

New luster formula for the characterization of hair tresses using polarization imaging

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1. Synopsis

Hair luster is one of the most important parameters of visual appearance perceived by consumers. Current luster formulae (TRI, Reich-Robbins, ...) are optimized for goniophotometric measurements. They are based on a mathematical decomposition of reflected light into specular and diffused light and the measurement of the shine peak width on the fitted angular distributions. In this expose, we are describing a polarization imaging system measuring Luster of hair tresses with an innovative algorithm.

Using polarization imaging allows to physically separating the specular light from the diffused light for each pixel of the imaged tress. Angular distributions of the specular and diffused light are obtained in a few seconds. Where conventional methods calculate the shine peak width on the angular distribution, the imaging system imitates the human eye and calculates the shine width directly on the image.

The new formula combines different measured parameters to objectively quantify luster. It was designed to exhibit a higher correlation with visual perception along with a higher sensitivity. Results obtained with conventional formulae are compared on different hair tresses, treated and untreated. The new formula is found to be consistent for a whole range of hair colors, from light to dark.

2. Introduction

The analysis of hair visual appearance has become strategic for the hair care industry. It enables product efficacy evaluation, claims substantiation and improvement of hair product formulation. For a long time, the evaluation of the visual appearance of hair has been done by experts. In order to deliver more precise and objective data, quantitative techniques have been developed (1-3), mainly based on the measurement of the light scattered by hair fiber (individual or hair tress). Goniophotometer is an excellent example of a technique used for the understanding of hair visual appearance. Scientific method closer to what the human eye sees is often required and digital image of the hair tress has proved fundamental to analyze its visual appearance. Optical imaging system is very powerful because it can deliver both data and images in real time. Light scattering in hair fiber is complex and needs a detailed investigation. Polarization analysis is a well known technique to deeply analyze the composition of the light scattered by an object (4-7). This paper presents the application of a new polarization imaging technique for the measurement of hair visual appearance. A new luster formula enabling the characterization and the measurement on any type of hair is proposed.

3. Scientific background

3.1. Polarization of light

Light can be described as an electromagnetic vibrating wave that can be characterized by three main properties (Figure 1):

- Its intensity: it is related to the amplitude of the light vibration. The higher the amplitude of light vibration is, the more intense the light is.
- Its spectrum: it is related to the frequency or wavelength of the light vibration. In the case of visible spectrum, red has a greater wavelength than blue.
- Its polarization: it is related to the spatial orientation and coherence of the light vibration. Light can be either polarized (the light vibration has a defined orientation) or depolarized. In this case, the light vibrates randomly.

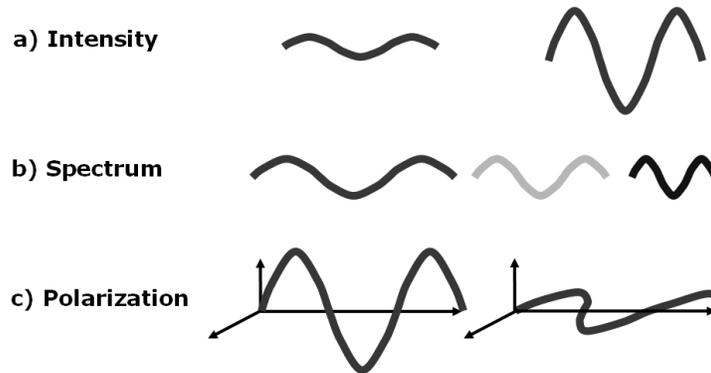


Figure 1 : Light is an electromagnetic vibration that has three fundamental properties: intensity, spectrum and polarization, which are respectively related to the amplitude, wavelength and spatial orientation of the light vibration

Along with intensity and spectrum, polarization of light carries abundant information (8-11) about the sample. Polarization is by far the less investigated of these three fundamental properties of light, mainly because of the lack of polarization sensor. However, polarization finds important applications for visual appearance measurement. One crucial property of polarization is the modification of the polarization of light after interaction with a sample. This modification allows characterizing the interaction. In the case of macroscopic objects, the type of interaction between light and matter can be separated into two main categories: coherent interactions and incoherent interactions (Figure 2). Coherent interactions preserve polarization of light. They include reflection and refraction at an optical interface. Incoherent interactions destroy polarization of light. They include scattering and diffusion.

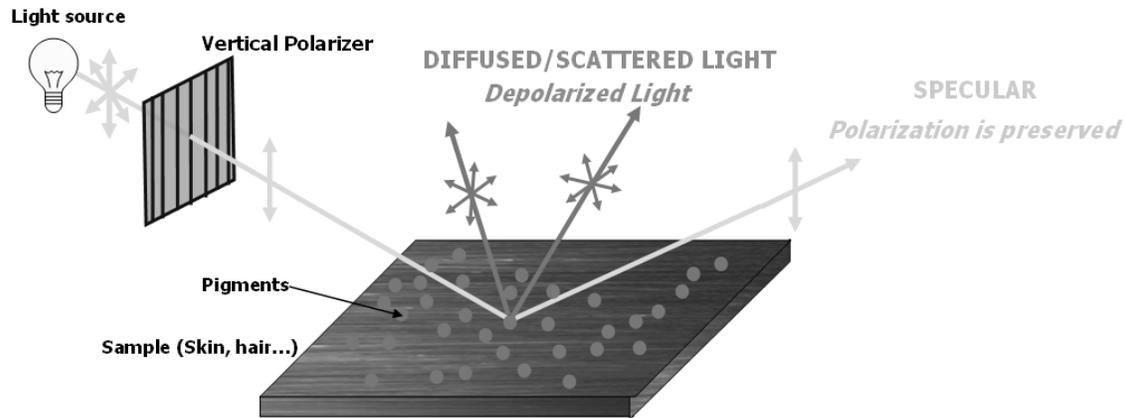


Figure 2 : Polarization set-up. Given the type of interaction with a sample, a polarized light will either keep its polarization if it is reflected off the surface of the sample or will be depolarized if it is scattered by the sample.

For instance, if the illumination is polarized, the reflected and refracted light will remain polarized while the scattered light will be depolarized. This fundamental property allows to measure independently the diffused light and the reflected light. The independent measurement of those two components is of prime importance for cosmetic evaluation.

3.2. Interaction of light with hair fibers

Hair has a very specific visual appearance (3,4,6,7,12,13). Hair fibers can be considered as transparent and partially absorptive fibers with small steps at its surface due to the hair cuticle. This structure causes the visual appearance of hair fiber. It is widely accepted that hair visual appearance comes from 3 different interactions of light with the hair fibers resulting in three components of light (Figure 3):

- The first component is called the shine band. It is caused by the reflection of the light on the surface of the hair fiber. Since this component consists of an external reflection, it remains polarized, it is “white” (more precisely of the same color as the illuminating light) and it appears as a band on the hair tress. The width of the band is determined by the roughness of the surface and the irregularities on the hair fibers. The cuticle angle induces a shift of the shine band from the direction a reflection would have on a fiber without cuticle.
- The second component is called the chroma band. It is caused by the refraction of the incident light in the hair fiber and the reflection on the back surface. Since this component only experiences reflections and refractions, it remains polarized. Since the light travels through the hair fiber, the chroma band is colored. Since this component is a reflection, it appears as a band on the hair tress. The width of this band is greater than the width of the shine band because it experiences the surface roughness of the hair fiber for one reflection and two refractions. The chroma band is also shifted by the cuticle angle in the direction opposed to the shine band.
- The last component is called the diffused light. It is caused by the light that is refracted into the hair fiber and scattered by pigments inside the hair fiber. Since this component experiences diffusion, it is depolarized. Since the light travels through the hair fiber, it is colored. Finally, since it is caused by scattering, which

is not a directive process, the diffused light does not appear as a band but as the background color of hair.

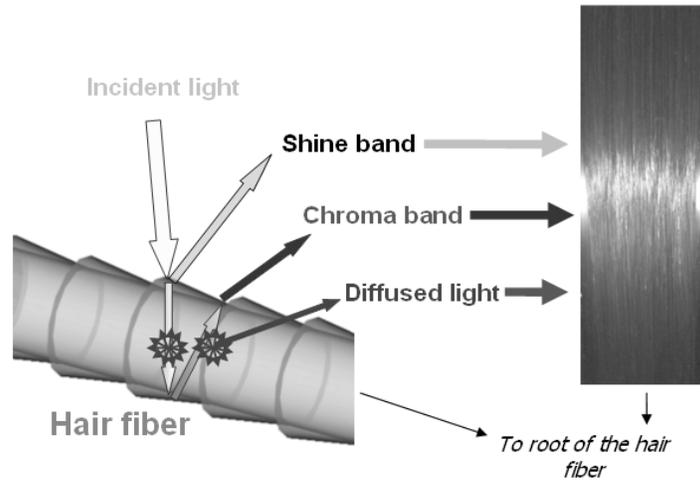


Figure 3 : Interactions of light with hair fibers. The incident light on a hair fiber can be either: reflected by the surface of the fiber, which creates the shine band, or reflected after traveling through the fiber, which creates the chroma band, or scattered inside the hair fiber, which creates the diffused light.

4. Presentation of the set-up

A set up to measure independently polarized and unpolarized light component is designed. The setup consists of three main elements: a polarized illumination, a polarization camera and a cylinder on which the sample is positioned. Using both polarization camera and polarized illumination allows the independent measurement of polarized light and unpolarized light.

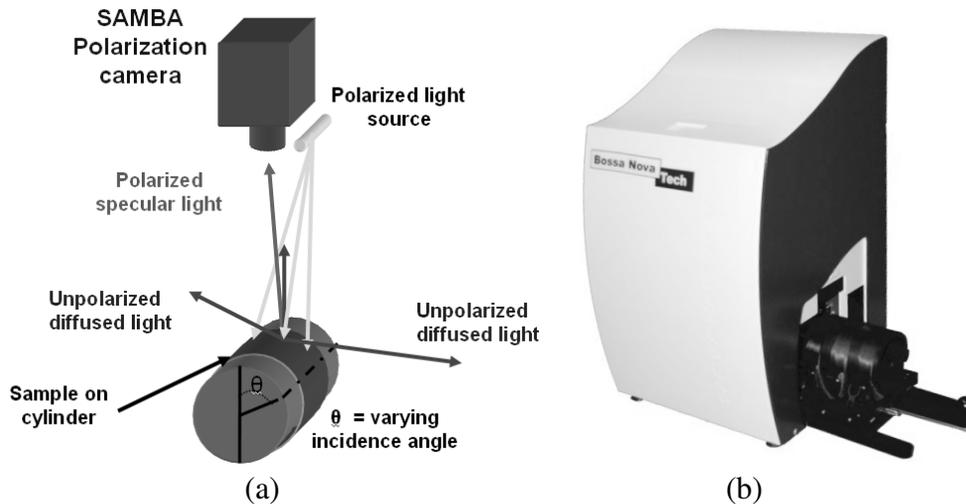


Figure 4 : (a) Optical set-up of the polarization imaging system. (b) Commercial system

Combining a camera with a cylinder allows recording the angular distribution of the sample without any moving parts. Acquiring an angular distribution requires a change of geometric configuration of the group illumination-sample-observation. This change of

configuration is created by the cylinder. The orientation relatively to the illumination and observation changes according to the point on the surface of the cylinder that is considered (Figure 5). The angle corresponds to the angle between the direction of the specular light and the direction of observation. Using an imaging setup has the advantage to record images that can be used as a visual control and a better understanding of the numerical data.

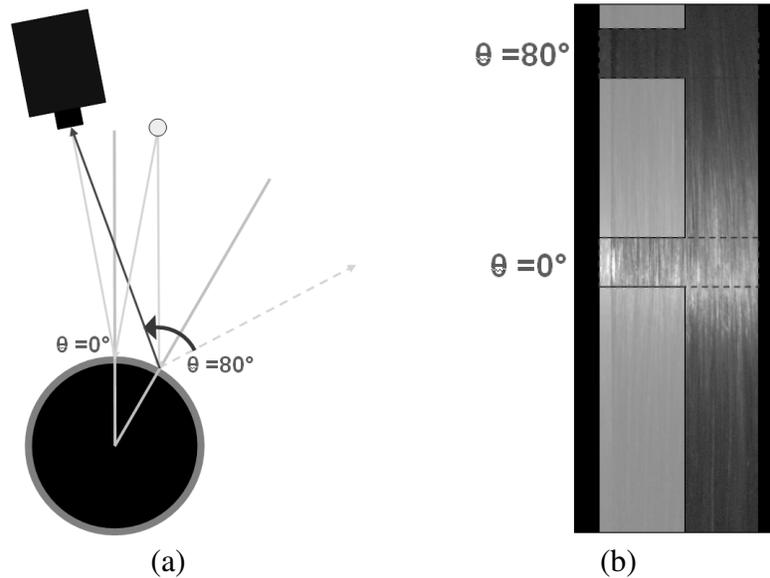


Figure 5 : (a) Sample positioned on the cylinder (b) Complete angular distribution with a single image

The use of both polarized illumination and polarization camera allows recording three types of images (Figure 6):

- A normal intensity image representing what a human eye would see.
- A specular image representing the light that is polarized. This polarized light shows only the reflections (first and second). These reflections are responsible for the visual sensation of hair luster.
- A diffused light image representing the light that is unpolarized. This unpolarized light shows only the light scattered inside the hair fiber. It is the background color of the hair.

Diffused light and reflections are physically separated without using any fits or mathematical decompositions. As reflections (shine and chroma) cause the luster sensation, polarization is a useful tool to help quantify luster.

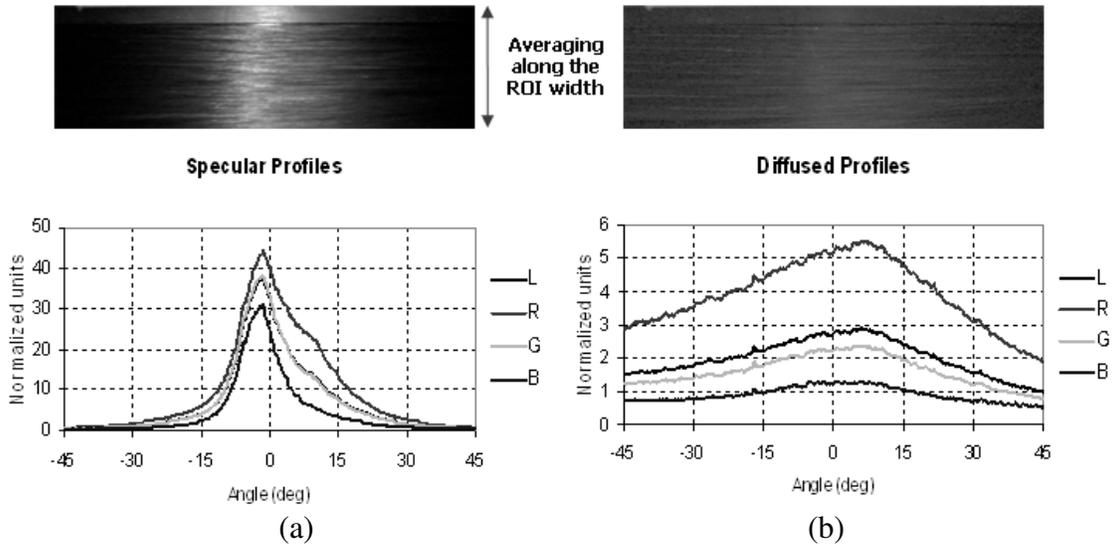


Figure 7 : Angular profiles computed from the images acquired by averaging along the width of the sample (a) Specular. (b) Diffused.

Further processing on the specular profiles using RGB information allows separate the shine band from the chroma band. This separation is based on the fact that the shine band is white. This final separation allows complete characterization of the hair visual appearance (Figure 8).

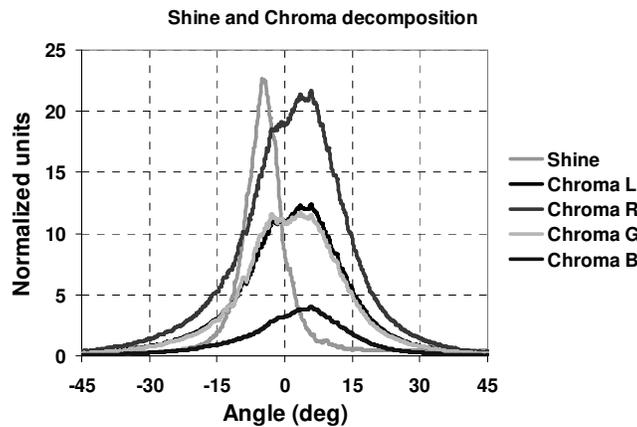


Figure 8 : Extraction of the shine and chroma bands from the specular profile. This separation is based on the fact that the shine band is white while the chroma band is colored.

5. Luster parameter

Luster is a term used to describe the state or quality of shining by reflecting light. Luster qualifies the visual appearance of the object. It is strongly linked to the idea of quality and beauty of an object. Scientists have tried to compute a parameter that would quantify the visual luster sensation (1,2,6,14). But obtaining one number that quantifies the luster sensation is not straightforward. Luster is generally considered to depend on 3 main parameters:

- The amount of reflected light. The more reflected light there is, the higher the luster will be.

- The distribution/width of the reflected light. For a same amount of reflected light, the more defined and more concentrated the reflected light is, the higher the luster will be.
- The background on which the reflection is observed. The darker the background is, the more contrasted the reflection appears and the higher the luster will be.

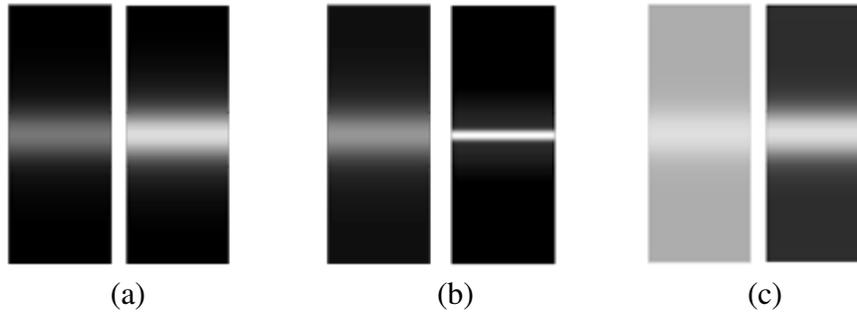


Figure 9 : Luster is considered to depend on three parameters. a) Increase of the amount of light reflected. b) Reduction of the width of the specular light while keeping the overall amount of specular light constant, so light is more concentrated for a smaller width. c) Increase of the diffused light (background) while keeping the reflected light the same.

Several luster formulae were developed and published by scientists using goniophotometers and other instruments to quantify human perception of Luster. The parameters used in the formulae are:

- S the total amount (integral) of the specular light
- D the total amount (integral) of the diffused light
- $\theta_{1/2}$ the width of the specular light distribution

The 4 most used formulae are the Reich-Robbins, TRI, Stamm and Guiolet formulae (Figure 10). Among these, Reich-Robbins and TRI formulae are the most used. For instance, Reich-Robbins is the direct mathematical translation of the three basic assessments about Luster. Reich-Robbins Luster is directly proportional to the amount of specular light S, so a two-fold increase of specular light results in a two-fold increase of Luster. It is also inversely proportional to the amount of diffused light, so if the background light is two times darker, the luster is two times greater. Finally, it is also inversely proportional to the angular width of the distribution so if the specular light width is divided by two, the specular light is twice as concentrated and the luster is two times greater. The TRI formula is similar to the Reich-Robbins one except that the diffused light is replaced by the specular plus the diffused light and that the luster is normalized by a reference angle. Stamm and Guiolet do not take into account the angular width of the distribution.

$$L_{\text{Reich-Robbins}} = \frac{S}{D * \theta_{1/2}} \qquad L_{\text{TRI}} = \frac{S}{S + D} \frac{\theta_{ref}}{\theta_{1/2}}$$

$$L_{\text{Stamm}} = \frac{S - D}{S} \qquad L_{\text{Guiolet}} = \frac{S}{D}$$

Figure 10 : the four most used luster formula are the Reich-Robbins, TRI, Stamm and Guiolet formulae.

5.1. Issue with previous luster formulae used with polarization decomposition

The previously detailed luster formulae were designed with mathematical separations of specular and diffused light (curve fitting and other methods). They can be calculated with the physical separation of diffused and specular light distribution obtained with polarization. However, it sometimes leads to results that are not correlated to the visual luster sensation, especially for very dark hair. The most obvious and problematic example with the previous formulae is for treatments on very dark hair. For instance, shine treatments will provoke a very important visual increase of luster, with the treated hair tress appearing to have much more luster than the same untreated sample. However, the increase observed with the Reich-Robbins and TRI formulae are way below the one observed by the eye. In some cases, usual formulae may only observe a few percents of increase while the visual difference is striking. This shows that the luster formulae used with polarization have a highly decreased sensitivity to luster changes for very dark hair. We investigated the cause of this lack of sensitivity. What happens is that for very dark hair, the diffused light is extremely low. As a matter of fact, even at the very edge of the distribution (high angles), the specular light is still higher than the diffused light. Considering the true polarimetric diffused light is not relevant in the case of very dark hair, for which the diffused light is negligible in front of the residual specular light located far from the specular peak. This is what causes the lack of sensitivity when the previous formulae are used with the true specular and diffused light measured with polarization. To keep a good sensitivity even when the diffused light is negligible, a new Luster Formula has been developed (Figure 11), named L_{BNT} (BNT for Bossa Nova Technologies). In this formula, the Specular light is split into:

- S_{in} , that corresponds to the peak of the specular light and contributes to increasing the luster.
- and S_{out} , that corresponds to the wings of the specular light (high angles) and contributes to decreasing the luster.

$$L_{BNT} = \frac{S_{in}}{(D + S_{out}) * W_{visual}}$$

Figure 11 : New luster formula. The specular light is divided into 2 components and uses a visual width rather than a width measured on the profiles.

This decomposition is made using selection functions and not fits. The key to the sensitivity of the new luster formula is to choose the good combination of selection functions to obtain a high sensitivity and to measure relative increases that are correlated to the visual sensation. With the new formula, bigger increases of luster are observed than with other formulae on dark hair. The observed increases are in the same order of magnitude as the increase observed with the eye. The previous formulae just fail to show increases correlated to the one observed by the eye.

5.2. Calculation of S_{in}

The selection function to isolate S_{in} in the specular light is a supergaussian function. A supergaussian function is defined by its width and its position. The FWHM (full width half middle) of the selection function is twice the FWHM of the measured specular profile. The selection function is centered on the same point as the specular light distribution. Then the selection function and measured profile are multiplied together which gives the S_{in} signal. The algorithm steps to calculate S_{in} are summarized below:

- Measurement of the maximum value of the specular profile.
- Measurement of the FWHM of the specular profile and position of the profile by computing the center at the location of the FWHM. The center is not the position of the maximum if the profile is skewed.
- From the FWHM and position of the profile, the selection function is calculated.
- Selection function and profiles are multiplied to get S_{in} signal.

These steps are summarized in figure 12.

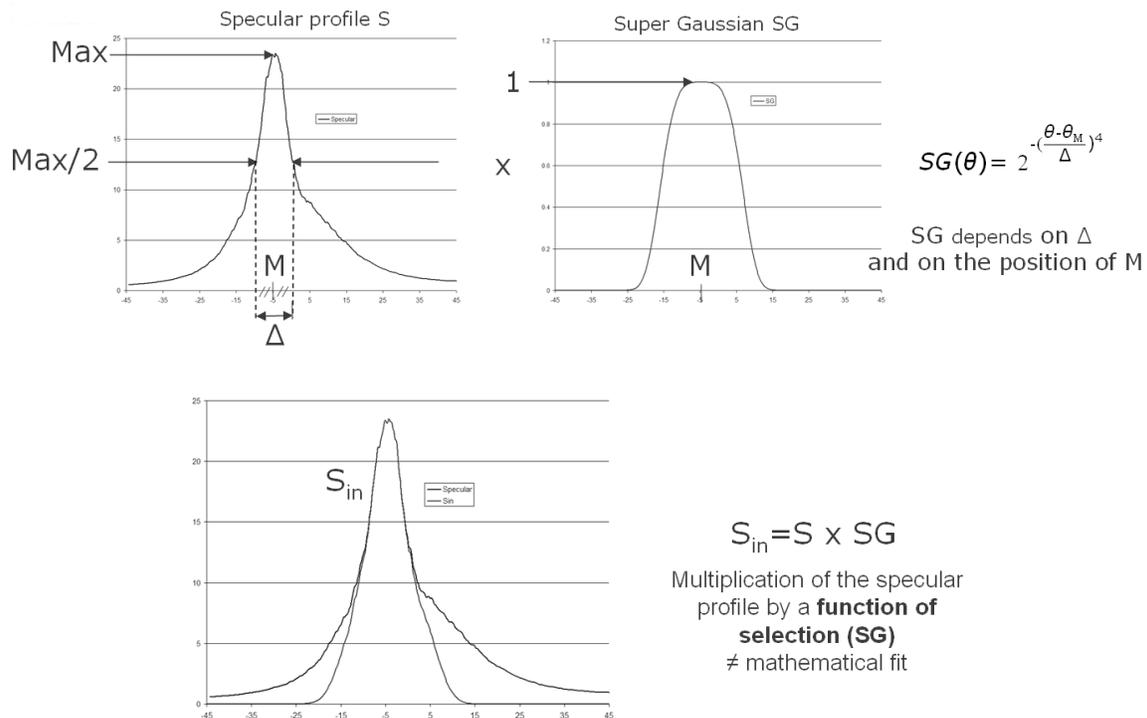


Figure 12: Extraction of S_{in} from the specular profile. The selection function is calculated with the parameters computed from the specular light distribution. Multiplying the selection function and the specular light profile gives the S_{in} profile.

5.3. Calculation of S_{out}

The selection function to isolate S_{out} is of the form 1-supergaussian. Many types of supergaussian functions have been tested to obtain the best sensitivity. The simplest solution would have been to take all the light that was not considered to be part of S_{in} .

However, we observed that this leads to relatively moderate increase sensitivity. This is caused by the intermediate part between the wings and the peak of the specular profile which has a behavior close to the one of the peak and dominates the S_{out} signal as it contains much more light than the far wings. After testing several cases, it was observed that the sensitivity was increased when S_{out} was taken further from the specular peak. In this case, some of the specular light is considered neither in S_{in} nor in S_{out} . As S_{out} is observed only in the wings while the diffused light is observed for all the angles, the ratio of S_{out} and the diffused light is not the ratio on the height of S_{out} and Diffused light in the wings of the distributions. S_{out} has to be multiplied by a constant to keep the ratio observed in the wings. Otherwise, the influence of S_{out} would be underestimated compared to the influence of D (Figure 13).

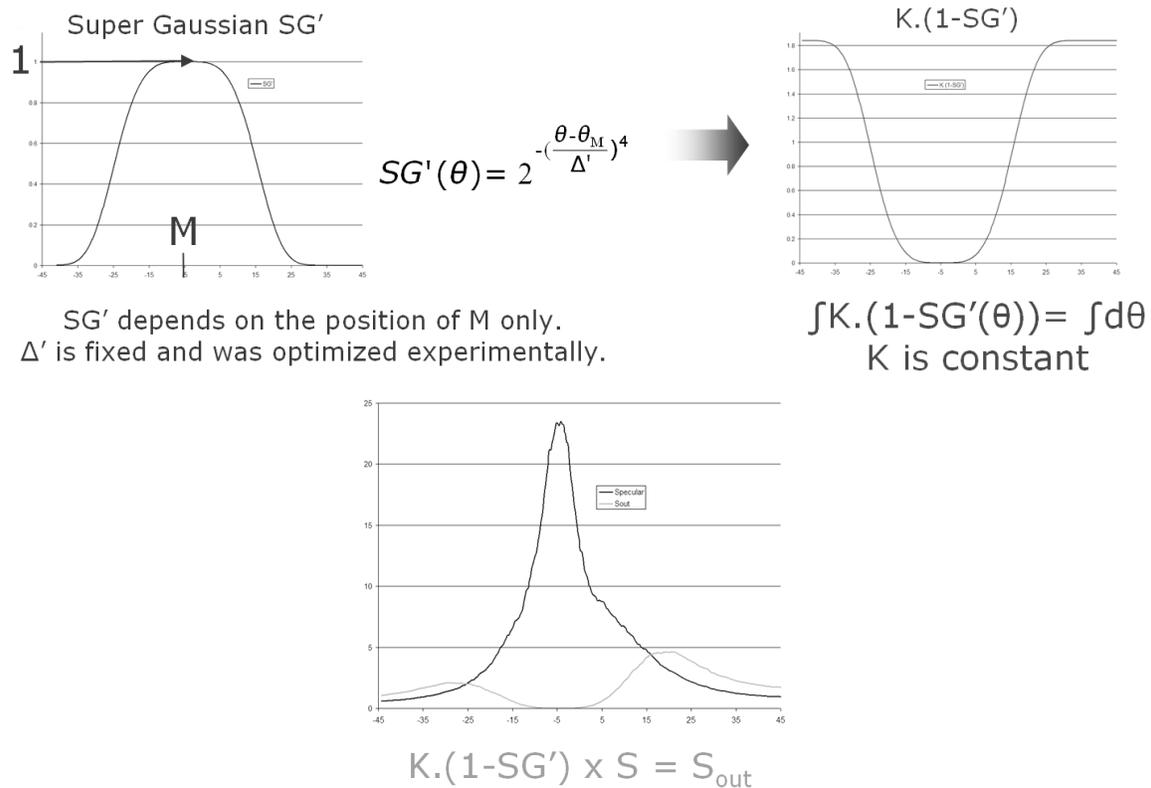


Figure 13 : Extraction of S_{out} from the specular profile. The selection function is calculated with the parameters computed from the specular light distribution. Multiplying the selection function and the specular light profile gives the S_{out} profile.

5.4. Visual width of distribution (W_{visual})

Among the advantages of polarization imaging, one is that images are available. Instead of measuring the width of the specular light on the distribution, the width is measured on the images, which permits to follow the band as the eye does (Figure 14). It keeps the advantage of averaging along multiple fibers while limiting the effect of misalignment and bad combing. The effect of following the band is particularly important for dark hair which does not show chroma. In the case of dark hair, the shine band can be narrower than the displacement of the band caused by combing. Measuring the shine

band width on the image helps reducing the combing effect for dark hair. For hair that shows a large width because of the chroma band (red and blond hair), measuring the width on the image does not significantly change the results.

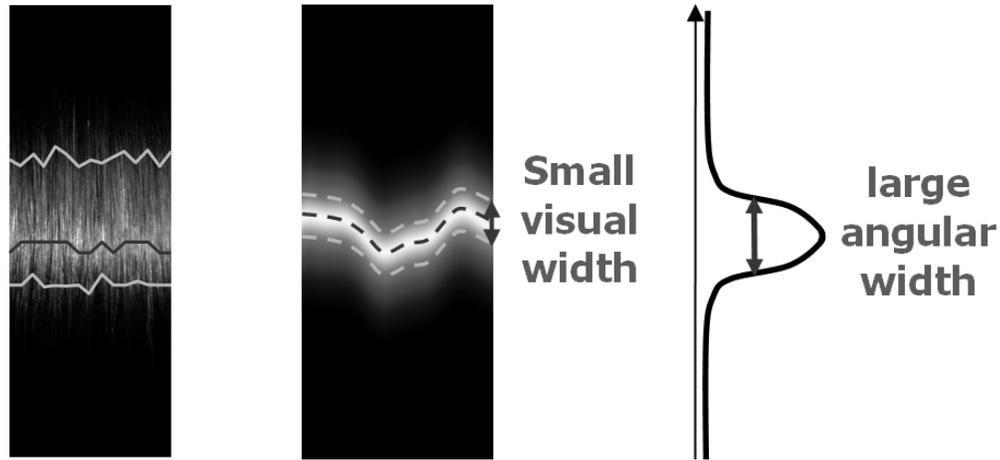


Figure 14 : On very dark hair that is not perfectly combed, the visual width can be significantly narrower than the width measured on the profiles. This also partly explains the lack of sensitivity observed for very dark hair.

6. Experimental results

The optical set-up has been tested on different type of hair in order to validate the new luster formula.

6.1. Measurement on black hair

The hair sample was treated with a silicon shine spray that visually created a tremendous increase of luster. The effect of the treatment can be clearly observed on the images, the treated sample being darker outside the peak of the distribution (Figure 15). However this darkening is mostly in the specular light and not in the diffused light. Reich-Robbins and TRI formulae give respectively a 16% and 27% increase of luster which is clearly much less than the visual sensation. Bossa Nova Technologies formula gives a 116% increase of luster, which is much more correlated to the visual change than the increase observed with Reich Robbins and TRI formulae.

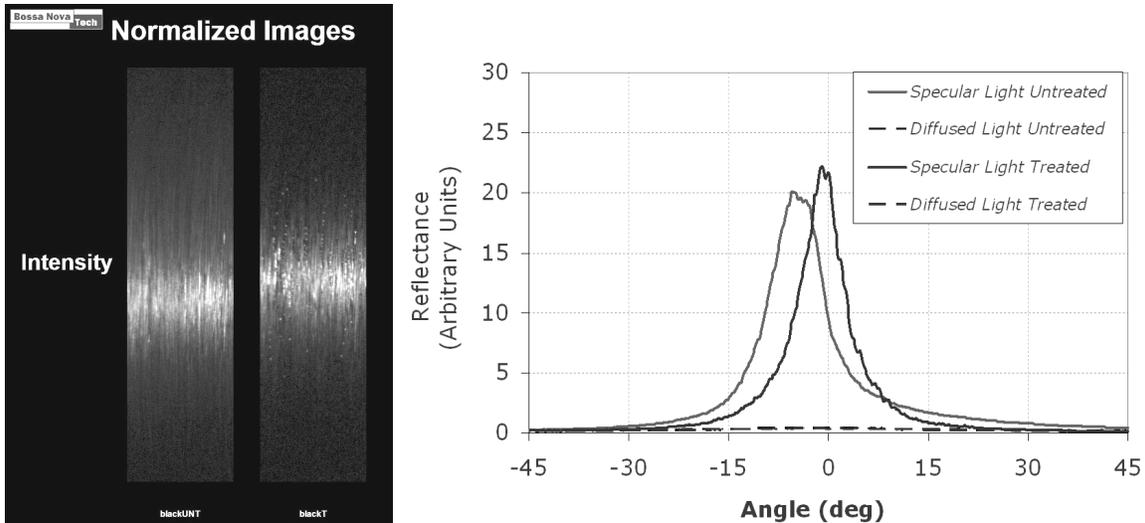


Figure 15 : Images and profiles of untreated and treated black hair. The treatment increases the peak of the distribution and decreases the light in the wings of the distribution. The contrast of the treated sample is much higher as seen on the images.

On black hair, the diffused light is negligible in front of the wings of the specular light. So in the Bossa Nova Technologies formula, $D+S_{out}$ can be approximated to S_{out} (figure 16). In this case, the Bossa Nova Technologies luster formula becomes a spatial contrast luster formula with the luster being the ratio of the light in the peak of the specular light over the light in the wings of the specular light.

$$D \ll S_{out} \quad L_{BNT} = \frac{S_{in}}{(D + S_{out}) * W_{visual}} \sim \frac{S_{in}}{S_{out} * W_{visual}}$$

Figure 16 : Experimental results on dark hair. D is negligible in front of S_{out} . The Bossa Nova Technologies formula can be simplified to a spatial contrast formula.

6.2. Measurement on red hair

The hair sample was treated with a silicon shine spray which visually created a very high increase of luster. The effect of the treatment can be clearly observed on the images (Figure 17) . Shine and chroma bands are superimposed after the treatment which leads to a smaller width of the distribution and higher contrast between the peak of the distribution and wings of the distribution. Reich-Robbins and TRI formulae give respectively a 63% and 34% increase of luster, which is less than the visual sensation for the TRI formula but consistent with the visual sensation for the Reich Robbins formula. Bossa Nova Technologies formula gives an 85% increase of luster which is also coherent with the visual change observed. On red hair, the diffused light is about the same level as the wings of the specular light. The Bossa Nova Technologies formula cannot be simplified (Figure 18).

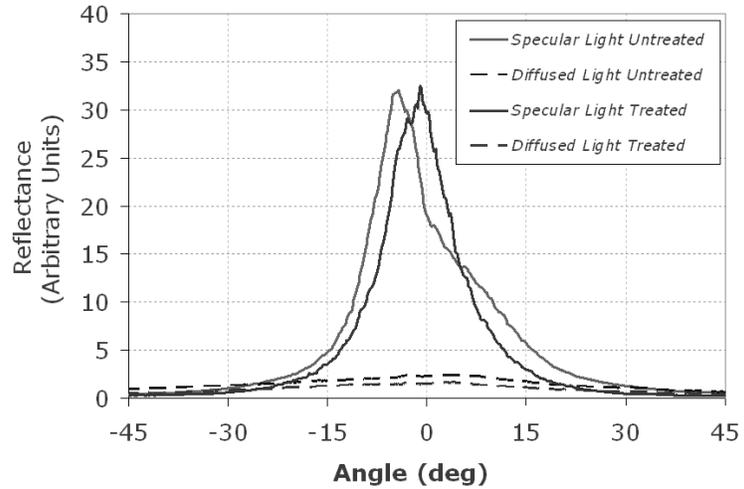
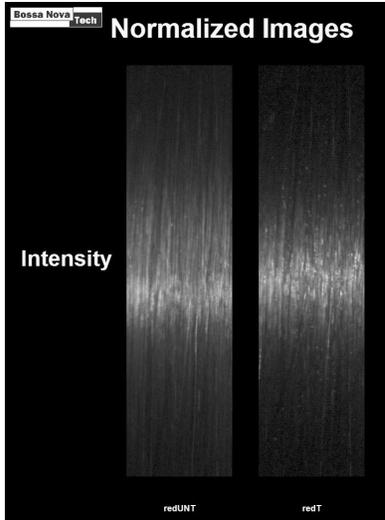


Figure 17 : on red hair the effect of the treatment is to superimpose shine and chroma bands and to darken the outside of the distribution. Visually the contrast is also strongly increased.

$$D \sim S_{out} \quad L_{BNT} = \frac{S_{in}}{(D + S_{out}) * W_{visual}}$$

Figure 18 : on red hair, S_{out} and D are of the same order of magnitude.

6.3. Measurement on blond hair

The hair sample was treated with a silicon shine spray which visually created a very high increase of luster. Again the effect of the treatment is to superimpose shine and chroma band and to darken the wings of the specular distribution (Figure 19). Reich-Robbins and TRI formulae give respectively 80% and 44% increase of luster, which is respectively coherent and less than the visual change observed. Bossa Nova Technologies formula gives a 110% increase of luster which is also coherent with the visual change observed. On blond hair and very light hair, the wings of the specular light are negligible in front of the diffused light. So in the Bossa Nova Technologies formula, $D+S_{out}$ can be approximated to D . In this case the Bossa Nova Technologies luster formula becomes equivalent to the Reich-Robbins formula (Figure 20).

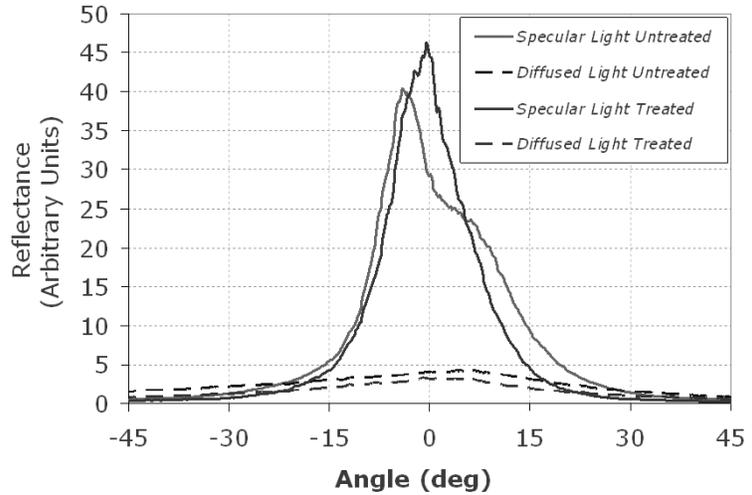
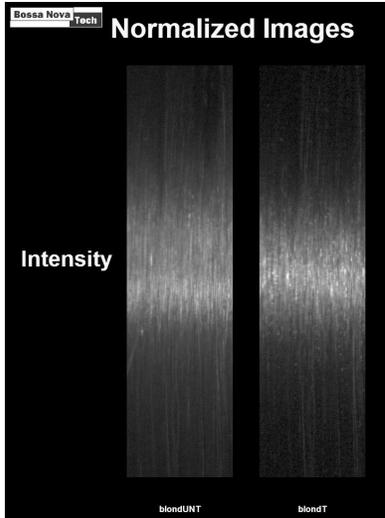


Figure 19 : on blond hair the effect of the treatment is the same than on red hair. Visually the contrast is also strongly increased.

$$S_{out} \ll D \quad L_{BNT} = \frac{S_{in}}{(D + S_{out}) * W_{visual}} \sim \frac{S_{in}}{D * W_{visual}}$$

Figure 20 : on blond hair, S_{out} is negligible in front of D , so Bossa Nova Technologies formula can be simplified to a Reich Robbins formula.

7. Conclusion

We have experimentally validated the polarization imaging technique to quantify the visual appearance of hair. Polarization enables an accurate and physical decomposition of the true specular and true diffused light. This decomposition is a powerful tool to improve hair visual appearance characterization and to better understand the effect of treatments. This technique delivers data and images related to the human visual assessment. Based on luster formulae developed mainly for photogoniometer, we introduced a new luster formula adapted to the polarization analysis. This new formula is a modified Reich-Robbins formula. It gives a high dynamic range and high sensitivity to small changes of Luster. This new luster permits measurement of every type of hair. It gives improved results in term of dynamic for dark hair and converges toward Reich-Robbins and TRI formulae for light hair. The combination of the polarization imaging technique and the new luster formula leads to a complete measurement of hair visual appearance.

8. References

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