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Instrumental Gloss Characterization – In the Light of Visual Evaluation: A Review

Mikael Lindstrand†

STFI, Swedish Pulp and Paper Research Institute, Stockholm, SWEDEN

Gloss, as has long been known, is a far more complex visual concept than the present methods of instrumental gloss evaluation are able to characterize. The instrumental analyses are either highly over-simplified (standard gloss meters) or over-simplified but with results still difficult to interpret (goniophotometry). The dimensionality and power of the directed reflectance information measured by existing tools is lower and less expressive than the information gained from a direct visual examination of a surface. The purpose of this paper is to review important gloss measurement issues, in the context of perceptual evaluation. This work gives a background for defining necessary requirements for an evaluation system that can reveal the perceptually relevant gloss features of the surface measured.

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Introduction

"The subject of glare from paper is one which has been attracting ever-increasing attention of late on the part of both publisher and paper maker.". This quotation is the introduction to an article by Ingersoll in 1914[1] but it is still as relevant now as it was then. Gloss is an important appearance characteristic of surfaces in general, and printed and unprinted paper surfaces are no exceptions. On the contrary, they constitute demanding special cases, partly due to their often pronounced and visible surface texture. The present work is directed towards surfaces in general, but due to its often visible surface structure, paper serves in many aspects as a challenging example. Hence most of the present work is related to paper characterization.

The context for this revision is instrumentally based measurement system, which provide an objective description of gloss. This description should be powerful enough to facilitate subsequent evaluations that have a potential to yield results in concert with the results of perceptual evaluation of gloss. That is, the description should bare the perceptually relevant gloss characteristics of the surface measured. Such an objective description has a range of applications. One such example is for detailed studies of the directed reflectance behavior of the surface.[2] Another application is to provide an objective measure in concert with human visual evaluation of gloss homogeneity.

The interdisciplinary character of this revision means that more than one subject must be treated, the most important of which are: perceived gloss, measured gloss and surface models.

Background

For at least 250 years, serious efforts have been made to characterize the phenomenon of gloss, but it is still difficult to objectively predict or to perceptually evaluate gloss appearance characteristics with certainty. One reason for this is the lack of a clear definition of gloss. For instance, according to ASTM "Standard Terminology of Appearance"[3]:

> "**gloss,** *n*–angular selectivity of reflectance, involving surface-reflected light, responsible for the degree to which reflected highlights or images of objects may be seen as superimposed on a surface. (See also **distinctness-of-image gloss, haze** (*in reflection*), **luster, sheen, specular gloss.**)"

The variables involved in visual gloss are mentioned, but how the gloss should be characterized is not specified. Also, most of the related concepts mentioned in the definition are hard to characterize. It is here important to stress a distinction. It is possible to give a physical definition of gloss, in terms of the ability of a surface to reflect light in the specular direction in relation to that of, e.g., a polished plane glass surface with a well defined optical property such as the refractive index. Gloss, so defined, is relatively easy to measure. Even more general, the physics and the theory of the interaction of light with a surface are well described elsewhere.[4–17] However, in the field of paper and print, the detailed physical description is complicated and consequently there is a lack of descriptive models and theory, although a number of articles are well worth mentioning. A com-

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†Corresponding Author: M. Lindstrand, mikael.lindstrand@sca.com; Present address: SCA Graphic Research AB, Sundsvall, Sweden

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monly used characterization approach is the Bidirectional Reflection Distribution Function (BRDF), which is a special case of the more general Bidirectional Scattering Distribution Function (BSDF). In BRDF only the reflected electromagnetic radiation is taken into consideration, hence for gloss related issues the BRDF, omitting the transmitted radiant, is in this respect sufficient. Methods for analyzing bulk and surface scattering have recently been presented,[18] and the concept of "positive scattering contrast range"[19] has been introduced, based on a BRDF. This measure defines the angular range in which there is a positive contrast between image and non-image areas, and it has been proposed as a quality measure. Gloss inhomogeneity has been characterized in terms of surface roughness and surface micro-roughness.[20,21] The evaluation based on measured data has shown good agreement with a perceptual evaluation.[22] It is not nevertheless possible to give a clear meaningful definition of visual gloss or gloss appearance. This has important implications for the present work and is dealt with in the following section.

The Perception of Gloss and its Relation to Print Quality

Image quality is hard to define objectively. There are a number of different aspects involved in a print judged to be of a high quality. The scale of quality is often not absolute. A print is judged in a specific context, as part of a whole set of prints evaluated. Nevertheless, a number of criteria have been identified as being of importance for perceived print quality. In a recent study[23] of paper surfaces, printed using either a digital or the offset technique, criteria for perceived print quality were evaluated, and it was verified that color reproduction, gloss, gloss variation, resolution and mottle, i.e., unwanted density variations over the surface, were important for the perceived print quality. These traditional print quality variables are thus also relevant for the newer digital printing technique. For halftone prints in black-and-white, "color reproduction" corresponds to the range and acuity of the gray scale achievable. For halftone color prints, the criterion of color reproduction can as a first approximation be split into the criteria of density range and acuity for each process color, which are a measure of the available color gamut for the process even if the topic of color is more complicated. Naturally it is desirable to have a large color gamut, in order to be able to print highly saturated and vivid colors with a large dynamic range, and also to achieve high dynamics in the non-chromatic dimension from deep black to pure white.

Physically, a high density, or possibly a high chromatic appearance, originates in principle from different locations in non-conducting (non-metallics, e.g., like paper) and conducting (metallic) materials. In the case of a conducting material, it is the surface reflection that yields the possible chromatic appearance, e.g., the deep reddish yellowish color tone of a polished copper surface. In the case of a non-conducting surface however, the surface reflection does not change the wavelength distribution of the incident light, and a non-chromatic reflection is obtained if the incident light is white. In such materials, it is the bulk scattering that may yield a chromatic appearance. If the bulk of the material is wavelength selective, e.g., with an ink which absorbs a certain range of wavelengths of the light, then the surface appears chromatic, i.e., colored.

Gloss is generally seen as a pure surface reflection and is thus, for non-conducting surfaces, non-chromatic. To achieve a highly chromatic appearance of a non-conducting surface like a paper, it is therefore necessary to avoid non-chromatic surface reflections in the direction where the chromatic sensation is to be perceived. If this is not done, surface reflections blend into the chromatic reflections and reduce the frequency selectivity of the reflected light, causing the color to appear less saturated.[24–26] For a surface of high gloss with a high degree of gloss homogeneity, e.g., a high quality photograph, the surface reflection is well concentrated in the specular direction and is hence easily avoided by an observer. The high gloss quality of a photograph is thus one important reason why it is possible to achieve highly saturated and vivid colors in that type of reproduction, and this is in turn an important factor in the overall high perceived image quality normally related to a photograph. The visual gloss characteristic is consequently one of the important quality factors of print quality, both directly (absence of disturbing glare effects) and indirectly (low reduction of color strength).

A well performed perceptual evaluation, where the panel consists of experienced judges recording their perceived gloss sensation, provides the best information about gloss related questions, e.g., the overall gloss quality of general surfaces. A procedure for visual gloss evaluation has been formalized,[27] but there is no generally used standard in this field. Since the concept of Quality is indeed subjective, this type of evaluation gives *The True Answer* – in principle no instrument can ever outperform a well performed perceptual evaluation. Nevertheless, it might be possible to develop an objective system that yields the same result as a perceptual evaluation but with less statistical uncertainty. In such circumstance the objective system would be preferable to the perceptual evaluation panel. There are further two severe drawbacks of perceptual evaluation.

(i) It is difficult to define the important "instrumental" characteristics of the evaluation panel. It is difficult to state the accuracy and precision of the answer and to say, e.g., how this is dependent on the choice of the panelists. Should the panel members be trained experts in the field, trained judges but with no other specific background, or just randomly chosen persons? If we find it necessary to have trained experts, e.g., in order to have a sufficiently high degree of reproducibility, how do we know that we have a panel of experts? There is also a risk of a drift in a perceptual evaluation panel.

(ii) It is difficult to separate and pinpoint the different principal components in a perceptual evaluation. It may therefore be assumed that a trained expert can make a conceptual integration of judgments over several principally different types of characteristic features. The judgment is thus an overall answer and provides limited information about the reason for a specific quality rating. Approaches based, e.g., on the "multi-dimensional scaling" (MDS) technique aim to map evaluation data into a similarity space of arbitrary dimensions. The strategy is basically a linear algebraic problem, where a vector, the evaluation data, of arbitrary dimensions is resolved into a limited set of basis functions and a residue. In MDS, the residue is a cost function, often called "stress". The stress indicates the lack of explanatory power of the model for a chosen dimensionality of the similarity space, i.e., the stress should be minimized. If the number of dimensions is increased, the degrees of freedom increase and hence the residue, not explained by the model, or "stress" decreases. The rate at which the increase in explanatory power decreases as a function of increasing number of dimensions provides an indication of the inherent dimensionality in the data set. The interpretation of what the different characterizing feature vectors actually represent in the MDS is normally difficult. Different judges may differ with regard to the most important set of characteristic features, and this may lead to problems in pin-pointing specific quality defects within the whole concept of gloss, e.g., striving for end product quality improvements.

One reason for the lack of definition of visual gloss or gloss appearance is that visual gloss is in general a multidimensional phenomenon, as has been pointed out by, e.g., Bouguer.[28] The work was originally written in Latin and translated, when published, into French, but a more accessible English translation,[29] on which the references in the present work are based, is available. Still others[30–32] have drawn the same conclusion about the multidimensional feature of the visual concept of gloss. Nevertheless, it is possible, using a set of selected samples, to obtain results that indicate a one-dimensional response from a human judge. In one study,[33] the multidimensional scaling technique was used to evaluate acrylic lacquer painted automotive panels in order to assess the number of dimensions reliably distinguishable by a judge, but it was concluded that, for the samples tested, only a one-dimensional response of the human judges was significant. This conclusion should however be used with caution. An extension to general surfaces to suggest that visual gloss is not a multidimensional phenomenon cannot be justified. A reasonable hypothesis is that, for a sufficiently coherent set of samples, it is possible and also quite reasonable to end up with a one-dimensional visual evaluation. The acrylic-lacquer painted automotive panels tested may have been such a coherent set of samples.

In two studies by Christie,[34,35] the theme of gloss appearance is given a thorough treatment. For all types of materials, Hunter[30] suggests that gloss appearance is well described by six perceptual terms: 1) Specular Gloss, 2) Sheen, 3) Contrast Gloss, 4) Absence-of-bloom Gloss, 5) Distinctness-of-Reflected-Image Gloss, and 6) Absence-of-surface-texture Gloss. Another suggestion[35] by CIE more or less adopts Hunter's concepts but reduces them to four main attributes: 1) Specular Gloss, 2) Contrast Gloss (Luster), 3) Reflection Haze and 4) Sheen. Two related attributes are a) Perceived Texture and b) Perceived Directionality. Another variation on the same theme was put forward by Billmeyer and O'Donnell[33] in their introduction: 1) Distinctness-of-Image Gloss, 2) Specular Gloss, 3) Contrast Gloss, 4) Reflection Haze, 5) Sheen and 6) Macroscopic Surface Properties, although, as was mentioned before, they concluded that there was a one-dimensional response of the judges for the specific surface set tested.

Ferwerda et al.[36] used image synthesis techniques to explore the relationship between the physical dimensions of glossy reflectance and the perceptual dimensions of glossy appearance. In the work they claimed to reveal the dimensionality of gloss perception and perceptually meaningful and uniform axes in visual "gloss space", to be able to predict just noticeable differences in gloss. They revealed two dimensions for perceived gloss: contrast gloss and distinctness of the reflected image, for the images evaluated. As the images were only computer generated simulating achromatic glossy paints, it is difficult to evaluate the generality of the results. Nevertheless, their approach of relating physical and perceptual dimensions is an important contribution. However, as the model, in its present form, does not involve texture it is not well suited for applications in the area of, e.g., paper surfaces.

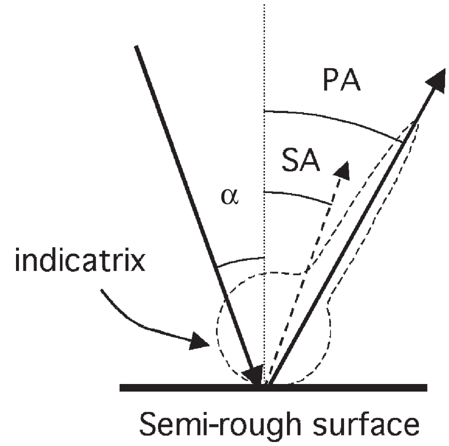

Figure 1. Illustration of Specular Angle (SA) and Peak Angle (PA) of a semi-micro-rough surface. The SA equal but opposite the angle of incidence (α). The directed reflectance may be considerably lower at the SA than at the PA.

Naturally, different types of materials show different characteristics and hence the subset of the most important attributes differs depending on the type of material being characterized. For most paper qualities it may be possible and desirable to focus on a subset of these attributes. The surface structure makes it reasonable to suggest that Perceived Texture and Perceived Directionality together with Specular Gloss are the most important characteristics of paper gloss.

The visual evaluation of gloss starts with an inspection phase, to obtain all the necessary information about the surface, etc. Depending on the characteristics of the surface inspected, the strategy may differ in order to gain information in an effective manner. In a study on paint specimens, Boshoff[37] stated that for highly glossy surfaces sharpness of image reflection is critical, whereas for less glossy surfaces the highest perceived brightness (near the specular direction) and the changes in brightness as the specimen is inclined to angles well away from the angle of highest brightness are the most important variables. Boshoff did not use the expression "highest perceived brightness" but rather "brightness at the specular angle". For glossy surfaces like these paint surfaces, the expressions may be used interchangeably, but for rough surfaces, such as an unprinted paper surface, a distinction is usually necessary.

The angular offset effect due to the roughness of the surface is well known and is theoretically well treated for illumination at normal incidence and perfectly conducting surfaces,[38] and for other surfaces,[5] and generalized in terms of incidence geometry.[39] The effect is also well documented in empirical studies on plain unprinted papers[40,41] as well as on printed papers.[22,41-43] The difference in angle can be as much as 5-10 degrees, and hence is important. This distinction is often neglected in the literature, but it is important when relating measured to observed gloss. Two definitions are given here. The first is adopted from ASTM, Standard Terminology of Appearance[3] and the second has been introduced previously[2] by the author, as indicated in Fig. 1.

Figure 2. Illustration of an effective way of inspection when subjectively evaluating the gloss characteristics of a surface.

- Specular angle (SA): the angle equal and opposite to the angle of incidence, i.e., SA = $-\alpha$.
- Peak angle (PA): the angle at which the directed reflection has its peak value.

An observer inspecting a surface under ordinary visual conditions does not however notice this distinction between SA and PA. The “specular behavior” is visually inspected under the direction of maximum reflectance, even if the SA and the PA are not equal. The distinction is however important when a surface is characterized instrumentally as a basis for predicting how the surface is perceived.

A study of an experienced judge when he or she is inspecting a surface exhibiting texture, shows that gloss is a true multidimensional phenomenon. The inspection is definitely not based on a single snapshot “image” of the sample. On the contrary, the inspection is performed partly in the PA direction, partly when the surface is distinctly inclined away from the PA, and also in the transition between these extremes, and in all cases the spatially resolved information is important. Inspection based on one direction alone would not yield sufficient information for a proper judgment. If the specimen is given a convex shape much of the gloss characteristics of the surface can be revealed, see Fig. 2. This permits simultaneous inspection in the direction of the PA as well as well away from the direction of the PA. The contrast gloss can hence be evaluated. The approach of bringing the surface into a convex shape, or using rigid convex (or occasionally concave) shaped objects has been used to illustrate different gloss characteristics[44–46] as well as to provide an effective means of visual inspection.[43,47] The approach has also been adopted to simulate gloss on a computer screen and to study the influence of the gloss on a subject’s ability to perceive the underlying intensity variation.[48] In the study in which the gloss was superimposed on a test patch, the subjects nevertheless managed to perceive an intensity variation close to the original patch. The observer was able to compensate for the added gloss effect, based on an “expected” intensity. A relation between the perceived shape of a surface and the gloss or intensity variations has also been reported.[49] The perceptual importance of intensity variations in the interpretation of the shape of a body was evaluated, where intensity variations on a computer screen simulated a convex shape. One result was however that texture, e.g., an illustration on a smooth surface, was even more important for the interpretation of shape than was the intensity variation simulating the gloss. Similar conclusions, that imaged based information is important for reflectance judgments have been drawn by others.[50]

One hypothesis to explain why the visual inspection of a surface is facilitated when it is bent into a convex shape is that the information obtained has a higher dimensionality than if the surface is macroscopically flat. There is a trade of information. The area of the sample having a specific inclination is reduced but the variety of simultaneous inclinations gives a new dimension to the information. If, during the inspection, the surface is slowly rotated around its axis of curvature, the information gained is further increased. The judge is then able to compensate for the reduced sample area in each direction and still have access to the angle-resolved dimension. The benefit of rotating a curved surface rather than changing the angle of a macroscopically flat surface during inspection may be that a higher degree of dimensionality of the information is accessible at each moment during the inspection.

Gloss quality is thus much more than a mean gloss level and the quality cannot therefore be characterized solely by a mean gloss level measurement. Gloss homogeneity is normally one important optimization criterion in the quest for higher perceived gloss quality.[42,51] High gloss surface reveals more of its surface irregularities than a low gloss surface due to an enhanced contrast. This high contrast is supposed to be the reason why the worst type of surfaces in terms of perceived gloss quality, are those with a high mean gloss and a pronounced surface topography. It is therefore of interest to characterize the entity of gloss variation in detail. Very small-scale and very large-scale disturbances are not as annoying as mid-range disturbances.[52,53] The peak sensitivity for the human visual system is, depending on the visual environment, in the region of 3 cycles per degree, which is equivalent to a cycle length of approximately 2 mm at a viewing distance of 300 mm. At, for instance, 0.5 and 10 cycles per degree, (cycle lengths of 10 and 0.5 mm respectively at a viewing distance of 300 mm.), the sensitivity is only a quarter of the peak value. This characteristic of the visual system is often described by the contrast sensitivity function (CSF), which shows the relative sensitivity for visual contrast as a function of spatial frequency. A word of caution: the high dynamics (high contrast) of the spatially resolved intensity in the reflection from a surface normally related to gloss implies that spatial frequencies in a range of low sensitivity according to the CSF may also be of interest. The spatial frequency range of interest is thus wider than for an ordinary (non-specular) viewing condition, due to the higher intensity variation often associated with gloss. In fact, at a sufficiently high contrast even spatially extremely small glare effects, well beyond what is indicated by the CSF may be discernable. The reason for this is that if the intensity of the small glare effect is high enough relative to the surrounding field, the corresponding receptor in the eye is excited even if the spatial dimension of the high intensity field covers only part of the receptor’s field of view. There is thus a difference between the shortest spatial wavelength of a pattern of some lateral extension that is *resolvable*, and how spatially small a single glare effect may still be and remain *perceivable*.

All the papers referred to, perhaps with the exception of that by Billmeyer and O’Donnell,[33] make the multidimensionality of gloss most reasonable. This of course also has implications for the metrology and instrumental characterization of gloss. The complexities of the visual and instrumental characterizations must match each other. If the multidimensionality of the input is crucial for a proper perceptual evaluation, then a well-performing instrumental characterization system must also access multidimensional information.

Gloss Measurement and Characterization Methods

Gloss, in the context of perception, is a demanding entity to characterize and there are numerous design parameters of importance. In directed reflectance measurements in general, polarizing filters are often used, both for the illumination and for the detector, in order to distinguish between surface and bulk reflectance. This is of interest when the paper is studied as an optical entity. If, however, the stimuli reaching the human visual system are to be characterized, the measurement should not use polarization filters. The small but non-zero contribution of bulk scattering then adds to the instrumental evaluation of gloss in the same way as it does to the perceived gloss in all directions including the specular direction.

In a general directed reflectance measurement, there are two fundamentally different types of variable, the chromatic (spectral wavelength) and the geometric variable. Gloss is a geometry-dependent property describing part of the reflectance behavior. Although gloss is normally seen as a non-chromatic entity, the standard gloss methods specify that the detector signal be weighted by the function $V(\lambda)$, where λ is the wavelength of the reflected light, to mimic the relative sensitivity of the human visual system.

There are a number of different principles for gloss characterization where we have not yet seen equipment sufficiently powerful to provide a basis for estimating the gloss appearance of a general surface. Since sufficiently good solutions are not available, approximations must be made and these are made on the basis of existing principles. The three most widely used are: a) specular measurement, i.e., in the SA direction, rather than the PA direction, where the latter is preferable if the measurement is to be related to perceptual evaluation, b) angularly resolved measurement and c) spatially resolved measurement, as follows:

a) The measurement of the specular reflectance by a gloss meter is the most straightforward and most frequently used instrumental technique for paper and print evaluation.

   Numerous standards describe the measurement conditions, a few references are given here.[54–57] One important difference between the standards is the angle of incidence, which differs from 20 to 85°, the angle being defined relative to the normal to the sample plane. Based on Louman,[58] Johansson[59] (paper IV) calculated the "roughness damping effect" as a function of angle of incidence. This function illustrated a general understanding that high gloss surfaces (low roughness) are best differentiated with a small angle of incidence and low gloss surfaces (high roughness) with a large angle of incidence. The specular gloss measurement is integrated over an area of several square millimeters and uses a single receptor, *a mono-receptor,* and there is thus no spatial resolution. The technique suffers from two drawbacks: the reflectance is measured (i) in only one direction and (ii) this direction is in the SA. The specular reflectance value is often inter-preted as a gloss quality indication – the higher the reflectance value, the better the product – but in many products, the aim is not to achieve as high a gloss as possible but to meet a desired level of gloss with a minimum of gloss inhomogeneity. The standard gloss meter, however, gives no information or indication about the gloss quality other than whether or not the desired mean gloss level is attained.

   Boshoff[37] characterized the just noticeable difference in gloss level. Gate and Leanity[60] explained anomalies in the relation between visual scaling of gloss level and standardized gloss measurement by pointing at that the acceptance angle of the instruments is of importance. In many systems, the acceptance angle is much greater than the acceptance angle of the human eye. Gate and Leanity gave examples of differences of over two orders of magnitude. This can reverse the order of visual and instrumental ranking for some surface samples. A small aperture, however, makes demands on the precision and stability of the measurement system, required to achieve precise and repeatable results.

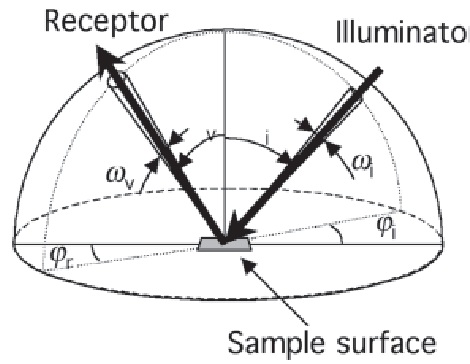

Figure 3. The main variables of a goniophotometric set up in its general form.

b) Angularly resolved reflectometry (scattering), also called "Goniophotometry", is a powerful measurement technique, probably first described in Bouguer's impressive work.[28,29] In the general case, *multiplane goniophotometry*,[61] see Fig. 3, measurements are made at a large number of different receptor positions $R(\varphi_1, \varphi_r)$ distributed over the whole hemisphere above the sample surface. The measurement can also be done for a (large) number of different positions of the illumination system $I(\varphi_i, \theta_i)$. A more modest form is *monoplane goniophotometry,* where $\varphi_i = \varphi_r$, i.e., the illumination device, the sample and the receptor all lie in the same plane, and the reflectance is measured over a large number of different positions over a semicircle above the sample. The illumination and receptor fields, ω_i and ω_r respectively, are adjustable to suit different types of measurement situations but are held constant within a measurement session. The surface area measured is normally at least one square millimeter, and the reflected light is measured by a mono-receptor, i.e., the data are not spatially resolved.

   Even if it is possible to arrange the monoplane goniometric measurement session otherwise, it has become a *de facto* standard procedure to present traditional goniometric results of an evaluation in a specific way. Normally the illumination is held fixed while the angle of the receptor is changed relative to the normal of the mean surface plane, to obtain an indicatrix which shows how the surface reflects light as a function of angle θ_r, for a given incidence angle. This differs from a visual inspection, however, where the illumination and the head are normally stationary while the sample is inclined in different directions for evaluation or, until, e.g., the disturbing glare effect is eliminated.

Nimeroff[62] characterized the goniometric curve by indices of dispersion, skewness, and kurtosis. A method based on the kurtosis index showed a better correlation to the visual impression of distinctness of the reflected image than a conventional specular gloss measurement. The method was later developed into a two-parameter approach[63] with varying receptor aperture, and this showed a good correlation with the visual impression of image brightness and image distinctness. Béland et. al.[22] used Von Mises distributions[64] to characterize a BRDF of paper surfaces that correlated well with a visual assessment. In this study, the spatial variation characterization technique,[65] and the standardized *TAPPI* 75° gloss method[56] also gave the same ranking.

A time effective variant of the goniophotometric technique uses a reflecting hemisphere and a CCD camera to resolve the angular distribution of the reflectance from the surface.[66] This principle is not, however, able in spite the spatially resolved CCD receptor, to resolve the information spatially over the surface measured, because the spatial coordinates of the receptor correspond to different reflectance angles from the region measured, in this setup.

Arney and co-authors have developed a number of different goniophotometric measurement approaches. One uses a cylindrical sample holder[67] according to a theory proposed by Arney and Stewart.[68] Two images of the sample are taken, the angles of incidence of the illumination being the same in magnitude but on opposite sides of the CCD camera. Assuming Lambertian behavior, the two spatially resolved reflectance maps can be used to derive spatially resolved slope information. Non-Lambertian surfaces can also to some extent be characterized. The authors present curves of α_{IA} versus α_G, where α_{IA} is the calculated surface angle and α_G is the enforced angle due to the circular sample holder. Assuming a perfect Lambertian surface, this would generate a linear function with a slope of unity, and any departure from linearity may due either to the topography or to a specular component in the reflectance of the surface measured, i.e., a false assumption of Lambertian behavior. Departures from Lambertian characteristics are hence described as (i) a surface specular reflection or (ii) a "diffuse specular reflection", i.e., a local specular reflection from a surface with a (macroscopic) topographic variation. Another similar approach uses a cylindrical sample holder and a differential image, but the difference between the two input images here is the state of polarization. Hence bulk reflection is differentiated from the surface reflection.[69] In a third approach[70] the sample is held macroscopically flat and a long thin gradient field illuminates the sample. First surface reflection is measured using polarizing filters. The gradient illumination field facilitates identification of surface local inclination, made possible through reflection level identification and ray tracing. The approach is thus angularly resolved.

c) Recently there has been an increasing interest in spatially resolved measurements, either (i) by combining single measurement spot instrumental techniques with a motorized *x-y*-table to facilitate multiple measurements which could be "stitched" together to cover a large area, or (ii) by replacing the mono-receptor by a matrix of receptors, e.g., a CCD camera. In the first approach the spatial resolution is limited by the area of the region measured, *the spot size,* which is normally in the range from one square millimeter to more than one square centimeter. In the second approach, the desired resolution is obtained with the help of magnifying optics. Since a CCD array has a fixed number of pixels, the drawback of choosing too high a resolution is that the sample area covered becomes small, but this can of course be overcome by using the x-y-table technique to stitch multiple measurements together. Another drawback of the CCD technique is that there is a risk that part of the measurement area may be out of focus, since the distance from the CCD to the surface varies in a gloss measurement setup. The problem can be reduced by adjusting the focal stop to achieve an extended focal depth. This however makes greater demands on the optics, e.g., tolerances of the lenses, and the tuning of the F-stop is normally an optimization stage. Another way of reducing the problem is to use a line-CCD instead of a matrix-CCD,[71] or to use only the row of the matrix-CCD which is close to the focus.

The previously described visual examination approach of bringing the specimen into a convex shape has been adopted for a spatially and angularly resolved surface reflectance measurement technique,[72] that was introduced in 1996 and has been developed further.[73] The approach has been patented.[74,75] A related work describes an interactive gloss visualization environment,[2] which was used as a tool in the context of perceptual evaluation of a set of black printed paper surfaces, measured with the just mentioned device.[73] The set of surfaces was demanding as the differences between the surfaces were small, still the correlation between the evaluations of the physical and the visualized surfaces was high, and it is suggested that the visualization environment is able to mediate essential information related to gloss and gloss variation. As the input to the visualization environment is based on the measurement made by the just mentioned reflectance measurement technique, the results also give indication of the relevancy of the measurement technique. However, as the set of samples was limited, further studies are required in order to verify the encouraging results.

Since gloss homogeneity is an important gloss quality criterion, it is of interest to be able to characterize this entity in detail, which demands at least spatially (and preferably also angularly) resolved data. Fujiwara et. al.[76] studied the standard deviation of paper surface reflection, using a single receptor at the specular angle of 75° in combination with a motorized *x-y*-table, and reported a correlation with the visual assessment of gloss uniformity. MacGregor and Johansson[77,78] used a matrix CCD camera to enable a spatially resolved measurement system, and could thereby perform a feature size spatial filtration in octave bands to take into account the relative sensitivity of the human visual system, often characterized by the Contrast Sensitivity Function (CSF).[52] The system gave results that correlated well with the results of a visual assessment. A similar approach including also confocal laser scanning microscopy (CLSM) to relate topography to gloss variations has also been reported.[51] These works[51,76–78] do however perform measurements in the specular direction only, and are verified by fairly coherent sets of paper samples. To characterize the gloss of gen-

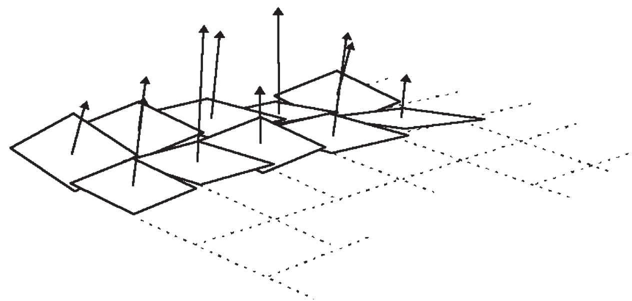

Figure 4. Conceptual model of a surface, a facet approximation with local variables "directed reflectance" (illustrated as a vector parallel to the normal vector of the facet and with a length proportional to the degree of directed reflectance) and the apparent inclination or "tilt" (the direction of the normal vector to the facet).

eral surfaces with a wider variety of deficiencies, the measurement must further be generalized to cover more of the perceptual important features, e.g., to include also angular resolution.

Even when the reflectance measurement of a surface is restricted to geometric variables, the dimensionality of the information is high. Each measurement technique yields a specific subset of the dimensions obtained in a perceptual evaluation of the reflectance information. The amount of information needed to characterize the reflectance behavior of a surface in detail is both large and complex. When the performance of an instrumental measurement is evaluated in relation to a visual evaluation, it is important to let the judges be allowed to assess information from all the adequate dimensions for a perceptual evaluation. If one of the dimensions is removed, e.g., if the judge is not allowed to change the inclination of the sample, the directed reflectance information and hence the result of the visual evaluation will inevitably become stunted.[31,40]

Models for Angularly and Spatially Resolving the Directed Reflectance

A very old approach to understanding the reflectance properties of a surface, first suggested by Bouguer in 1760,[28,29] is to see the surface as consisting of a large number of small surface elements, *facets*, with individual reflectance and tilt (angular setup) properties, as shown in Fig. 4.

In 1939, Barkas[79] described surfaces showing low gloss as consisting of facets of either a diffusing or a reflecting type. Later he described equipment constructed with a Meccano™ toy-set(!) where "The pre-war price of the components is under ten shillings".[80] The facet approach is however controversial, and the criticism has at times been very hard, as indicated by the translator's note 31 on p. 112 in the work of Bouguer[29]:

> "Bouguer's treatment of this subject, which forms such a large part of the second book, is the least satisfactory part of the whole work. He was not the last to make the assumption that a rough surface could be analyzed into little mirrors, nor the last to fail to get any very useful results by doing so [see V. G. W. Harrison, *Definition and Measurement of Gloss* (Leatherhead, Surrey: The Printing and Allied Trades Research Assn., 1945)]. Our footnotes in this part of the work will be infrequent, partly in consequence of the rather limited success (to put it mildly) of his treatment. But he did establish the subject of goniophotometry."

The technique has, as indicated, nevertheless been adopted by others authors and the theory has also been extended to include, e.g., shadowing and masking effects of adjacent facets.[8] A high surface area inter-occurrence (78%) between facet angle determined by a confocal laser scanning microscopy (CLSM) and gloss intensity variations has been demonstrated for paper surfaces.[51] The facet approach has been adopted to describe surfaces deviating from Lambertian behavior, showing masking, shadowing and interreflections between points on the surface[15] and also for developing a unified surface reflection description based both on physical and geometrical optics.[14]

Roughness and Texture in Relation to Perceived Gloss

The directed reflectance from a surface is a function of the refractive index and the roughness, i.e., the topographical variation. A single roughness value characterizing the whole surface may however be too coarse in a visual context, as the human visual system is sensitive to structure in the visual field. In a refined description, the perceived gloss of a surface is a function of the refractive index and of the *texture*, i.e., topographic variation and directionality, of the surface. Which of these entities, refractive index or texture, is the more important depends on the type of material studied.

Surfaces differ not only in their degree of topographic variation, but also in the spatial wavelength of this variation. The human visual system, as already mentioned, has a limited spatial bandwidth within which it is able to resolve spatial variations and there is also a frequency dependent sensitivity within this frequency range.[52,53] Nevertheless, even if a topographic variation with a very high spatial frequency is not spatially resolvable by the visual system, the variation can still cause (second order) optical effects that are visually perceivable. A matt surface may differ from a glossy in that there is a micro-topography that is not resolvable by the unaided eye, although its effect in causing the surface to appear matt is perceivable. This frequency dependent characteristic of the human visual system should be included in any instrument based measurement system in order to obtain results in close correlation to results from a perceptual evaluation.

The most frequently used topographic characterization parameter is the root-mean-square (rms) roughness σ. All measurements of roughness, whether optical or mechanical, are dependent on the measurement tool used and on its spatial resolution. The roughness is thus not an intrinsic material property. Important structural information about the surface is lacking in the rms roughness, but its simplicity makes the parameter frequently used. The specular reflectance of a perfectly conducting surface at normal incidence can, according to Davies, be derived from the root-mean-square roughness.[38] His application was used for radar wave reflection from sea waves, under the assumption that the height distribution is Gaussian and that the radar waves are totally reflected from the surface. The derivation was generalized by Bennet and Porteus[5] to apply to less than perfectly conducting surfaces and a finite reflectance ratio. Torrance[39] developed the theory further to include non-normal incidence. He derived the ratio

R/R_0, where R is the specular reflectance for the material and R_0 is the specular reflectance of a perfectly smooth surface of the same material, as:

$$\frac{R}{R_0} = \exp-\left(\frac{4\pi\sigma_0 \cos\theta}{\lambda}\right)^2 + \frac{2^5 \pi^3}{m^2}\left(\frac{\sigma_0}{\lambda}\right)^4 \Delta\omega \cos^3\theta, \quad (1)$$

where σ_0 is the root-mean-square roughness, θ is the (mean) angle of measurement, λ is the wavelength of the incident radiation, m is the root-mean-square slope of the surface profile, and $\Delta\omega$ is the acceptance solid angle of the instrument. Although it is questionable how realistic this model is for such a complicated optical material as paper, it nevertheless indicates general qualitative behavior, and important conclusions can be stated based on this relationship. The first of the two terms in Eq. (1) represents the specular reflection, and the second the diffuse reflection. Louman[58] put forward derivations and general comments in relation to standardized gloss meters, on the basis of Eq. (1), with informative illustrations of the functional dependences of the ingoing variables:

- the specular reflectance increases with (i) decreasing σ_0/λ ratio and (ii) increasing θ
- the diffuse reflectance increases, in order of descending importance, with (i) increasing σ_0/λ ratio, (ii) decreasing θ [the impact is a function of θ, the effect is most dominant near $\theta = \pi/4$, less dominant near $\theta = 0$ (normal incidence) and $\theta = \pi/2$ (grazing incidence angles)], (iii) decreasing m and (iv) increasing $\Delta\omega$.

The relationship between texture, roughness, and visual gloss in paper and board are far from being fully understood. The relationship between topography and surface light scattering has however been treated in depth by Béland[81] Granberg[82,83] and Hansson.[84] The roughness of paper typically has a large spatial bandwidth. When the directed reflectance from a surface such as paper is characterized, the spatial scale is thus particularly important. Formally, all height variations over the surface can be defined as roughness. The large scale roughness is however more often defined as texture.

Gloss Characterization

A measure of gloss, in relation to print and gloss quality, should consider at least two parameters: 1) *the mean level* and 2) *the variation*. The mean level should preferably be characterized in the PA, as that is the direction of interest to the human judge. The variation can be split into two aspects: 2a) *the spatial coordinates* and 2b) *the angular coordinates*. The spatial coordinates provide information about reflectance variations as a function of change in x- and y-coordinates (different locations) over the surface. The angular coordinates provide information about variations as a function of inclination of the sample.

It is difficult to set a general scale space of interest for the measurements, i.e., a range of spatial frequencies of interest for the characterization algorithm. For example, a matt paper surface can be perceived as homogeneous with regard to gloss and therefore of high quality, but at a low mean gloss level. The surface is however matt because it is rough on a micro-scale, a scale not resolvable by the unaided human visual system. It is desirable to have the same principal behavior in an instrumentally based gloss characterization.

Instrumental characterization methods have been developed for task 1) (although almost always the SA, not in the PA preferred direction), but for task 2) few studies have been reported. In perceptual studies, however, gloss quality is usually characterized as an integrated concept, i.e., tasks 1) and 2) are considered together. Among the exceptions are the following (where 1), 2a) and 2b) correspond to the above):

1) Boshoff[37] characterized the just noticeable difference in gloss level, i.e., a parameter closely related to maximal directed reflectance. Gate and Leanity[60] explained anomalies in the relation between visual scaling of gloss level and standardized gloss measurement by pointing at that the acceptance angle of the instruments is of importance. In many systems, the acceptance angle is much greater than the acceptance angle of the human eye. Gate and Leanity gave examples of differences of over two orders of magnitude. This can reverse the order of visual and instrumental ranking for some surface samples. A small aperture, however, makes demands on the precision and stability of the measurement system, to achieve precise and repeatable results.
2) a) Fujiwara et. al.[76] studied the standard deviation of paper surface reflection, using a single receptor at the specular angle of 75° in combination with a motorized x-y-table, and reported a correlation with a perceptual evaluation of gloss uniformity. MacGregor and Johansson[65] characterized gloss variation of printed papers as a function of spatial coordinates, and performed a spatial filtration to take into account the relative sensitivity of the human visual system, often characterized by the Contrast Sensitivity Function (CSF).[52] The system gave results that correlated well with the results of a perceptual evaluation. A similar approach including also confocal laser scanning microscopy (CLSM) to relate topography to gloss variations has also been reported.[51]
   b) Nimeroff[62] characterized the goniometric curve by indices of dispersion, skewness, and kurtosis. A method based on the kurtosis index showed a better correlation to the visual impression of distinctness of the reflected image than a conventional specular gloss measurement. The method was later developed into a two-parameter approach[63] with varying receptor aperture, and this showed a good correlation with the visual impression of image brightness and image distinctness. Béland et. al.[22] used Von Mises distributions[64] to characterize a Bidirectional Scattering Distribution Function (BSDF) of paper surfaces that correlated well with a perceptual evaluation. In this study, the spatial variation characterization technique,[65] and the standardized *TAPPI* 75° gloss method[56] also gave the same ranking.

An interesting suggestion put forward by Leekley et al. already in 1970 is that a more direct measure of gloss would be the degree to which surface reflections can be excluded from the viewing angle.[24] For instance, how much must the surface be inclined in order to exclude the annoying glittering effects on a print? To answer this question information resolved both in spatial and angular dimensions is required. As both the spatial and the angular variables are important in the perceptual evaluation of gloss, any instrumental characterization in relation to perceptual evaluation of gloss should be resolved both spatially and angularly.

Apart from one exception,[72] no technique has, to the author's knowledge, been reported in literature providing a resolution in these three dimensions (the two spatial dimensions and the angular dimension) high enough to have a potential of being suitable for in-depth perception related studies of gloss. Restrictions are made in one or more dimensions. Lalonde and Fournier[85] quite recently also stressed this lack of progress in the field of empirical measurements and characterization tools. They emphasized the demanding task of reflectance characterization, with the massive data set stored and computed in order to reach visual acuity in simulations. A wavelet representation was suggested as a compact representation of reflectance information. The lack of directed reflectance measurement tools able to characterize the perceptually relevant features related to visual gloss is still, however, a fact.

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References

1. L. R. Ingersoll, A means to measure the glaze of paper, *Electrical World* **63**(12), 645–647 (1914).
2. M. Lindstrand, An interactive gloss visualization environment - For measured or simulated surface data, *J. Imaging Sci. Technol.* **47**(4), 346–356 (2003).
3. Standard Terminology of Appearance, Standard Procedure No. E 284-99a, *ASTM* 1999.
4. E. M. Berry, Diffuse reflection of light from a matt surface, *J. Opt. Soc. Amer. Rev. Sci. Instr.* **7**, 627-633 (1923).
5. H. E. Bennett and J. O. Porteus, Relation between surface roughness and specular reflectance at normal incidence, *J. Opt. Soc. Amer.* **51**(2), 123-129 (1961).
6. P. Beckmann and A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces,* Pergamon Press, New York, 1963.
7. F. E. Nicodemus, Directional reflectance and emissivity of an opaque surface, *Appl. Opt.* **4**(7), 767-773 (1965).
8. K. E. Torrance and E. M. Sparrow, Theory for off-specular reflection from roughened surfaces, *J. Opt. Soc. Amer.* **57**(9), 1105-1114 (1967).
9. G. C. McCoyd, Polarization properties of a simple dielectric rough-surface model, *J. Opt. Soc. Amer.* **57**(11), 1345-1350 (1967).
10. K. E. Torrance, Theoretical polarization of off-specular reflection peaks, *J. Heat Transfer* **91**(2), 287-290 (1969).
11. T. S. Towbridge and K. P. Reitz, Average irregularity representation of a rough surface for ray reflection, *J. Opt. Soc. Amer.* **65**(5), 531-536 (1975).
12. J. T. Kajiya, Anisotropic reflection models, *SIGGRAPH*, Vol. 19, pp. 15-21, San Francisco, US, 1985.
13. H. XiaoDong, K. E. Torrance and F. Sillion, A comprehensive physical model for light reflection, *Computer Graphics* **23**(4) (1991).
14. S. K. Nayar and T. Kanade, Surface reflection: Physical and geometrical perspectives, *IEEE Trans. Pattern Anal. Mach. intell.* **13**(7), 611-634 (1991).
15. M. Oren and S. K. Nayar, Generalization of the Lambertian model and implications for machine vision, *Int'l. J. Computer Vision* **14**(3), 227-251 (1995).
16. B. V. Ginneken, M. Stavridi and J. J. Koenderink, Diffuse and specular reflectance from rough surfaces, *Appl. Opt.* **37**(1), 130-139 (1998).
17. A. V. Gitin, Radiometry. A comprehensive approach, *J. Opt. Tech.* **65**(2), 132-140 (1998).
18. L. Mattsson and R. Usbeck, A technique for analysis of surface and bulk scattering of paper sheets, *International Printing and Graphic Arts Conference*, pp. 131-137, 1996.
19. M.-C. Béland and L. Mattsson, Optical print auality of coated papers, *J. Pulp and Paper Sci.* **23**(10), J493-J498 (1997).
20. P. Oittinen, Surface reflection of coated papers and prints, *Adv. Printing Sci. Technol.* Vol. 15**,** Lillehammer, Norway, June 1979, Pentech Press, London, UK, 1980, pp. 344-372.
21. M.-C. Béland and J. M. Bennett, Effect of local microroughness on the gloss uniformity of printed paper surfaces, *Appl. Opt.* **39**(16), 2719-2726 (2000).
22. M.-C. Béland, S. Lindberg, and P.-Å. Johansson, Optical measurement and perception of gloss quality of printed matte-coated paper, *J. Pulp and Paper Sci.* **26**(3), 120-123 (2000).
23. S. Lindberg, N. Pauler and M. Heiden, Perceived print quality in digital and offset printing, *Adv. Printing Sci. Technol.* **26,** Munich Germany, 1999, Pira International, UK, 2000, pp. 151-173.
24. R. M. Leekley, C. W. Denzer, and R. F. Tyler, Measurement of surface reflection from papers and prints, *TAPPI* **53**(4), 615-621 (1970).
25. P. Oittinen, Relations between print gloss and print density, *Graphic Arts in Finland* **20**(2), 3-7 (1991).
26. E. N. Dalal and M. Natale-Hoffman, The effect of gloss on color, *Color Res. Appl.* **24**(5), 369-376 (1999).
27. Standard Test Method for Visual Evaluation of Gloss Differences Between Surfaces of Similar Appearance, Standard Procedure No. D 4449-90, *ASTM* 1995.
28. P. Bouguer, Traité d'optique sur la gradation de la lumiere (Ouvrage posthume de M. Bouguer), M. l'Abbé De La Caille, Paris, 1760.
29. P. Bouguer, *Optical Treatise on the Gradation of Light* (English translation with introduction and notes by W. E. Knowles Middleton.), University of Toronto Press, Toronto, Canada, 1961.
30. R. S. Hunter, Methods of determining gloss, *ASTM* **30,** 783-806, 1936.
31. R. Sève, Problems connected with the concept of gloss, *Color Res. Appl.* **18**(4), 241-252 (1993).
32. G. Kigle-Boeckler, Measuring gloss and reflection properties of surfaces, *TAPPI J.* **79**(9), 194-198 (1996).
33. F. W. J. Billmeyer and F. X. D. O'Donnell, Visual gloss scaling and multidimensional scaling analysis of painted specimens, *Color Res. Appl.* **12**(6), 315-326 (1987).
34. J. S. Christie, Review of geometric attributes of appearance, *J. Coatings Technol.* **51**(653), 64-73 (1979).
35. Anon, Evaluation of the attribute of appearance called gloss, *CIE-Journal* **5**(2), 41-56 (1986).
36. J. A. Ferwerda, F. Pellacini, and D. P. Greenberg, A psychophysically-based model of surface gloss perception, *Proc. SPIE* **4299,** 291-301, SPIE, Bellingham, WA, 2001.
37. M. C. Boshoff, Gloss Scale for Paint Surfaces, *J. Opt. Soc. Amer.* **48**(10), 741-746 (1958).
38. H. Davies, The reflection of electromagnetic waves from a rough surface, *Inst. Electrical Eng.* **101,** pp. 209-214, 1954.
39. K. E. Torrance, Monochromatic directional distribution of reflected thermal radiation from roughened dielectric surfaces, M.Sc. Thesis, University of Minnesota, Minneapolis, 1964.
40. V. G. W. Harrison, *Definition and Measurement of Gloss: A Survey of Published Literature*, Printing and Allied Trades Research Association, Cambridge, 1945.
41. J. M. Fetsko, F. E. Witherell, and G. W. Poehlein, Relationship between gloss and surface roughness of paperboard samples and prints, *Adv. Printing Sci. Technol.* **12,** 67–72, Versailles, France, IPC Science and Technology Press, 1973.
42. J. M. Fetsko and A. C. Zettlemoyer, Factors affecting print gloss and uniformity, *TAPPI* J. **45**(8), 667-681 (1962).
43. A. Paul, Measuring technology for assessing gloss, *Professional Printer* **38**(2), 13-16 (1994).
44. R. S. Hunter, *Gloss Evaluation of Materials*, ASTM Bulletin No. 186, ASTM, 1952.
45. R. S. Hunter, New gloss tests of paper products, *TAPPI* **38**(1), 17-24 (1955).
46. R. S. Hunter, Methods for evaluating the gloss of ink films, *TAPPI* **46**(7), 162A-167A (1963).
47. U. Schultz and A. Paul, Meßtechnische und visuelle Beurteilung von Glanz bei Drucken, 5.023, Fogra - Forschungsbericht, 1992.
48. E. Mingolla, J. T. Todd, and J. F. Norman, Perception of lightness of glossy surfaces, *Proc. SPIE* **4299,** 302–311, SPIE, Bellingham, WA, 2001.
49. J. T. Todd and E. Mingolla, Perception of surface curvature and direction of illumination from patterns of shading, *J. Experimental Psych.: Human Perception and Performace* **9**(4), 583-595 (1983).
50. S. Nishida and M. Shinya, Use of image-based information in judgments of surface-reflectance properties, *J. Opt. Soc. Amer.* A **15**(12), 2951-2965 (1998).
51. M. A. MacGregor, P.-Å. Johansson, and M.-C. Béland, Measurement of small-scale gloss variation in printed paper, *International Printing and Graphic Arts Conference*, TAPPI Press, Atlanta, GA, 1994, pp. 33-43.
52. F. W. Campbell and L. Maffei, Contrast and Spatial Frequency, *Scientific American* **231**(5), 106-114 (1974).
53. O. R. Mitchell, Effect of spatial frequency on the visibility of unstructured patterns, *J. Opt. Soc. Amer.* **66**(4), 327-332 (1975).
54. Paper and board. Measurement of specular gloss Part 2: 75° gloss with a parallel beam. DIN method, Standard Procedure No. ISO 8254-2, International Standards Organization, 1999.
55. Standard Test Method for Specular Gloss of Paper and Paperboard at 75°, Standard Procedure No. D 1223-93, *ASTM* 1998.
56. Specular gloss of paper and paperboard at 75 degrees, Standard Procedure No. T 480 om-99, Technical Association of the Pulp and Paper Industry, 1999.
57. Specular gloss of paper and paperboard at 20 degrees, Standard Procedure No. T 653 om-98, Technical Association of the Pulp and Paper Industry, Atlanta, GA, 1998.
58. H. W. Louman, Relation zwischen Oberflächenreflexion und Druckglätte, *Wochenblatt für Papierfabrikation* **111**(14), 496-500 (1983).
59. P.-Å. Johansson, Optical Homogeneity of Prints, *Doctorate Thesis*, KTH, Royal Institute of Technology, 1999.

60. L. F. Gate and K. Leaity, New aspects on the gloss of coated paper, *TAPPI Coating Conference*, TAPPI Press, Atlanta, GA, 1991, pp. 473–481.
61. Standard Practice for Angle Resolved Optical Scatter Measurements on Specular or Diffuse Surfaces, Standard Procedure No. E 1392-96, *ASTM* 1996.
62. I. Nimeroff, Analysis of goniophotometric reflection curves, *J. Res. NBS* **48**(6)(1952).
63. I. Nimeroff, Two-parameter gloss methods, *J. Res. NBS* **58**(3), 127-135 (1957).
64. H. Rothe and D. Hueser, Application of circular and spherical statistics for the interpretation of BRDF-measurements, *Proc. SPIE* **3141-02,** 13-24, (1997).
65. M. A. MacGregor and P.-Å. Johansson, Gloss uniformity in coated paper, measurement of commersial papers, *TAPPI Coating Conference*,*TAPPI* Press, Atlanta, GA, 1991, pp. 495-504.
66. G. J. Ward, Measuring and modeling anisotropic reflection, *SIGGRAPH 92*, Association for Computing Machinery, Vancouver, Canada, 1992, pp. 265-272.
67. J. S. Arney, T. Tantalo, and D. Stewart, The measurement of surface topography of materials by analysis of goniometric reflection of light: Factors governing precision and accuracy, *J. Imaging Sci. Technol.* **38**(5), 489-494 (1994).
68. J. S. Arney and D. Stewart, Surface topography of paper from image analysis of reflectance images, *J. Imaging Sci. Technol.* **37**(5), 504-509 (1993).
69. J. S. Arney and H. Tran, An inexpensive micro-goniophotometry you can build, *Proc. IS&T's PICS Conf. Proc.*, IS&T, Springfield, VA, 1998, pp. 179-182.
70. J. S. Arney, J. Michel and K. Pollmeier, Instrumental analysis of gloss and micro-gloss variations in printed images, *Proc. IS&T's PICS Conf.*, IS&T, Springfield, VA, 2002, pp. 126-129.
71. P. Oittinen, H. Saarelma and P. Tuovinen, Micro scale gloss of pPapers and prints, *International Printing and Graphic Arts Conference Proc.*, TAPPI Press, Chicago, IL, 1990, pp. 147–151.
72. M. Lindstrand, A conceptual approach to describe gloss variation in printing paper, M.Sc. Thesis, Linköping University, Sweden, 1996.
73. M. Lindstrand, An angularly and spatially resolved reflectometer for a perceptually adequate characterization of gloss, *J. Imaging Sci. Technol.* **49,** 72 (2005).
74. P.-Å. Johansson and M. Lindstrand, Swedish patent 9600816-4 (20 December 1999).
75. P.-Å. Johansson and M. Lindstrand, U.S. patent 6,147,750 (14 November 2000).
76. H. Fujiwara, C. Kaga, and I. Kano, Measurement of Gloss Profile, *TAPPI* Coating Conference, Boston, TAPPI Press, Atlanta, 1990, pp. 209-218.
77. M. A. MacGregor and P.-Å. Johansson, Submillimeter gloss variations in coated paper. Part 1: The gloss imaging equipment and analytical techniques., *TAPPI J.* **73**(12), 161-168 (1990).
78. M. A. MacGregor and P.-Å. Johansson, Submillimeter gloss variations in coated paper. Part 2: Studying "orange peel" gloss effects in a lightweight coated paper., *TAPPI* J. **74**(1), 187-194 (1991).
79. W. W. Barkas, Analysis of light scattered from a surface of low gloss into its specular and diffuse components, *Proc. Physical Society*, A **51**(2), 274-295 (1939).
80. W. W. Barkas, A geared photometer turntable suitable for surfaces of low gloss, *J. Sci. Instr.* **19**(2), 26-29 (1942).
81. M.-C. Béland, Gloss variation of printed paper: relationship between topography and light scattering, Ph.D. Thesis, KTH, Royal Institute of Technology, 2001.
82. H. Granberg, Light scattering in paper Angle-dependent light scattering measurements and analysis, Licentiate Thesis, KTH, Royal Institute of Technology, Sweden, 2001.
83. H. Granberg, Optical Response From Paper Angle-dependent Light Scattering Measurements Modelling and Analysis, Ph.D. Thesis, KTH, Royal Institute of Technology, Sweden, 2003.
84. P. Hansson, Surface Chracterization using Radiometric and Fourier Optical Methodes, Ph.D. Thesis, Uppsala University, Sweden, 2003.
85. P. Lalonde and A. Fournier, A wavelet representation of reflectance functions, *IEEE Trans. Visualization Comp. Graphics* **3**(4), 329-336 (1997).