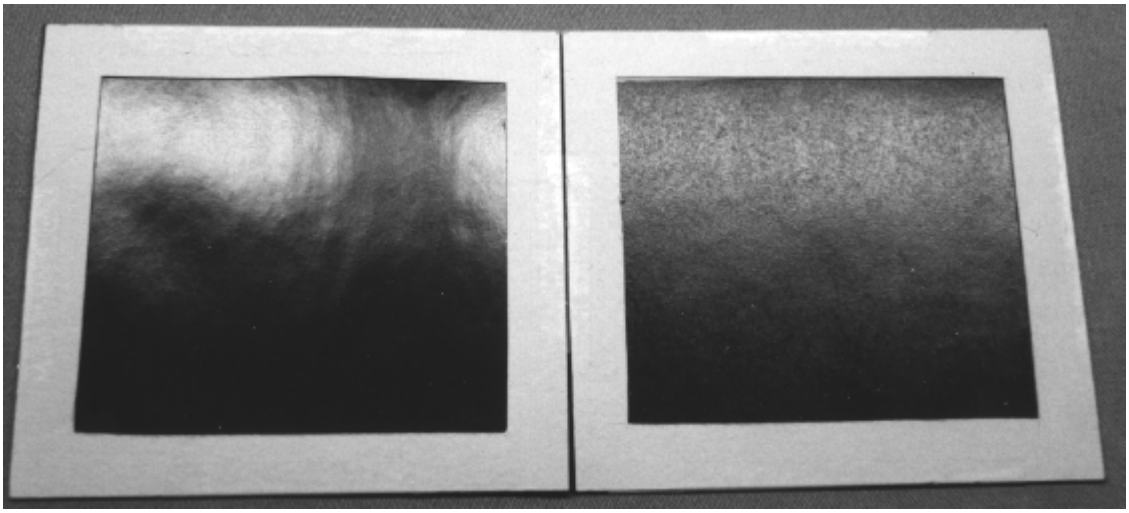

Figure 1.2. An example of large difference in print gloss mottle.

2 Measuring subjective preferences

We have just stated that print quality is a multi-dimensional entity. It is therefore of interest to apply multi-dimensional scaling (MDS) methods as has done by Lyne et al. (1979, 1981). With such methods, the number of useful dimensions can be found and their relative strength can be estimated. The nature of the dimensions need not be known in advance, but can be deduced by correlation with physical parameters. Being based on pair-wise comparisons, the MDS is however very time-consuming and limits the number of samples that can be evaluated

in an experimental series. Newer methodological developments by Donderi (1997, 1998) have made it possible to handle larger series of samples in multidimensional analysis. Attempts to unify different aspects of print quality has been reported by Saarelma and Oittinen (1991, 1993).

In the present work however, we have mainly limited ourselves to one-dimensional analysis of a single parameter at a time, like gloss variations or density variations. Nevertheless, it is quite possible, and we have seen indications, that even the gloss variation experience is multi-dimensional, Paper V.

The methods for creating preference scales have mostly been based on panel pair comparisons and order ranking, as outlined in an early methodology publication by Bristow and Johansson (1983). In some cases magnitude estimation was also employed as in Paper III.

3 Print quality development and the need for instrumental measures

Although there are ways of deriving quantitative measures from subjective evaluations, there is certainly a need for objective instrumental methods for quality appreciation.

A good instrumental method should meet certain demands:

- The measures should be physically well defined and should be reproducible.
- The measures should be in concordance with subjective image quality.
- The measures should preferably be possible to link to other parameters in order to yield clues to the reasons for the defects.

The potential for good print quality is actually the main price factor associated with a graphic/publication paper grade. We accept the limited quality of newsprint because the price of a high quality grade would be unacceptable for the volumes of newsprint that we consume. On the other hand, the demands for high print quality in an exclusive brochure or in an art book can justify the high price of specially treated print surfaces.

The producers of paper as well as other materials for the graphical reproduction chain thus have a need for comprehensible and quantitative figures to provide the link between manufacturing parameters and the end-user's quality experiences.

An elegant model of factors and parameters linking physical and perceptual quality has been presented by Engeldrum (1995) with his "Image Quality Circle", IPQ ™.

He there points out:
1) Technology Variables
2) Physical Image Parameters
3) Customer Perceptions
4) Customers Quality Preferences.

These entities are connected by system models which can describe in turn the build-up of the physical image, the visual perception and the image quality experience. Eventually we want a full understanding of every step in this chain, but on the way there it can also be fruitful to use this scheme to bring order among different contributions in print quality research.

4 Different forms of reflectance variations - density, gloss and shading

The most obvious form of optical inhomogeneity stems from varying light absorption over the printed surface. This is what is seen as print mottle in diffuse or directed but not specular illumination. If, on the other hand, a printed sample is viewed so that specular reflections become visible, gloss mottle may appear. A grazing illumination, nearly parallel to the sample surface, will instead bring out topographical features as shadings over the printed surface. All these three cases may in different ways give a less than pleasing impression of the viewed sample. In the following sections, we shall discuss how to capture and present useful information in the three basic cases of reflectance variations mentioned.

There is however no completely sharp distinction between the cases. Rather, zones of transition exist between them where the effects can interfere. If, for example, density variations are viewed with the illumination close to the normal optical axis of the viewer, elements of specular gloss may disturb the optical density. If the illumination is more parallel to the sample, disturbances may instead arise from variations in the surface topography.

5 Paper and printing parameters influencing optical homogeneity

5.1 Paper reflectance

If the paper itself varies in lightness or color, this variation will be more or less visible even in the printed state. Most inks besides black are transparent, and even black prints will show paper reflectance in the screened halftone areas.

However, since most papers do not vary very much in reflectance, this is not a dominating reason for print mottle, except for dots and specks in some mechanical or recycled grades.

A special case is the use of FWAs (fluorescent whitening agents) that can be unevenly spread in the paper structure and can thus create mottle in the presence of UV-containing illumination.

5.2 Optical dot gain

If the light-scattering properties vary over the paper surface, another risk for print mottle emerges. The lower the scattering coefficient is, the longer is the average path the light travels in the sheet and thus, the greater is the probability that it becomes trapped under halftone screen dots. For modern views of this so-called optical dot gain or Yule-Nielsen effect see Wedin (1995), Gustavson (1997) and Arney et al (1999). This internal shadowing effect tends to make areas with less pigment filler or a thinner coating layer look darker when printed with

halftones. Gustavson (1997) has made calculations that indicate a possible mottle contrast of 0.05 density units from this effect (based on an assumed variation in coating thickness from 0 to 6 μm). Since the limit of detection is known to be of the order of 0.01 density units, this effect should be clearly visible.

5.3 Opacity mottle – print-through mottle

Most paper sheets are not opaque but partly translucent. This means that a single sheet viewed against a dark background will show a mottled appearance due to its inhomogeneous structure. This pattern will also add to the possible print mottle pattern if the print is viewed or measured against a dark backing. Therefore it is important to use an opaque pad of the same paper as a backing if only the printed mottle pattern is to be evaluated. It is important to remember that a flat-bed scanner equipped with a glass backing for transmission film scanning will act as a dark background when used for reflective scanning.

This “look-through” mottling can be more accentuated if the reverse side of the inspected paper sheet is also printed. In this case, the effect of a possibly uneven penetration of ink from the rear adds to the uneven opacity pattern. The general effect of print-through, *i.e.* visible print on the reverse side of the printed paper, is also probably more disturbing when it appears as a mottled pattern rather than an even shading.

5.4 Ink layer thickness and paper topography

The most obvious reasons for reflectance variations on a printed paper are of course related to the amount of ink on the paper. The variations may come in the ink layer thickness or in the inked area coverage.

5.4.1 Full-tone areas

If we firstly limit ourselves to the full-tone case, i.e. no halftone screening, the film thickness may vary due to a varying efficiency in the ink transfer. With a hard non-compressible print form under moderate printing pressure, only the higher parts of the paper topography will come into contact with the ink film with obvious mottle as a result.

A thicker ink film and a higher printing pressure will improve the contact between paper and ink, but they will also lead to a lateral redistribution of the ink so that the resulting ink film thickness will be lower on peaks in the topography and higher in surface depressions. This behaviour is also rather common for flexographic prints since the low viscosity ink used here can easily spread laterally. If however the surface depressions are deep (and steep) enough, the ink will not reach the lowest regions of the paper surface with an unprinted speck as a result. Ink skips of this type are also quite common in gravure prints.

Lithographic offset, in contrast to letterpress and flexography, uses a higher ink viscosity and a compressible printing form which can adapt to the paper surface irregularities and deposit a more even ink film on the paper.

5.4.2 Half-tone areas

When screened half-tones are printed, both the ink film thickness and size of the printed dots may vary. In flexography, the ink can be squeezed out of the dots of the printing form to produce a “collar” of extra high ink thickness. This rather uncontrolled spread of ink can of course be a reason for mottling.

5.4.3 Ink splitting

Even if a perfect ink film is formed between an ideal form and an ideal substrate, this film must split after the printing nip into a portion staying on the form and a portion transferred to the substrate. This splitting will not take place as a smooth separation into two homogeneous layers. Rather, depending on geometry, speed and ink viscosity, the ink will form filaments that will break in a chaotic process leaving an inhomogeneous ink film that will only partly smoothen before it is immobilized and settled. The patterns thus formed may sometimes be visible as a disturbing pattern (especially in flexo). In other cases, this can lead to a change in the chromatic utilization of the ink, which can lead to mottle if the effect is changing in strength over the surface.

5.4.4 Ink refusal

In multicolor offset printing, the paper is increasingly wetted by fountain solutions as it passes the print stations through the press. This wetting of the surface may cause problems in the ink transfer to the paper in the last print stations. The effect is sometimes denoted ink refusal.

5.5 Ink setting – backtrap mottle

The most common reason for print mottle is probably varying absorptivity over the paper surface. This causes differences in the speed of immobilization of the ink layer on the paper. A locally high rate of absorption of the low viscosity oil vehicle of the ink will cause the ink layer to develop a higher tack and become more immobilized on this spot of the paper. On other less absorbing spots, the ink will keep a lower viscosity and more of the ink will tend to be re-transferred to the printing forms of successive print stations. These so-called backtrap effects have been thoroughly investigated and described in articles and a thesis by Engström (1993).

5.6 Half-tone dot shape as quality factor?

When a half-tone area gives an uneven impression, it is natural to look at the quality of the screen dots and if possible measure their size and density. One might expect visible macro-unevenness to be connected to deformed dots, with maybe ragged edges or other defects. As noticed by others, and by us, this need not be the case. A mottled print may show perfectly round dots in micro-scale, whereas an even print may be built up by ragged dots. The explanation of this is that edge features of a dot are completely invisible at normal viewing distances. The important factor is rather the integrated optical effect of the dots within areas

with a size in the mm range. Grouped variation of the dots may appear whether they are smoothly round or ragged.

However, the large-scale spreading of ink along fiber structures, that may appear especially in ink-jet printing, will pose a risk of mottling. Also in offset printing the spreading of ink can give rise to mottle when closely printed structures tend to merge, as reported by Ängskog and Johansson (1995).

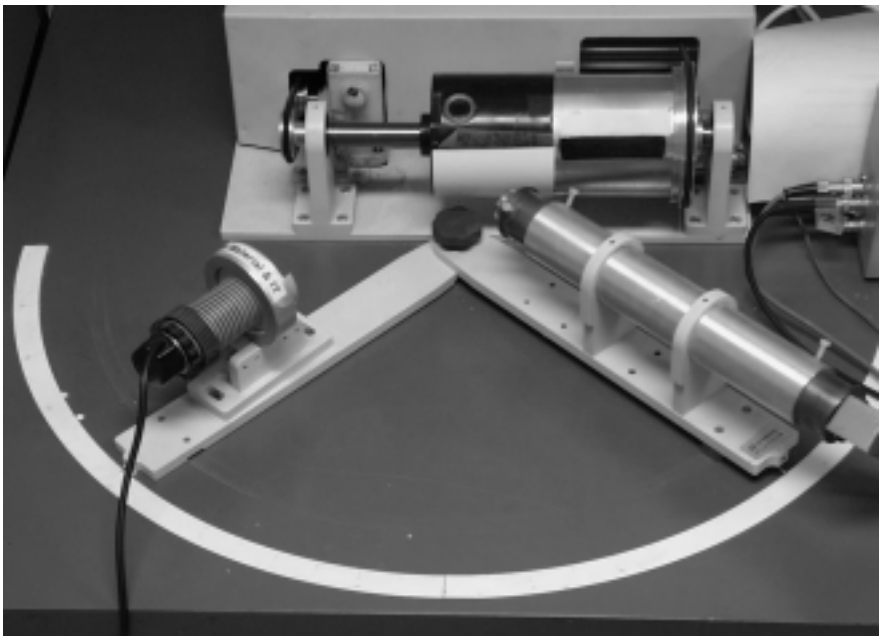

Figure 6.1. Goniophotometric gloss-scanner, reconstructed after Bryntse and Norman (1976).

6 Signal sampling

A sensor of sufficiently high lateral resolution is a prerequisite for the measurement of spatial variations of any property. In the case of print mottle, some form of scanning micro-densitometer has long been a natural choice. Early examples of drum-scanning devices have been described for instance by George et al (1976), Ginman (1976) and Ullman and Qvarnström (1973, 1976). In all cases, the focus was on the uniformity of gravure prints. Norman and Wahren (1974) used a drum-scanner of their own construction for formation studies and Bryntse and Norman (1976) constructed another drum-scanner for goniophotometric gloss and density studies, Bryntse (1981). This scanner was reconstructed and used in the work reported here in Paper IV, see *Figure 6.1*. However the advent of image analysis technology with CCD-camera input led us to work with 2-dimensional images rather than linear analysis of separate drum-scanned tracks. In the density mottle case, a ring-shaped illumination at an angle of approximately 45° was used together with a camera with normal detection (0°). This set-up has later been replaced with a flat-bed scanner. In the gloss case the drum-scanner used in Paper IV was replaced in Paper V with a 20° illumination/20° detection CCD camera device of our own construction, *Figure 6.2*. For the optical topography studies in Paper VII, yet another image-capturing device was constructed with left/right illumination angles of 72° and normal detection, see *Figure 6.3*.

Figure 6.2. Apparatus for imaging of 20° gloss variations over a 10x10mm^2 sample area.

Figure 6.3. Apparatus for simultaneous imaging of surface topography and reflectance distribution.

7 Signal treatment

The aim has been to find a unified, simple, yet informative way of presenting data on structural variations. The main approach chosen has been a power spectrum presentation with constant relative wavelength bands, preferably octave bands. The “power”, in our cases corresponding to the variance or squared coefficient of variation, is given in units per octave band. The formalism is outlined in Paper I. The reasons for a constant relative bandwidth is that it gives a good overview when checking measures that may span several orders of magnitude in scale. By presenting the total unscaled variance that belongs to each band, *e.g.* an octave, we obtain a “fractal” overview over scale dependence in the disturbances, and can for instance easily see whether the scale range 1-2 mm contributes more or less than the 10-20 mm range. The band limits can also easily be graded in spatial frequency instead of wavelength without any change in the form of the spectrum. A similar way of presenting spectra is often used in the field of audio equipment where 1/3 octave bands seem popular.

For the purpose of formation analysis, Paper I, we often use combinations of semi-high resolution power plots with 1/8 octave resolution, together with a standard deviation or coefficient of variation spectrum with some sets of bands available. The set of octave bands may be seen as a reasonable compromise between sufficiently fine resolution for spectral comparison and sufficiently coarse to provide a few compact measures when that is needed. The technique can be applied all kinds of spatial serial data besides what is here mentioned. One application example is surface profiles. Wågberg and Johansson (1993) reported a comparison between optically and mechanically scanned roughness profiles using this approach.

The octave bands can be utilized to identify those parts of the spectrum that correlate best with other variables including subjective quality, or those parts of the spectrum that best separate the samples in a series.

8 Summaries of the papers

8.1 Methods for evaluating Formation, Print Unevenness and Gloss Variations developed at STFI (Paper I)

The paper is mainly concerned with STFIs method for the evaluation of paper formation, *i.e.* the local variations in sheet grammage. This is an example of how spatial spectral analysis can bring out valuable information from random-like structures and present it in a useful way. The concept of spectral power per relative wavelength length (octave bands) is introduced for formation descriptions. This is analogous to the STFI methods for print density mottle and gloss mottle, as well as some other structural descriptions.

In formation studies, the first obstacle is the detection of local grammage. This has been accomplished at STFI and other places through beta-radiography, a technique where the transmission of beta rays from a radioactive source through a paper sample is recorded on x-ray film material. The true local grammage can be calculated from the calibrated density of the processed film. Profiles or maps of sheet grammage can thus be achieved by suitable point scanning or imaging devices. The present analysis set-up utilizes standard desktop flat-bed film scanners for the input of image data.

The formation metric used is the band-passed coefficient of variation of grammage, $F(a,b) = \sigma_w(a,b) / \overline{w}$, where σ_w denotes the standard deviation of the grammage, $\overline{w}$ the mean grammage, and (a,b) the limits of the wavelength interval. This measure, the formation number F(a,b), has the advantage of being physically well defined, meaning that it can be measured with different techniques and not only on a specific make of instrument.

The formation number is normally calculated from a power spectrum containing the squared coefficient of variation given per frequency unit. Integrating the power spectrum between frequency limits corresponding to the desired wavelength interval (a,b) and taking the square root of the integral yields the formation number F(a,b). The formation number can also be normalized from the actual sample grammage *w* into a standard grammage *n* by multiplying the F value by the factor $\sqrt{w/n}$. A "specific formation number" is gained with n=1g/m^2.

The whole formation spectrum can be presented in different ways, the choice of which is partly a matter of taste. Since the wavelength interval may span two or more orders of magnitude (decades), a logarithmic wavelength or frequency axis is a natural choice for combining fine-scale resolution and large-scale overview. Grading the axis in terms of wavelength or of frequency is equivalent, but wavelength units may be intuitively easier to link to features in the sheet structure. High grammage floc features of diameter D, separated by thinner parts also with a typical diameter of D will then correspond to a wavelength of 2D.

The formation spectra have traditionally been presented as spectral density per wavelength unit (Norman and Wahren, 1974) and (Haglund et al, 1974). With a logarithmic scale for the spectral density, the typical spectrum exhibits a strong negative slope with lower readings at longer wavelengths. This is a consequence of the chosen representation and the characteristics of the pseudo-random process of papermaking. As shown by Norman and Wahren, randomly spread small particles would constitute a "white noise" structure, *i.e.* variations with equal power per frequency unit. Represented as power per wavelength unit this transforms into a

slope of –2, meaning that the power density value falls two decades when the wavelength increases by one decade.

Although this representation is quite correct, it in practice obscures the relative contribution from different parts of the spectrum to the total formation number *i.e.* the total coefficient of variation. Or differently put: all spectra of the type “power/wavelength unit” look more or less the same, although they may contain important differences in *e.g.* the flocculation behavior.

To improve this lack of visibility, we have introduced another representation, namely spectral density per relative bandwidth, or in our case: per octave band. The motifs for such a presentation are quite straightforward:

1) Since the wavelength scale numbers may cover several orders of magnitude, a logarithmic wavelength axis is preferred.
2) In such a spectrum we wish to show the contribution from each interval as the height of the spectrum curve in that interval.

The calculation of the data for this type of spectrum presentation is simply to integrate the power data for the frequencies corresponding to the desired wavelength range. Plotted on a linear power y-axis, the distribution of disturbances is clearly discernible as the area beneath the curve, and the square root of that area is the formation number, F(a,b).

The transformation from the “traditional” representation, power/wavelength unit, to what is here suggested, is simply a multiplication of the values by the corresponding wavelength. The “new” spectral plot then has a slope of –1 for white random noise. Real paper, however, normally shows more large-scale flocculation than the random arrangement of fibers would predict. In fact, the spectra plotted with relative band densities often exhibit a more or less planar behaviour with their main deviations in the cm-range of the wavelength. This power in the cm-range can be higher or lower than that in the mm-range depending on the flocculation tendency of the sheet-forming process.

The concept of power in bands of constant relative width is actually a form of “fractal” characterization in that it shows scale-independent features in the structure if such are present.

Besides the power spectrum containing the relative variance in a suitable resolution (at STFI we use 1/8 octave) one can also show a linear representation of formation numbers in suitable classes. Typical classes may include octave bands as well as decade bands; in our case 0.3-3 mm and 3-30 mm. These latter two bands have been found to be useful in destinguishing between the more fiber-dependent mm-range and the more flocculation-dependent cm-range. The structural content of octave bands is shown in *figure 8.1.1.*

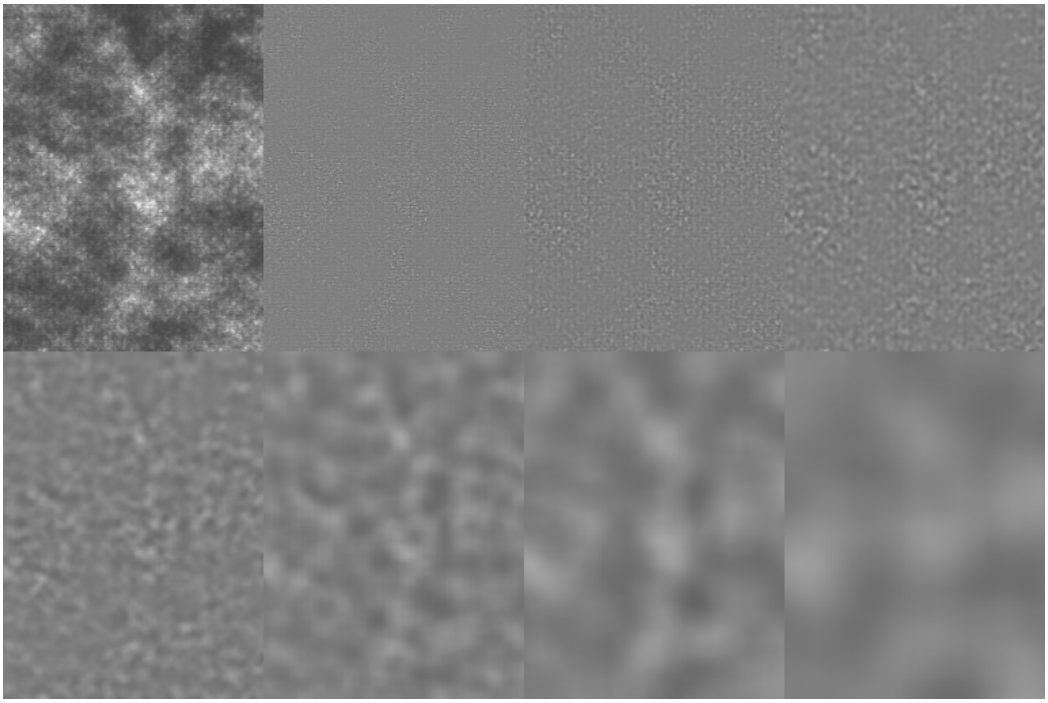

Figure 8.1.1. *A transmitted light image of a paper sheet broken down into a series of octave band images. The structural features giving the variance contributions to each octave band are clearly visible.*

One point that Paper I stresses is that virtually all variation measurements contain some kind of band-pass limitation. Consider for instance a spot sensor with diameter d, measuring at random points over a sample of length L. Such an arrangement will mainly measure variations within the wavelength range from 2d to L. This should be remembered when measurements from different apparatus are compared. Clearly stating the relevant spatial band limitations of a method will clarify many instrumental differences that can otherwise be puzzling. For an overview of formation measurement, see Kajanto et al (1989). For the relation between formation and print mottle, see Kajanto (1990,1991) or Ness et al (1992). We have also tried combining the formation grammage map with a mechanically point-scanned sheet thickness map so that even a sheet density map can be achieved, (Schultz-Eklund, Fellers and Johansson, 1991). The information thus gained is useful for evaluating the effects of calendering of the printability.

Paper I also refers to the application of similar techniques for the analysis of print mottle, gloss mottle, height profiles or thickness profiles. The general aspects of usefulness are equally relevant in these cases, especially if wide ranges of scales are to be compared. A profile of paper properties may indeed range in size from micrometers up to kilometers in the production direction. The comparisons made possible by using similar spectral approaches for different properties can also give important clues to causal relationships between *e.g.* paper structure and print unevenness.

8.2 Print mottle evaluation by band-pass image analysis (Paper II)

This paper treats suitable ways of quantitatively assessing the print mottle phenomenon in concordance with its perceptual impact. Print mottle, being local variations in print density, obviously needs some kind of spot-wise reading of the reflection properties if it is to be evaluated. The reading can be done by a scanning spot-meter device or by an image scanner or digital camera whose pixels will contain a large number of local reflectance values.

Reflectometric considerations

However, it is not immediately self-evident what metrics and statistics should be calculated from these readings. Possible metrics could include the standard deviation of the reflectance (σ_R), the coefficient of variation of reflectance ($COV_R=\sigma_R/R$), the standard deviation of print density (σ_D) or the coefficient of variation of density ($COV_D=\sigma_D/D$).

Basic models for the human visual system can be found in standard textbooks on image analysis, (*e.g.* Pratt,1978) or in literature specializing on spatial vision (*e.g.* De Valois,1988). Assume that a subject is trying to see the contrast between two adjacent areas of reflectance R and R+dR. From psychometric research it is known that the human threshold for optical contrast, when expressed as a Weber fraction, dR/R, tends to be constant ≈ 0.02, over a wide range of reflectance levels R. This implies that the response to stimuli of optical contrast should follow a logarithmic law (Fechner's law). This is the background to the common way of expressing the darkness of a print, namely as print density, $D = \log (R_{paper} / R_{print})$. From these facts it is reasonable to believe that the standard deviation of density, σ_D, should be a suitable metric. In Paper II it is also shown that the coefficient of variation of reflectance, COV_R, is proportional to σ_D and that COV_R should thus be an equally suitable metric for print mottle.

There is no immediate psychometric reason to suspect that the density coefficient of variation COV_D should be a superior measure of print mottle, although this has been claimed in the case of direct-litho and letterpress printing on newsprint (Trollsås, 1983, 1988). Also we have noted that the COV_R (or σ_D) tends to overestimate the disturbances on dark prints in comparison with those on lighter ones. According to our findings, however, a normalization of σ_D into a coefficient of variation in density ($COV_D=\sigma_D/D$) will overcompensate so that the opposite error occurs, *i.e.* the lighter samples receive a higher disturbance value than is perceptually motivated. We do not, however, consider this to be a serious problem since comparisons of mottle in light and dark prints seldom are meaningful. The average density of acceptable samples must be close to the intended density, and at a constant density level throughout a series the ranking will be the same whether COV_D or COV_R is used.

The logarithmic law of Fechner has also been questioned and in many cases it has been replaced with power laws for the psychometric responses to stimuli of different types. A power expression with an exponent equal to 1/3 has been accepted for lightness values (Stevens and Stevens, 1963) or (Gescheider, 1985) and is used for the L-value in the CIELAB color system. Differentiation of $L = k_1 \cdot R^{1/3}$ yields $dL = k_2 \cdot dR / R^{2/3} = k_2 \cdot R^{1/3} \cdot dR / R$, and this implies that perceptually equal steps in mottling, independent of the reflectance level, may in fact require the coefficient of variation in reflectance (COV_R) to be multiplied by the cube root of the reflectance. We have not, however, pursued this idea, since according to the

motivation above, comparisons of mottle in light and dark prints are not meaningful for optimizing print quality. By keeping COV_R as the main metric for print mottle, we also gain the instrumental advantage of having more stable measurement values. This is due to the inherent compensation for illumination variations etc in the dR/R-expression, as long as the light response of the system is linear.

Lateral spectral analysis

The subjective relevance of print mottle readings can however be enhanced further by the use of lateral spectral analysis, which is the main theme of Paper II. By spectral analysis we mean the separation of density variations into lateral size classes, e.g. cm-sized “cloudiness” or below-mm-sized “graininess”. A draft ISO-standard (ISO 1996) defines mottle as “random fluctuations in blackness generally at frequencies lower than 1 cycle/mm” (corresponding to a wavelength larger than 1 mm). Smaller fluctuations are there called graininess. It is reasonable to assume that different feature sizes in the mottled image have different impacts on the viewer, even if their amplitudes and thus their standard deviations are the same. In fact, it is well known that the detection threshold of the human visual system for a sinusoidal pattern varies with the lateral wavelength of the pattern with a maximal sensitivity in the range of 2-6 cycles/degree depending on the luminance level (*e.g.* De Valois, 1988). At a viewing distance of 30 cm this transforms into a lateral wavelength range of 0.9-2.6 mm. One can suspect, but it is not self-evident, that patterns of this size are also the most annoying at levels higher than the detection threshold. The wish to investigate these questions implied a need for spatial spectral analysis of the inhomogeneity of prints.

The calculation of a Fourier transform power spectrum will give detailed spectral information of the frequency content of scanned line profiles or 2-dimensional images. However, the completeness of such a description means that little data reduction takes place. To obtain a more compact description, we have instead used an octave-band-based description of the spectral content. Octave here denotes a spectral band containing a doubling of the frequency just as in musical terminology. As is more intuitive, we use spatial wavelength rather than frequency. A series of octave wavelength bands may then have the form of 0.5-1 mm, 1-2 mm, 2-4 mm, etc.

A special technique for the calculation of such bands without the Fourier trigonometric formalism is also dealt with in the paper. The technique is based on the calculation of differences between images laterally averaged to different resolutions, (Johansson, 1983a). The filter transmission properties of such schemes of calculations are discussed and it is shown that a series of octave filters, although without sharp cut-off limits, can be achieved with a limited number of fast calculations, *Figure 8.2.1.* The idea can in fact be seen as a software generalization of the idea of comparing the density of spot to its nearest surrounding, which has been used in a hardware implementation at STFI for the evaluation of gravure speckle (Ekman, Johansson, Larsson, 1976).

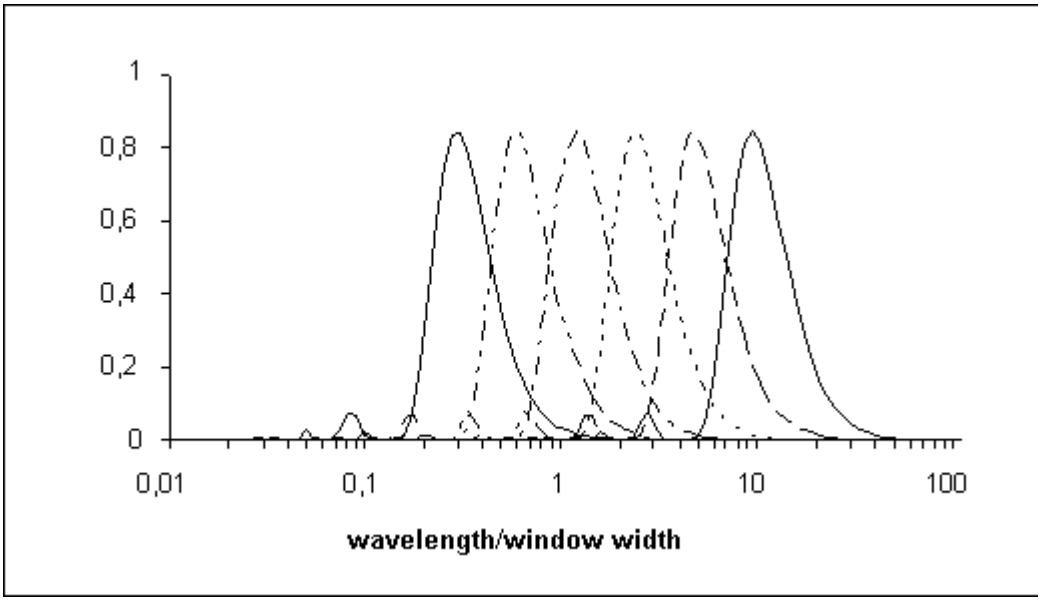

Figure 8.2.1*. The variance transmission of a series of band-pass filters created through window averaging in the spatial domain. The effect of such filters can be seen in Figure 8.1.1 and Figure 8.5.1.*

The fact that these filters do not have a sharp wavelength cut-off need not be a drawback. The soft filter edges will prevent “ringing” effects that will appear if sharp narrow bands are re-transformed from the frequency domain. “Ringing” here denotes exaggerated amplitudes and false contours of features corresponding to the typical frequency of the filter.

Moreover, the type of filtering characteristics visible in *figure 8.2.1* may indeed be a part of our visual system. From animal experiments it has been found that the nerve signals from the eye to the brain indicate this type of soft filter with an approximate bandwidth of one octave. The reason is probably that the eye performs types of lateral average and difference calculations similar to those which we have implemented. There is not by far a separate nerve transmission to the brain for every light receptor in the eye. Instead a more compressed and information-effective multi-channel “wavelet-band” representation is transmitted. The human visual filter system is however more complicated and includes also orientation-sensitive filters (De Valois, 1988). The analogy between the biological systems and modern computer techniques for image compression is obvious here. However, the possible analogy between the human visual system and our octave band image analysis scheme does not in itself validate the latter as a good mottle measure. The conclusion is only that the information reduction in our method need not be very harmful. The actual validation of the method must instead come from comparisons with subjective evaluations.

The band-pass technique described in Paper II was initially developed as a high-speed integer arithmetic alternative to Fourier techniques, (Johansson, 1983b). The speed advantage is however becoming less important now that the increasing computer speeds available make full Fourier spectra quickly attainable, and the Fourier approach has indeed been chosen in later work at STFI. From Fourier power spectrum data, suitable bands can easily be extracted through masking operations.

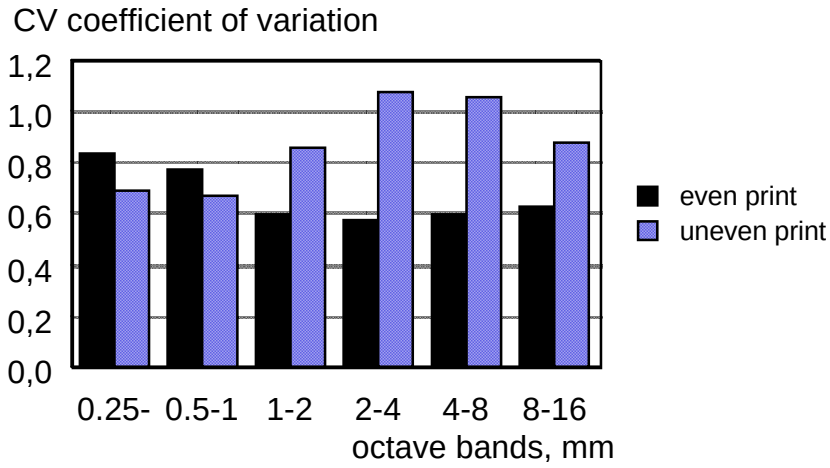

Figure 8.2.2*. The greatest difference in COV between the even and uneven prints here occurs in the 2-8 mm wavelength range. Note the erroneous order in the 0.25-1 mm range.*

The variation data available as a set of octave bands is sufficiently detailed to show the general spatial spectral characteristics of the mottle patterns. *Figure 8.2.2* shows examples of two offset prints, where one is even while the other has an uneven mottled character. It is obvious that the differences in the coefficient of variation are not evenly distributed over the spatial bands; the greatest difference occurs in fact in the 2-8 mm wavelength range. The 1-2 and 8-16 mm bands also exhibit a marked difference, with lower coefficient of variation values for the print with a more even character. In contrast to this, the two bands in the short wavelength range, 0.25-1 mm, exhibit an “inverted” behavior, in that the visually more even print has a higher variation level in this range. Clearly, data collected in the short wavelength range only would give quite misleading results concerning the print quality. Nor would the integrated variation from all bands or the unfiltered variation signal be as good a measure as the more relevant bands, 1-16 mm in this case.

Another and more general way of selecting a relevant wavelength band is to perform a subjective assessment of print evenness with a panel of judges and then to investigate the correlation between this perceptive assessment and the variation in different bands. *Figure 8.2.3* shows the result of such an experiment on offset prints. The highest correlation is found in the 2-8 mm wavelength range, but the whole range of 1-16 mm can be said to give positive contributions in this case.

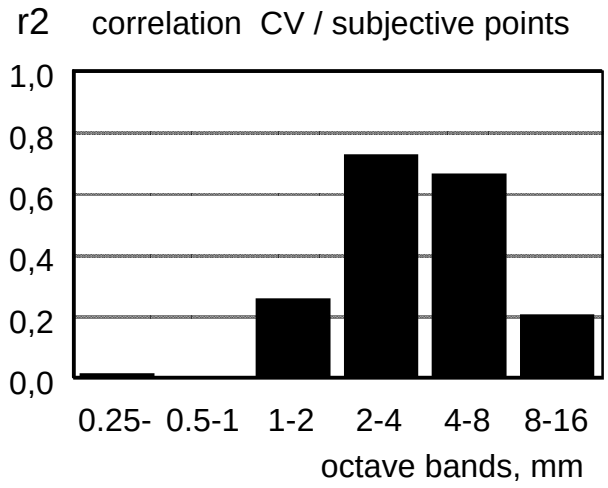

Figure 8.2.3. *Coefficient of determination, r^2, between subjective scores of print mottle and COV_R-values for a series of octave filters.*

One experiment of this type only provides a clue to a general conclusion of suitable bands. One must remember that the achieved correlation in different bands depends not only on our visual sensitivity for different feature sizes but also on the actual occurrence of disturbing features of different sizes. If, for instance, the only quality difference between samples in a given test print series, were more or less of features of say 12 mm in wavelength, then only the 8-16 mm wavelength band would show a significant correlation to the visual scale. However, several experiments on different test series have indicated that 1-8 mm is a useful range in most cases. In some cases, other bands, for instance 1-16 mm, can be superior and for continuous control work for a specific paper grade in a specific printing process it is possible to fine-tune the evaluation by an optimized choice of band limits.

Paper II also briefly discusses another way of taking the spatial properties into account through the so-called Mottle Index, utilizing a specific perimeter analysis. For more information on this and other forms of texture analysis, see Nguyen and Jordan (1989).

The method has also been successfully applied on coating thickness variations through so called burn-out tests (Engström et al, 1989) and (Engström and Rigdahl, 1989). In gravure printing on the other hand, are the typical defects sparse white spots of skipped ink transfer. According to our experiance are such defects best measured when counted through image analysis rather than mottle-analyzed as above, (Johansson, 1983a).

8.3 Optical Homogeneity of Traditional and Digital Prints (Paper III)

The STFI print mottle analysis method, based on the measurement of the coefficient of variation of the reflectance (COV_R) within a defined spatial wavelength band, was described in Paper II. Paper III describes further developments and tests of this method with regard to perceptual linearity and threshold levels of the measures. We also wanted to find out whether ordered "deterministic" noise patterns would be measurable with the same techniques and metrics or whether other approaches were needed. This question is of growing interest, since the emerging digital printing processes are more prone to exhibit such pattern effects.

With regard to the general mottle measurements, it is noted that the use of commercial flatbed scanners instead of CCD-cameras for image input will normally give a better signal-to-noise ratio at affordable prices. Scanners will thus make it possible to measure lower mottle levels, at the limits of human detectability. The reason for this performance/price favor of the scanners is partly that they use mechanical movement of a 1-dimensional light-sensitive array, while the cameras use a 2-dimensional array to achieve sufficiently high frame rates. Another reason is the much wider pre-press market for flatbed scanners in comparison with that for high performance CDD-cameras. Other advantages of the scanner image acquisition are the constant illumination configuration, which means less operator influence and also the available color possibilities. It is shown that the mottle method can now rank samples in an order consistent with human judgement even for series of samples where the visual judgement is far from being easy and self-evident. From the judgements of papermakers, the upper noise limit for high quality acceptance in full-tone cyan printed areas seem to be in the 1-1.5 % range, measured as COV_R in the 1-8 mm wavelength range, *Figure 8.3.1.*

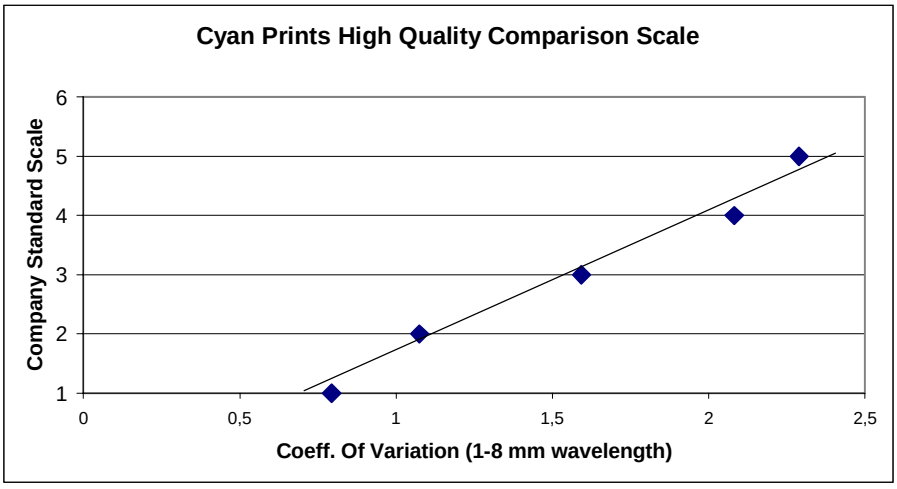

Figure 8.3.1. *Cyan offset samples, chosen to be approximately equidistant in noise levels, show good linearity against the COV-value. The two samples with the lowest noise level represent excellent print homogeneity.*

A comparison between instrumental measures and samples judged to be approximately equidistant in quality shows a linear relation. It was however considered valuable to further establish the possibly linear relations between stimulus level and the responses of judges and

instruments. We here tried an experimental design based upon simulated print disturbances. In the simulations we added known quantities of three types of print disturbance, *Figure 8.3.2*:

1) Random noise resembling ordinary print mottle
2) Wire-mark pattern
3) Streak patterns resembling the stripes sometimes visible in inkjet prints

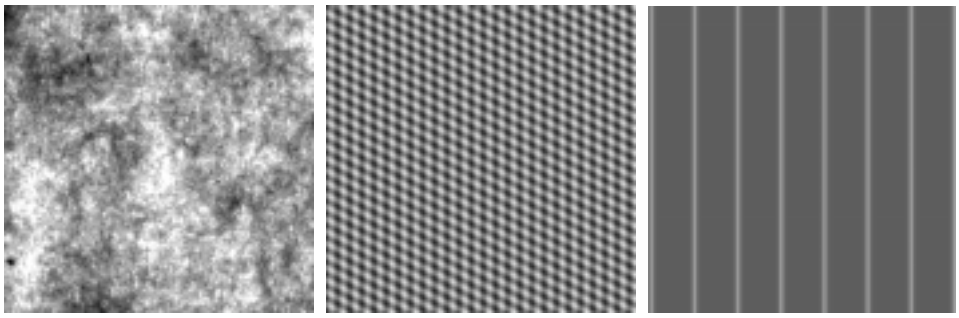

Figure 8.3.2. *Three types of noise were created for the simulations.*

These three patterns were blended into a portrait image in the pre-press stage. Different levels and mixtures of the patterns were utilized and test image hard-copies were produced on a high quality print proofing equipment.

A panel of judges was employed first to establish thresholds for detection of the three noise types. Further, the panel also established a quantitative “freedom-from-noise” quality scale. The noise levels in neutral areas of the samples produced were also measured with our standard mottle analysis routine.

One important finding was that the subjective scale achieved was indeed linearly related to the measured coefficient of variation (COV_R) up to about 2.5 %. This range can be said to include all interesting quality levels, since higher noise levels correspond to a clearly unacceptable quality.

Another question was the visual impact of different types of noise. Panel experiments were carried out to find the thresholds for noise detection among the portrait images with added noise. It was found that a random noise COV_R of 1.3 % was detected by half the judges in the panel. The corresponding levels for half panel detection were found to be a COV_R of 0.73 % for the simulated wire mark and only 0.31 % for the streak pattern. These levels depend of course on the image motif and noise pattern details. However it is probably true to say that a regular pattern may be 2 times or even 4 times as visible as a random pattern in terms of its detection COV_R in images.

Similar experiments on the subjective quality of images at noise levels higher than the threshold confirmed the stronger visual quality reduction that was caused by the ordered “deterministic” noise patterns, *Figure 8.3.3.*

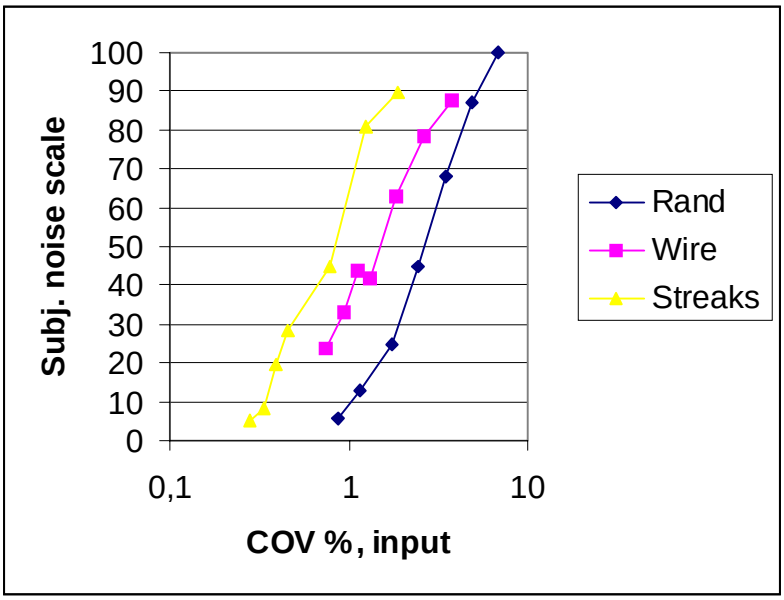

Figure 8.3.3. *Subjective noise experience vs. mathematical noise level. The visual severity is greater for ordered noise than for random noise. When plotted on a logarithmic COV-axis, the responses for different noise types appear to be parallel i.e. with a constant sensitivity shift factor.*

The conclusions drawn in this paper include:

- The technique for mixing images with simulated noise disturbances of known character and strength proved to be a valuable tool for perceptual studies of noise effects.
- Spectral structure analysis of stochastic print mottle works well. The use of commercial flatbed scanners for image acquisition and spatial band extraction from FFT power spectra, have made the STFI method more stable and accurate than the earlier camera-based method.
- The visual severity of stochastic noise seemed to be proportional to the noise signal in terms of coefficient of variation of reflectance. This refers to the low levels of noise typical of high quality reproduction.
- Human perception is far more sensitive to ordered textures in images than to stochastic noise. It is therefore necessary to extract information about periodic disturbances separately in order to perform a complete print mottle analysis, especially in the case of ink-jet prints.

8.4 Instrumental Evaluation of Gloss Variations (Paper IV)

Gloss is generally considered to be an indicator of quality or even exclusiveness of paper and printed matter. To achieve gloss, the papermaker must create a surface smooth enough to promote the specular reflection of light that gives the customer a sensation of gloss. Obviously, for product control and development, there is a need for equipment that can measure 'gloss' in accordance with the visual experience. The definition of gloss is however far from self-evident. For an overview of paper gloss, see Oittinen (1980,1981,1983b,1990). In fact, several definitions have been proposed addressing different aspects of gloss. The angle of incidence/reflection is usually 75° from the normal according to TAPPI standard T480 (1985) or, less usually, 60, 45 or 20º ASTM (1967). The choice of angles will be further discussed below, but the basic rule is that a lower angle (more closely normal incidence) is more suitable for more glossy materials.

All paper products do not however aim towards the highest possible gloss levels. Rather, there is a demand for several other types of surface finish, matte, semi-matte, silk finish etc. As a matter of fact, there has been a tendency towards papers with lower gloss levels in recent years.

However, another aspect of gloss quality is its homogeneity over the surface. For instance a semi-matte surface can be quite appealing if it is even over the surface. On the other hand, any surface with blotches or speckle of gloss deviations, upwards or downwards, gives an impressionl of low quality. The gloss variations may come from partial coverage of the coating or from fiber raising effects which are common in heat-set offset printed papers containing mechanical fibers, (Aspler and Béland, 1994).

As opposed to gloss level measurements, there is little of equipment available for gloss *variation* measurements. The aim of the work presented in Paper IV was to develop a procedure suitable for gloss variation evaluation.

The paper is concerned with the choice of measuring geometries for gloss variation in relation to the roughness levels of the sample. Only unprinted paper is considered here. Starting from known equations for the dependence of the reflectance on specular angle and sample roughness, one can show that the suitable angle for good separation of samples will depend on the average roughness level. Or to exemplify: two different samples both with high but slightly different gloss can only be distinguished if the incidence/reflection angle is small (= close to the normal). On the other hand samples with a coarser surface structure must be evaluated at larger angles (=further from the normal) to achieve any measurable gloss at all.

To be able to study the gloss variation, a point-scanning gonio-photometric measuring unit was set up. It was based on an earlier equipment constructed at STFI by Bryntse and Norman (1976). For the present work it was however modified from laser light to unpolarized white light to more resemble the visual case. The local gloss signal from a moving spot 0.1 mm in diameter was fed into a frequency analyzer to achieve the type of wavelength spectrum that we had earlier found useful for the analysis of paper formation and print mottle.

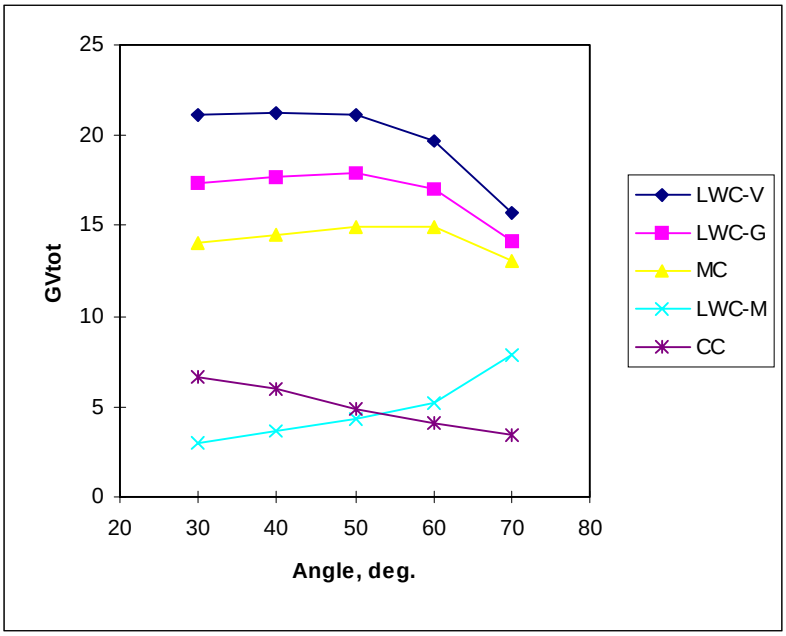

Figure 8.4.1. *The measured gloss variation (GVtot) varies with the analyzing angle. The matte sample (LWC-M) increases its value with increasing angle, while the glossier samples show the opposite behavior.*

Papers of different gloss levels were analyzed for gloss variation in different angles at the 30-70° range. It was found that the choice of angle was not very critical in the range between 30° and 50° concerning the separation power between different samples. However, at 60 and especially at 70° rather drastic changes take place, in that the measured gloss variation is reduced and the sample separation is almost extinguished for the glossier samples. The opposite behavior is noted for semi-matte samples, where the gloss variations increase with increasing (=more parallel to the surface) illumination angles, *Figure 8.4.1.* This means that no single geometry can be utilized for all types of paper samples. It also means that there is no simple relation between general gloss level and gloss variation. Gloss variation or "gloss mottle" is a property in itself that can be more or less abundant and disturbing at high or low gloss levels. It is of course more likely that a high gloss variation is associated with an intermediate gloss level since a varying surface must contain local areas of higher and lower gloss. Very high or very low gloss samples (cast-coated and matte samples respectively) are both shown to have low gloss variation when measured on our equipment.

The general conclusion is then that different geometries are needed for high gloss and low gloss samples respectively. For high gloss samples (LWC grades and above) small angles, i.e. close to the surface normal, are needed to resolve the quality differences. The actual choice for such papers may not be very critical since the measured unevenness reading, the gloss COV, does not seem to change very much for angles smaller than 40°.

8.5 Gloss Uniformity in Coated Paper (Paper V)

The need for a measure of gloss non-uniformity has already been stated in Paper IV. It was there pointed out that variations in glossier paper grades need to be viewed and analyzed at angles close to the normal to the paper plane. The gloss deviations on high quality paper are also small in size, implying that a good lateral resolution is needed in the analysis. This led us to try a digital image analysis approach for the mapping of local gloss over the paper surface. In the set-up used, the illumination and the camera detection unit are both 20^{o} from the normal to the paper plane. An angle of 20^{o} is in fact a standard geometry for high gloss papers (Tappi Method T653) and, according to the results in Paper IV, the influence of the angle on the measured coefficient of variation data is probably small for angles in the $0\text{-}40^{o}$ range.

With an angle as small as 20^{o}, it is possible to detect the gloss in an area of 10x10 mm^2 on a paper within the depth-of-field for acceptable focus. Since the captured area of 10x10 mm^2 is digitized into 512 x 512 pixels (picture elements), each pixel is roughly 20x20 μm^2. We thus acquire a quarter of a million local gloss readings without any mechanical scanning of the sample. The "gloss image" is then available for suitable statistical treatment and also for visual inspection. MacGregor and Johansson (1990a, 1990b, 1991a) utilized this gloss-imaging technique to make direct comparisons with registered maps of coating thickness and ink absorbency.

Further efforts were made to develop a gloss homogeneity measure. Since the coefficient of variation of light intensity had proven to be a useful metric for print mottle and since it also seemed promising for the mechanical gloss scanning approach in Paper IV, it was a natural choice to try also here. However, the non-normalized standard deviation as well as combinations between gloss level and gloss variation data were also tried. It was further natural to try a spatial wavelength analysis of the image data, so the gloss image data was filtered into a series of octave band-pass filters by analogy with the print mottle analysis, *Figure 8.5.1.*

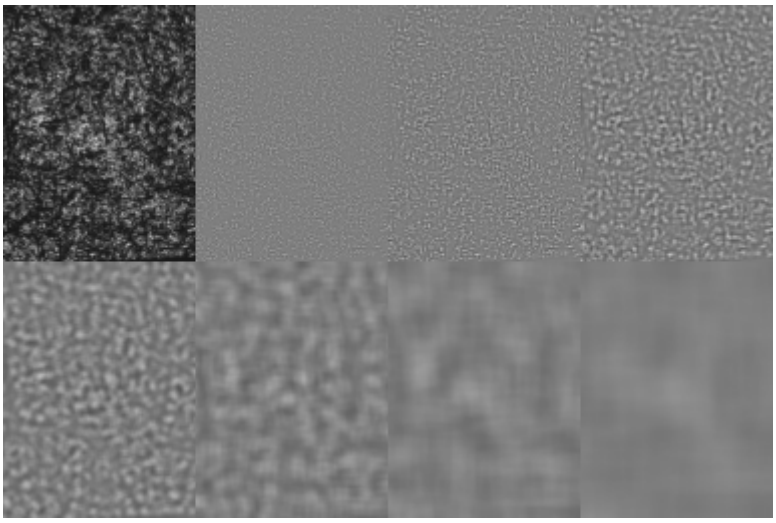

Figure 8.5.1. *Octave band-pass representation of 20° gloss variations in a printed LWC (light weight coated) paper. The unfiltered image in the upper left corner has a height of 10 mm.*

It was found that the variation intensity was highest at the shortest wavelength measurable (40 μm) and then decreased with increasing wavelength. As a matter of fact, even very smooth surfaces exhibited a very grainy microstructure. Bright spots in a gloss image indicate a facet that casts a reflection in the specular direction defined by the paper plane, while dark spots mark places where a facet is tilted away or a spot of low reflectance.

Samples from print trials were collected from manufacturers of coated paper in Scandinavia and North America. In total, the collection contained 65 samples most of which were available in both the printed and unprinted states.

When the measured gloss variation was compared with the mean gloss level it was found that very different levels of variation could be found at any given mean gloss level. In other words, gloss variation is not a property that is linked to the mean gloss in a simple way. Therefore, ordinary gloss measurements that average the gloss over maybe 100 mm^2, cannot give a complete quality characterization. The greatest range of variation was found at intermediate mean gloss levels.

One question of interest was whether gloss variation increases or decreases when the paper is printed. This was evaluated and the result was that both types of change were almost equally common. This may at first seem surprising, but the fact is that while the ink in almost all cases increases the gloss level, it can both raise or lower its variation. Typically, high quality surfaces are further "varnished" to a greater smoothness with less variations, while on rougher surfaces the ink tends to bring out the surface irregularities visually when the local gloss increases in an inhomogeneous way.

29 printed samples were ranked according to their visual gloss uniformity by a panel of judges. Although some judges found it difficult to compare samples of different characters, *e.g.* printed in different colors, the whole panel showed a high degree of consistency in their rankings. The 95 % confidence interval for the rank numbers was typically ±2 rank numbers among the 29 samples.

The subjective evaluation data was related to the image analysis data and interesting correlations were found. The measured gloss variation (COV) including all wavelengths from 0.1 mm to 6.6 mm showed a coefficient of determination r^2=0.78 which is a good value for visual vs instrumental data agreement. (It shall be noted that a wavelength of 1 mm corresponds to a pattern of 0.5-mm brighter and 0.5-mm darker areas or "features"- In this paper we mostly refer to feature sizes, which thus correspond to a wavelength of twice the feature size.)

Although the correlation found was quite good, a plot of the rank numbers against both gloss variation and gloss level showed that there was an influence from the gloss level, so that a print with a given gloss variation was ranked better if its mean gloss level was higher. A multiple linear regression analysis gave R^2=0.91 when the gloss level was also included. However, when the relation between visual data and measurement gloss variation was inspected in individual octave bands, it was found that the correlation is markedly higher for the bands in the range 0.2 to 3.3 mm in wavelength with the best value, r^2=0.85, obtained for the 0.8-1.6 mm octave band. This value, r^2=0.85 or r=0.92 without including multiple regression with the mean gloss level, is in fact so good that COV in a suitable band can probably be taken as a satisfactory metric for the gloss uniformity (or rather gloss variation).

The fact that the inclusion of mean gloss improved the subjective relevance so much in combination with the *wide* band (0.1-6.6mm) variation data may in fact be an indirect effect. It is shown by image examples that an even high gloss sample can have the same amount of total variations as an uneven sample of lower gloss. However, for a smooth sample, the variations mainly come in the fine-scale bands where they do not contribute to an uneven subjective impression. On the other hand, the visually uneven samples instead have their high and low gloss areas respectively clustered into larger aggregates that are more visible and which are detected in longer wavelength bands. This is probably the mechanism behind the good subjective correlation achieved at the longer wavelengths. Different combinations of octave bands were tried and as a standard choice, with some versatility for different types of unevenness, the combination of three octaves into a merged bandwidth of 0.4-3.3 mm was chosen.

Unprinted papers were also measured to see if their gloss variations could predict the printed gloss variations, which would be useful. With regard to the white unprinted samples, the conclusion was that these were far more difficult to judge for the panel and that the correlation between subjective and instrumental data was low. It is obviously harder to see the gloss characteristics against the diffusing bulk-scattered white light than in the printed test samples where the surface-scattered light stands out in better contrast to a dark print. Since it was also shown that the gloss variations of the unprinted paper had little prediction power for the gloss variation in the printed state, we concluded that the present method should be seen as an evaluation tool mainly for printed paper.

It has thus been shown that gloss imaging at 20° illumination/detection angles, followed by the calculation of the coefficient of variation of local gloss within a spatial wavelength range of 0.4-3.3 mm provides useful information on gloss uniformity, a property for which few means of measurement are available. The main application area should be prints on coated grades. Gloss variations on printed uncoated paper, even on newsprint, can also be of interest but another measuring geometry with larger angles is then needed. Further research is of interest concerning the nature of the glossy and non-glossy regions of the paper surface in order to be able to optimize the surface finishing operations.

8.6 Optical measurement and perception of gloss quality of printed matte-coated paper (Paper VI)

The gloss properties of a print are of course effects of its surface topography on a micro- and macro-scale as discussed by Oittinen (1981, 1983). In an earlier work (MacGregor, Béland and Johansson, 1994), an approach was made to model the surface with small facets fitted to a topography map from confocal microscopy. It was there shown that the area regions not giving a specular reflection in the 20° gloss image were mostly tilted away from the average surface plane.

In Paper VI, this approach is taken further to see whether the distribution of the facets orientation is a useful quality measure for gloss variations. This could possibly be an alternative to the band-passed coefficient of variation described in Paper V. The measurements of facet orientation were carried out by Béland at the Institute of Optical Research, IOF, Stockholm. The main method was here to evaluate the angle-resolved bi-directional scattering distribution function (BSDF) from a TMA TASC scatterometer.

The angular distribution of reflected light can be described with a von Mises distribution. In this distribution, the concentration parameter κ (kappa) is sensitive to small changes in the scattering distribution.

The topography of the samples was also evaluated by a confocal laser scanning microscope, and 8 μm x 8 μm facet planes were fitted to the local topography. The samples were also evaluated with the 20° micro-gloss variation apparatus at STFI.

The sample set consisted of 32 commercially produced European matte-coated papers. The coating thickness and the surface roughness varied among the samples but they were basically all competing within the same market segment for 4-color sheet-fed offset printing. The evaluated prints were "400%" black (100 % each of Black, Cyan, Magenta and Yellow) and due to the thickness of the ink layer they showed a “glossy” appearance in spite of the matte-coated finish of the papers. However, depending on the character of the coating, the gloss of the print was more or less affected by disturbances. These disturbances also appeared in different forms, sometimes on a fine scale linked to individual swollen fibers and sometimes on a larger scale like marks from a hammer, due perhaps to the floc structure of the base paper. The subjective evaluation therefore became somewhat complicated due to the multidimensionality of the gloss character.

The subjective evaluation was performed with the judges standing by a table and being allowed to pick up the samples for closer inspection and to rearrange them on the table. The illumination consisted of pairs of fluorescent tubes mounted slightly behind the table so that direct reflection of the tubes could be seen on a very glossy sample. These formed a light arrangement rather narrow in depth (15 cm) but 2 m wide left to right. It is to be observed that the illumination must be rather concentrated if gloss inhomogeneties are to be visible. It was in fact noted that a light arrangement greater in depth (more light tubes in parallel to each other) actually made the comparisons more difficult.

Each judge within a panel of 13 was instructed to sort similar samples into groups and to assign each group a preference number in relation to the other groups. This so-called magnitude estimation scaling leads to a scale with proportionally meaningful distances

between the sample values. The data here collected, lends itself to further multi-dimensional analysis that will be reported elsewhere. Here we just use the main data as a measure of general gloss quality.

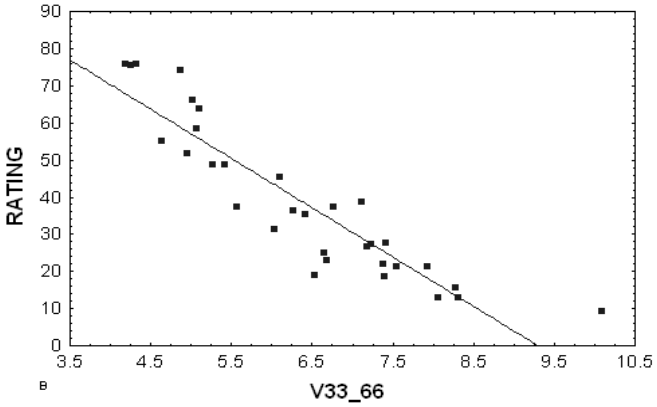

Figure 8.6.1. *Gloss quality rating vs COV in the 3.3-6.6 mm wavelength octave band, which was the one showing the best linear correlation, $r^2 = 0.83$.*

Application of the STFI micro-glossmeter again showed good agreement with the subjective reading. The best correlation, $r^2 = 0.83$, was achieved with the octave wavelength band 3.3-6.6 mm, see *Figure 8.6.1.* The relationship is actually somewhat curve-linear so that a logarithmic curve fit will reach an even higher coefficient of determination. The result is quite good considering that the series was far from easy to evaluate, so that the mean inter-individual correlation between judges was $r^2 = 0.62$ (range 0.35-0.79). The mean judgement is however probably a good indicator of general quality since it was validated against a completely different evaluation by other judges based on a comparison against a five-step gloss quality company scale. The correlation between these two subjective evaluations was $r^2 = 0.90$.

It is worth noticing that the maximal correlation here achieved was at a longer wavelength, 3.3-6.6 mm rather than the 0.4-3.3 mm range, which was recommended in Paper V. One reason for this is probably that the samples were here viewed from a standing position, so that the viewing distance was twice as long and there was a shift in angular resolution by a factor of two, corresponding to a shift of one octave class. It is also probable that this set contained more of large-scale variations (“hammer beat marks”) which would increase the importance of long wave bands.

The evaluation based on the light-scattering parameter κ also gave good correlation with $r^2 = 0.81$. The topographical measure of median facet angle deviation from the plane gave a reasonable $r^2 = 0.72$. The facet angle was in fact closely related to the light-scattering parameter κ. Although the light-scattering and topographical descriptions explained much of the quality differences within the series, some of the variation remains unexplained, probably due to large-scale clustered variations that are not picked up by point-wise evaluations. One important conclusion is that the bandwidth limits associated with a measurement should always be considered. The measured values of many properties like roughness, facet angles or gloss variation will depend on bandwidth-limiting factors like detector resolution, cut-off length, instrument configuration and deliberate spatial filtering.

8.7 Topography and Reflectance Analysis of Paper Surfaces using a Photometric Stereo Method (Paper VII)

The reasons for optical inhomogeneity in prints are mostly related to variations in the amount of ink deposited on the paper. The reason for an uneven ink layer may in turn be surface irregularities that influence the transfer and redistribution of the ink in the printing nip. The surface smoothness is indeed considered to be a most important property for printing papers, especially for those intended for gravure printing, see (Bristow and Ekman, 1981) or (Antoine et al, 1995). The effect of incomplete ink transfer can actually be used to characterize the paper surface (Singh, Johansson, Bristow, 1996). Measurements of surface smoothness or roughness can be performed with different equipment based on different physical principles. In the paper industry, the most common principle is an air-leak measurement, *e.g.* PPS or Bendtsen. Of these, the PPS value gives an average value of the surface profile deviations from an edge pressed against the paper surface, (Parker, 1981). However, such an average roughness value will not distinguish between small but frequent deviations on the one hand and deeper but less frequent deviations on the other. In some printing processes, it may be only the deeper surface pores that constitute a problem for the ink transfer and thus for the evenness in the print result. It is therefore of interest to be able to characterize individual pores to find the crucial surface features rather than an average roughness value.

Other approaches to the roughness measurement problem are the point scanning profile recorders, which may use a mechanical stylus in contact with the paper or some kind of focused light to follow the surface profile, (Wågberg and Johansson, 1993). These instruments provide the freedom to perform more detailed analyses of profile features including the depth of individual pores etc. If, however, the analysis is based on a few profiles spread over a surface the probability of finding critical surface pores may be low. It is of course of interest to scan a complete 2-dimensional surface region with full resolution in the x- and y-directions, both for statistical reasons and because it makes it possible to visually or mathematically evaluate any 2-dimensional features of the topography. A complete 2-dimensional scanning is of course possible with point scanning devices but it is quite time-consuming so that a single image field of say 1x1 cm^2 may take from 15 minutes up to several hours in the case of mechanical scanning. Such an analysis has been made by Mangin (1989) who models the surface topography as an Equivivalent Surface Pore. There are other techniques like confocal scanning light microscopes that can capture a 2-dimensional surface height map in a reasonable time but then only over small image fields typically less than 1x1 mm^2. Antoine et al has made such confocal topography mapping which underlines the usefulness of surface pore analysis for print quality research, (Antoine et al, 1995). To collect larger image fields, sub-images can be “stitched” together by image-processing techniques, but this is rather complicated and somewhat uncertain. Clearly there is a need to acquire larger topographic maps with good resolution preferably with a simultaneous recording of the ink occurrence in the case of printed paper. Paper VII describes a new technique that we have developed for this purpose.

It is a common observation that when sun light falls along a wall, it brings out the surface irregularity of that wall as a pattern of highlights and shadows. The print quality researcher may also use this effect when inspecting an uneven printed surface. If a grazing light illumination is used, the depressions in a paper surface will become visible. Arney et al made

statistical measures of these shading variations and related them to the visual roughness of paper surfaces, (Arney et al., 1992). The effect can in fact also be used to calculate a quantitative surface height map.

The basis of the method is the fact that the apparent brightness of a surface element is dependent both on the light absorbency of the element and on the angle of the element relative to the illumination. To achieve quantitative data, a photometric stereo method is applied to separate surface topography and reflectance. In the reported work it is first shown how the brightness in two images of a surface, illuminated from the left and right respectively, can be used to determine a partial derivative of the surface height, regardless of the local reflectance. This requires a model for the light scattering properties of the surface. The model used divides the scattered light into a bulk-scattered, Lambertian part and a specular, surface-scattered part. The specular part is eliminated with the help of crossed polarizers. was In an earlier stage we tried to integrate the partial derivative line by line through summations to achieve a surface height function. The result of this integration was however heavily disturbed by accumulated noise. In the present method, the integration is carried out in the Fourier transform domain with the help of a Wiener filter, which suppresses frequencies with an expected poor signal-to-noise ratio. More details of the mathematical signal treatment is given in another publication (Hansson and Johansson, 1999b) alternatively (Hansson, 1999). The principle is flexible in scale so that even quite large areas can be analyzed as long as they can be optically imaged. A similar but not identical procedure has been utilized in a scanning electron microscope by Enomae et al (1993).

Comparisons between surface profiles measured with the method and profiles scanned with optical or mechanical methods show a good agreement, r^2=0.95. At the same time, through summation of the left- and right-hand illuminations, the reflectance image will also be available for point-to-point comparisons with the height map, *Figures 8.7.1-8.7.2.*

Application of the method on gravure-printed surfaces shows that areas with a greater probability for missing dots can be revealed through band-pass filtering and thresholding of the surface height function. A threshold level, 1 μm below the local average level, can be seen as a critical value in the investigated case. A prediction of where missing dots would occur if printing were attempted in non-printed areas can also be given. Other models for the types of surface irregularities that causes print inhomogeneities can be applied on the topographical map and the result can immediately be compared with the real print result.

Flexographic prints have also been studied. In this case, a full-tone area contains small white spots, or ‘skips’. The simultaneous distribution of reflectance (ink) and surface height in a high-pass filtered version of the topography is used to construct a model for the influence of local surface height on the ink distribution. The model is then used to predict the print result on an unprinted area.

The preliminary measurements show the value of the method as a tool for studies of the links between surface topography and print result. Compared to other methods, it is fast and can be applied on different scales so that small as well as large fields of view can be analyzed.

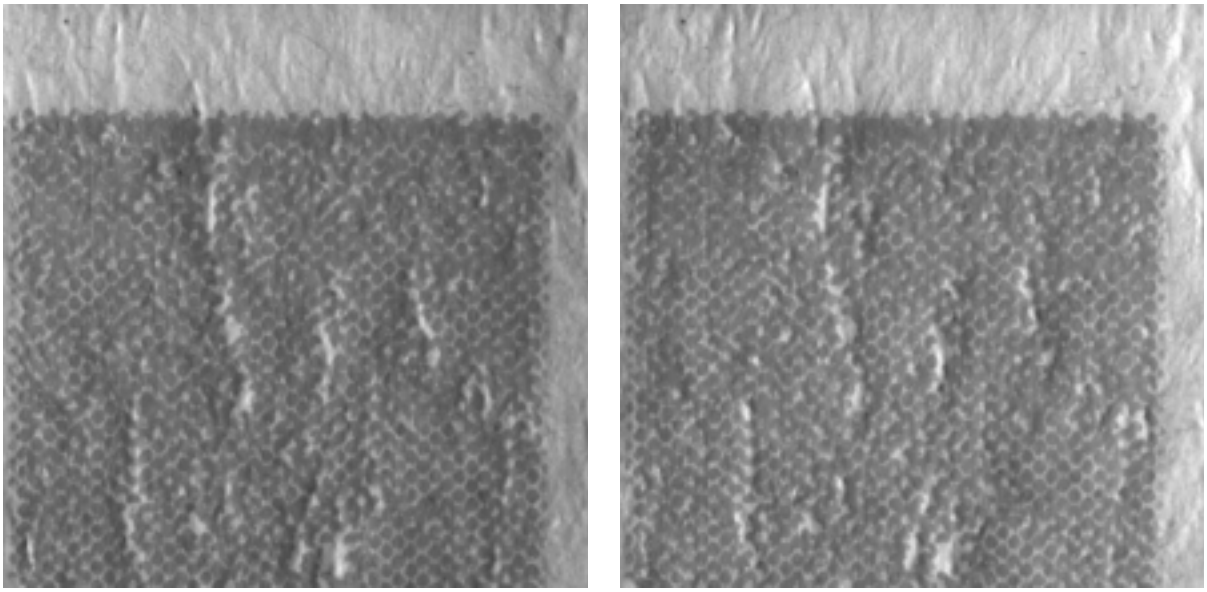

Figure 8.7.1. *Gravure printed surface illuminated from the left and from the right respectively.*

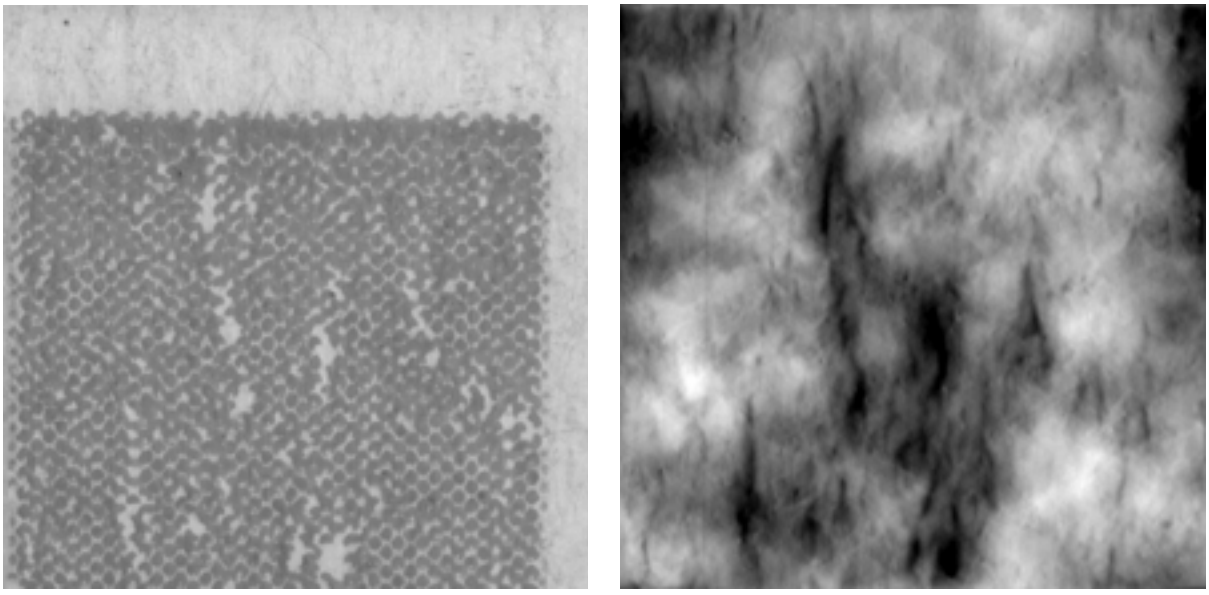

Figure 8.7.2. *New images calculated from the pair above. On the left a reflectance representation and on the right a topographic representation where dark stands for surface depressions. With this type of image pair, direct comparisons of print failures and surface depressions can be made.*

9 Suggested future work

The work presented in this thesis does not answer every question in the treated fields, but rather raises several new ones that could be interesting for future research efforts:

- The present noise analysis techniques have shown a very good correlation with subjective evaluations of *monochrome* prints. It is however of interest to expand the analysis to *multicolor* printing. Analysis of variations in CIELAB-coordinates may serve this purpose.
- The COV_R threshold for print mottle varies with the average darkness of the samples. To be able to state universal COV_R limits for acceptable quality, this effect and the suggested $R^{1/3}$-correction should be further looked into.
- The sensitivity of the human eye to ordered patterns should be further modeled and implemented in a general analysis routine.
- The gloss defects in white unprinted paper are more difficult to assess with panels of judges as well as with instruments, making further research welcome here.
- The glare effects around the angle range of maximum gloss are probably also important for the subjective impression of gloss quality and ought to be included in a gloss quality model.
- Models for the mechanistic part of ink transfer in different printing processes should be developed, utilizing the opportunities made available through the new optical topography analyzer developed in the present work.

10 Conclusions

We have sought a unified way to measure and represent inhomogeneities in prints as well as in underlying paper structures. For the data treatment and presentation we have found the power spectrum with constant relative bandwidth bands (mainly octaves) a useful tool in itself and as an input data set for different models.

For the acquisition of image data we have stated the profound importance of the illumination and detection angles, the choice of which will influence the information gained in a radical way. Technical and psychometric studies have led us to the conclusion that by using a $45^{\circ}/0^{\circ}$ illumination/detection geometry and calculating the reflectance coefficient of variation (COV_R) within a 1-8 mm spatial wavelength range, we gain a valuable tool for estimating the perceptual severity of print mottle. The method has gained acceptance in research and production control laboratories of the industry in Sweden as well as in several other European countries.

In a similar approach but with a $20^{\circ}/20^{\circ}$ specular reflection geometry the gloss character of prints was investigated. Also here, a spatial band-pass analysis of intensity COV, this time with a 0.4-3.2 mm wavelength range, gave measures with a very good correlation to subjective quality ratings.

The analytical approaches here developed, have also been applied by other researchers for other structural features of paper, *e.g.* coating thickness and surface profiles. The spectral characteristics of the inhomogeneities in such properties can give strong clues to possible causes of print mottle. Even stronger implications can of course be achieved if different properties can be directly compared and correlated point-by-point between in-register maps depicting different properties over the same sample area.

The final part of the work deals with how such maps of reflectance and surface topography can be calculated from images acquired with yet another choice of illumination geometry. Through summation, subtraction and integration of image pairs with different illumination angles, a separation of the ink distribution and the surface topography was made possible. This in turn has provided new opportunities to test different hypotheses on the influence of topography on ink transfer. The method, which is patented, will probably be of special interest for the development of optimized surfaces for gravure and flexographic printing.

Finally, it is our hope and belief that the findings on subjective sensitivity and the instrumental methods derived in this work will contribute to the striving towards increased print quality.

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