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Illusory gloss on Lambertian surfaces

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It has recently been shown that an increase of the relief height of a glossy surface positively correlates with the perceived level of gloss (Y.-H. Ho, M. S. Landy, & L. T. Maloney, 2008). In the study presented here we investigated whether this relation could be explained by the finding that glossiness perception correlates with the skewness of the luminance histogram (I. Motoyoshi, S. Nishida, L. Sharan, & E. H. Adelson, 2007). First, we formally derived a general relation between the depth range of a Lambertian surface, the illumination direction and the associated image intensity transformation. From this intensity transformation we could numerically simulate the relation between relief stretch and the skewness statistic. This relation predicts that skewness increases with increasing surface depth. Furthermore, it predicts that the correlation between skewness and illumination can be either positive or negative, depending on the depth range. We experimentally tested whether changes in the depth range and illumination direction alter the appearance. We indeed find a convincingly strong illusory gloss effect on stretched Lambertian surfaces. However, the results could not be fully explained by the skewness hypothesis. We reinterpreted our results in the context of the bas-relief ambiguity (P. N. Belhumeur, D. J. Kriegman, & L. Yuille, 1999) and show that this model qualitatively predicts illusory highlights on locations that differ from actual specular highlight locations with increasing illumination direction.

Keywords: 3D surface and shape perception, shading, ecological optics

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Introduction

An image contains too little information to reconstruct the shape, light field and (optical) material properties unambiguously. The reason behind this is the dimensional loss when projecting a scene that includes a 3D spatial layout, a 5D (neglecting temporal changes and color) light field and some unknown reflectance functions upon a 2D image. Nevertheless, humans do not seem to experience much problems in interpreting, for example, a photograph of a 3D scene. We perceive a stable solution, although not necessarily the veridical one. Inspired by computer vision, it is often thought that the human visual system uses an 'inverse optics' strategy to reconstruct the original scene: what optical conditions (the 'problem') could have resulted in a certain image (the 'solution'). This inverse problem is evidently underdetermined and the consequences of this are manifested through perceptual interactions. Perception of a single scene property (e.g. the shape) is affected by changes in other scene properties, e.g. light and reflectance (Adelson, 2001). For example, it was shown that a glossy object can appear matte by illuminating it by a diffuse instead of a collimated light source (Adelson & Pentland, 1996; Dror, Willsky, & Adelson, 2004; Pont & Te Pas, 2006). Also, the (meso) shape of 3D textures appears more rough for grazing illumination (Ho, Landy, & Maloney, 2006).

To decrease the ambiguity, assumptions (boundary conditions) can be used to solve the inverse optics problem. The observer can use assumptions that are based on mathematical constraints such as depth ordering by occlusion and shape inference by contours (Koenderink, 1984) but the observer can also base assumptions on regularities in nature such as global convexity (Langer & Bülthoff, 2001; Pentland, 1982) and light direction (Ramachandran, 1988; Sun & Perona, 1998). A class of assumptions that has recently received much attention are image statistics. It is thought that certain statistical properties may convey 'direct' information that supposedly bypasses the complex inverse optics scheme. For surface gloss, it has been proposed that the skewness of the luminance histogram can be diagnostic (Motoyoshi, Nishida, Sharan, & Adelson, 2007). According to this study, skewness is positively correlated with perceived glossiness. These types of mechanisms would greatly reduce the inverse optics scheme since direct knowledge of surface reflectance reduces the amount of ambiguity.

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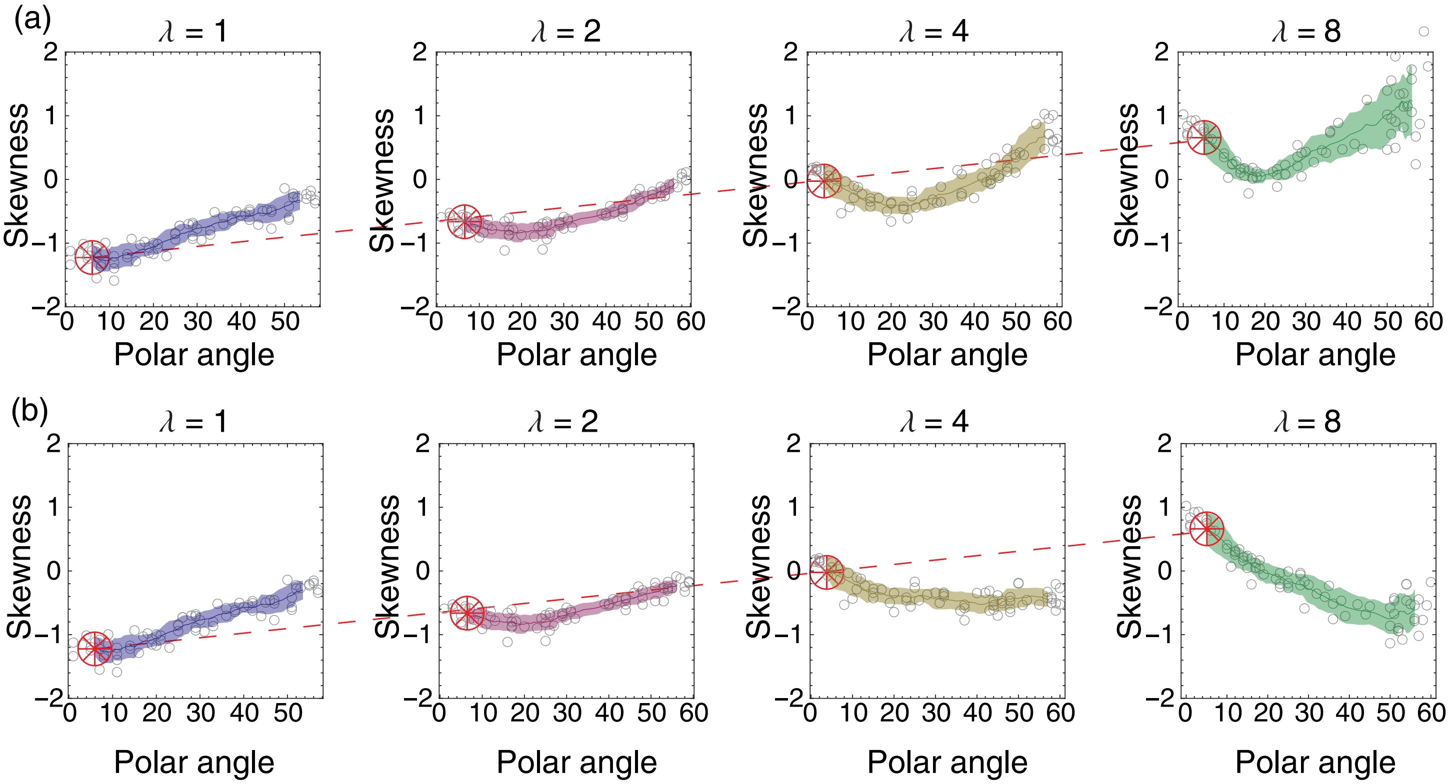


Figure 3. Skewness as a function of illumination direction for four stretch values. Above the black pixels were included, below excluded. The red symbol shows the skewness values for near-frontal illumination.

the first factor can be found in the difference between skewness values with and without taking into account black pixels as shown in Figure 3. The model predicts that for low reliefs there is a positive relation between skewness and polar angle and a negative relation for high reliefs (Figure 1d). This is indeed found for the Brownian surfaces when black pixels are not taken into account. However, black pixels are present in our stimuli and could have played a role in the psychophysical results. Furthermore, we did not take into account interreflections, which could have influenced both the skewness values and the psychophysical data. Secondly, the model did not take into account variations in the y-direction ($\frac{\partial z}{\partial y} = 0$). Since the model (Figure 1d) and data (Figure 3b) seem to agree qualitatively rather well, this assumption seems to be justified.

While our predictions about the dependence of skewness on stretch and illumination are in line with the stimulus data, the psychophysical data seems to partly contradict the relation between skewness and perceived gloss. For near-frontal illumination (indicated by the red symbols), the skewness hypothesis seems to hold: when the relief

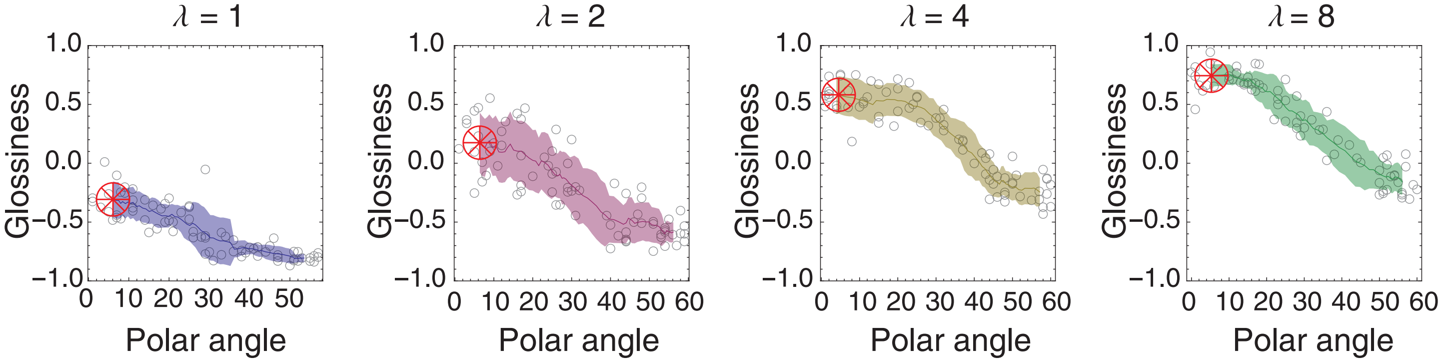
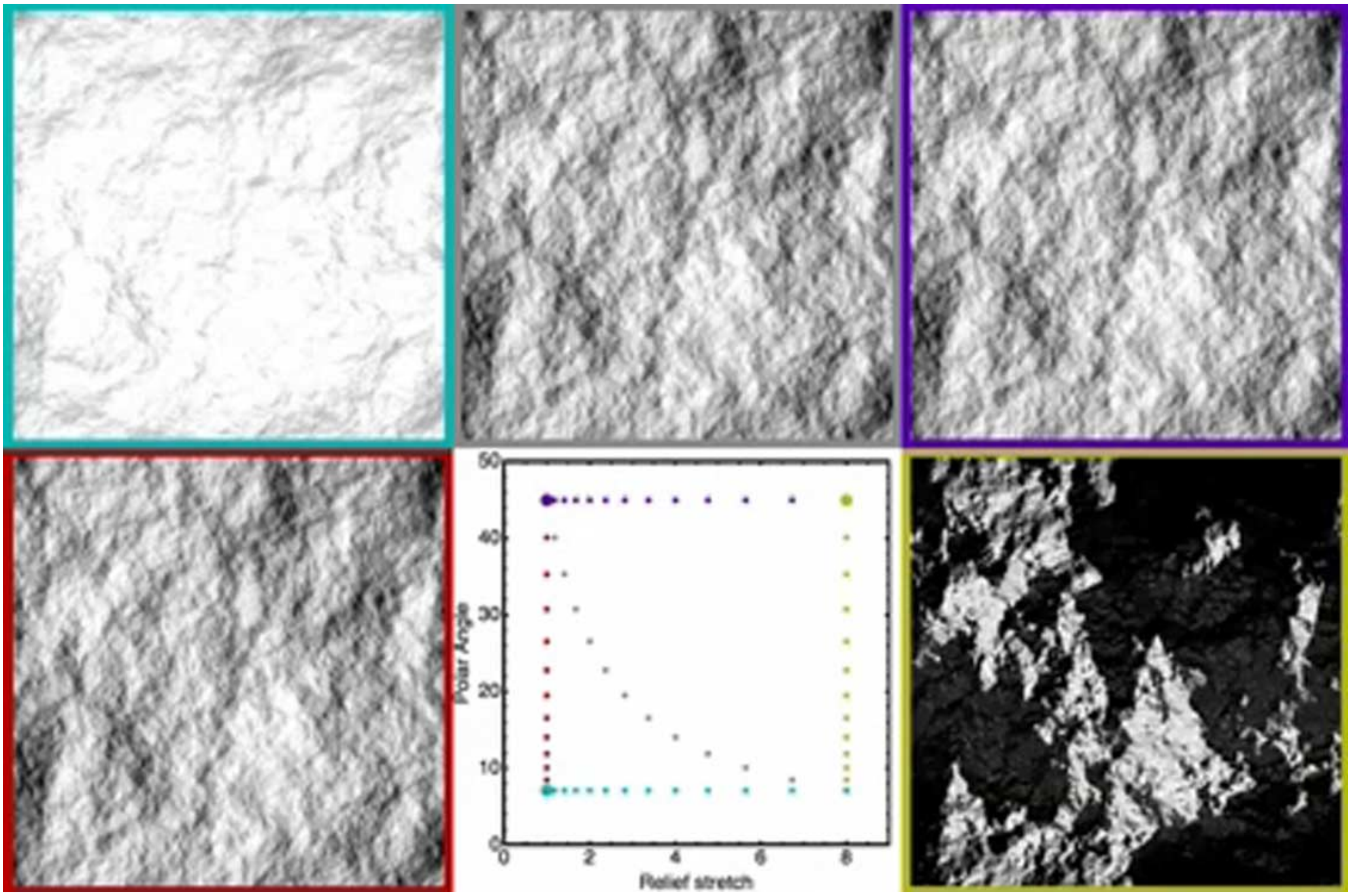


Figure 4. Perceived gloss as a function of illumination direction for four stretch values. On average the gloss increases with increasing relief but decreases with increasing illumination direction.

BRDF was to show that it could be perceived as glossy. A collimated light source may be less natural than for example HDR environment maps. High order (in terms of spherical harmonics) light fields are important for the appearance of actual glossy stimuli (Fleming, Dror, & Adelson, 2003). However, they are of lesser importance for the appearance of Lambertian stimuli (Basri & Jacobs, 2003). Since our stimuli are Lambertian, it is reasonable to use a simple light field such as collimated illumination. Lastly, the absence of inter-reflections in our stimuli is an important difference with ‘reality’. Especially because the scattering of light in high reliefs may decrease the local contrast by enlightening the dark slopes and thus decreasing the glossy appearance. To qualitatively assess the potential effect of interreflections we produced renderings with *Radiance* (Ward, 1994). To increase the understanding of how the appearance of a Brownian surface changes under the shape and light transformations we used in our experiments, we present a movie that shows five paths through this shape-light parameter space. Movie 1 is without inter-reflections and Movie 2 is rendered with 2 ‘ambient bounces’. The colors of the frames relate to the five parameter space paths. The gray path indicates the bas-relief ambiguity relation, which will be discussed later. The other paths denote changes in either the illumination or the relief stretch, keeping the other constant. In the last frame of the movie, the blue, gray, and yellow framed images should appear optimally glossy: high relief in combination with near-frontal illumination. As can be seen, it seems that there is no pronounced difference in gloss appearance between the with and without inter-reflections images. Besides renderings, we also photographed two real surfaces in our lab. Two Gaussian surfaces that only differed with respect to a stretch transformation were photographed with a collimated light source (a theatre spot light). The surfaces were computer milled and were approximately matte. As can be seen in Figure 5, the high relief surface (on the right) shows similar illusory gloss as we found in our experiments. Thus, from these illustrations it does not appear that inter-reflections play an important role in the gloss illusion.



Movie 2. Similarly organized as Movie 1 but the renderings are now performed with two inter-reflections (ambient bounces). The inter-reflections are most pronounced in the cast and body shadows in the yellow and purple framed images.

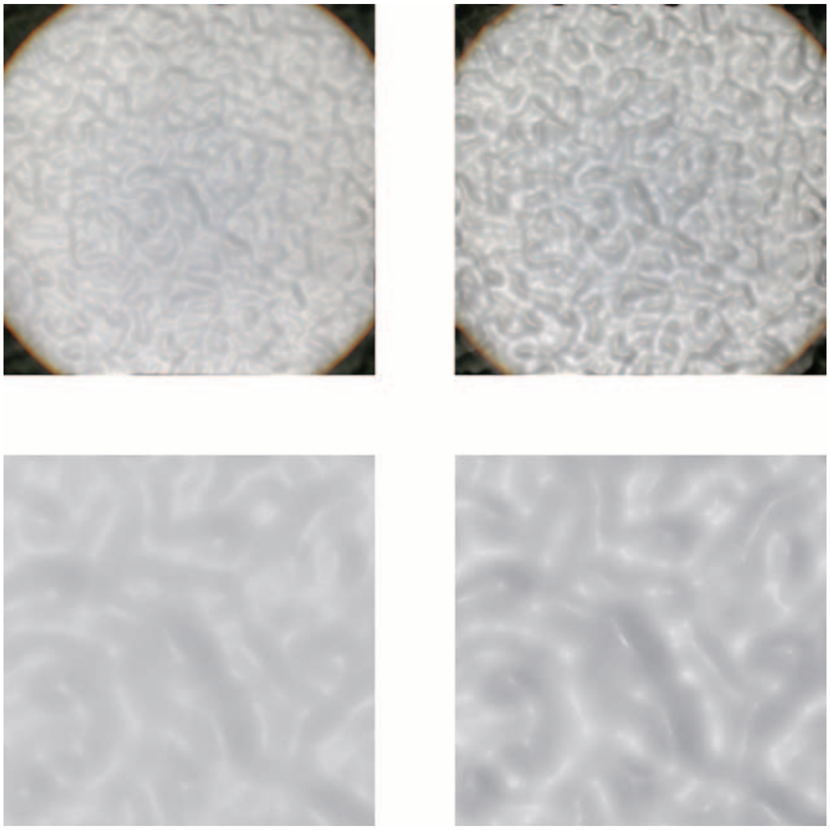


Figure 5. Photographs of real Gaussian surfaces. On top the whole surfaces are shown, at the bottom a magnification of the middle is shown. The left relief is has a three times shallower relief compared to the right surface. Both surfaces were 40 cm wide.

Besides differences between renderings and realistic images, our stimuli may be deprived from cues that help to disambiguate between gloss and depth. Moving surfaces, such as used by Nishida and Shinya (1998), may increase gloss constancy with respect to static images, both from the movement of specular highlights (specular flow) and structure-from-motion. It is likely that these additional cues will disambiguate the depth-gloss ambiguity but the strength of this disambiguation should be quantified experimentally and is beyond the scope of the current investigation.

The relation between skewness and perceived glossiness

Although our results are in line with the study of Ho et al. (2008), it is yet unclear whether we can explain both outcomes with the skewness hypothesis. Our results show that for near-frontal illumination, the relation between relief stretch and perceptual gloss can be explained by the skewness hypothesis. However, the relation of perceived gloss with increasing illumination polar angle is not in line with the skewness hypothesis. Recently, Anderson and Kim (2009) have argued against the validity of the skewness hypothesis. They found that if the highlights are artificially rotated or translated in the image (keeping the skewness constant), the perceived gloss decreases. Since the highlights should be in the 'correct' position with respect to the geometry of the stimulus, they argue that perceived gloss is mediated by a photo-geometric process instead of the luminance histogram skewness which is a purely photometric statistic. Furthermore, they argue that the stimulus set used by Motoyoshi et al. (2007) was rather restricted: only one illumination direction was used. Anderson and Kim (2009) note that altering the illumination direction may have an important effect on the skewness. Our study shows that this is indeed the case. Although the study presented here was motivated by the hypothesis that the shape-gloss interaction reported by Ho et al. (2008) could be explained by a shape-skewness interaction, our results seem to contradict the skewness hypothesis (Motoyoshi et al., 2007) and are more in line with the photo-geometric hypothesis by Anderson and Kim (2009). However, these two hypotheses are both extremes of possible mechanisms underlying gloss perception. On the one hand, the luminance histogram skewness is both an image based *and* non-spatial statistic. On the other hand, the photo-geometric hypothesis is based on a complex inverse-optics scheme. According to Anderson and Kim (2009), the actual geometry of the surface should be known after which the visual system can check whether the highlights are in the 'correct' positions. However, this requires surface geometry knowledge which can only be attained by having assumptions about the reflectance and illumination. As Anderson and Kim (2009) write, the shape, reflectance and illumination are all conflated in the 2D image. Precisely this difficulty would be solved if a 'short-cut' existed that is purely based on image statistics. An intermediary hypothesis could involve a *spatial* image statistic that depends on the geometry of the image instead of the geometry of the imaged scene, for example histograms of (multiscale) image structure curvatures or the statistics related to illuminance flow (Pont & Koenderink, 2003).

The bas-relief ambiguity

We found that two variables influence illusory gloss: relief stretch and illumination direction. The highest gloss was found for a high relief and small polar angle while the lowest gloss was found for a low relief and large polar angle. This relation resembles the relation between light and shape known as the generalized bas-relief ambiguity Belhumeur, Kriegman, and Yuille (1999). They prove that for any Lambertian shape illuminated by a collimated light source, an equivalence class exists of affine transformed shapes and illumination directions that result in a similar image. Thus, an image of a Lambertian shape is unique up to an affine transformation if the illumination direction is unknown. However, the proof also includes a local albedo transformation that depends on the surface attitude. For small shape transformations, the albedo transformation is small and thus negligible, but for larger transformations, e.g. a stretch difference of a factor 4, the albedo transformation becomes substantial. In Figure 6 (see also Movie 3, and the gray framed images in Movies 1 and 2) we have rendered a single Brownian surface for four different stretch values and illumination directions according to the generalized bas-relief transformation, as indicated by the plot. No albedo correction has been applied.

As can be seen, the reflectance of the surfaces appears to be increasingly glossy for increasing stretch magnitude. Thus, the bas-relief ambiguity seems to introduce an extra ambiguity, that of surface appearance. Belhumeur et al. (1999) showed that the appropriate albedo correction can be written as

$$\tilde{a} = \frac{a}{\lambda}\left(\frac{(\lambda f_x + \mu)^2 + (\lambda f_y + \nu)^2 + 1}{f_x^2 + f_y^2 + 1}\right)^{\frac{1}{2}}, \tag{2}$$

where μ and ν are the affine shear components in the x and y direction, respectively. Since we only considered stretch in the viewing direction, these two values are zero.

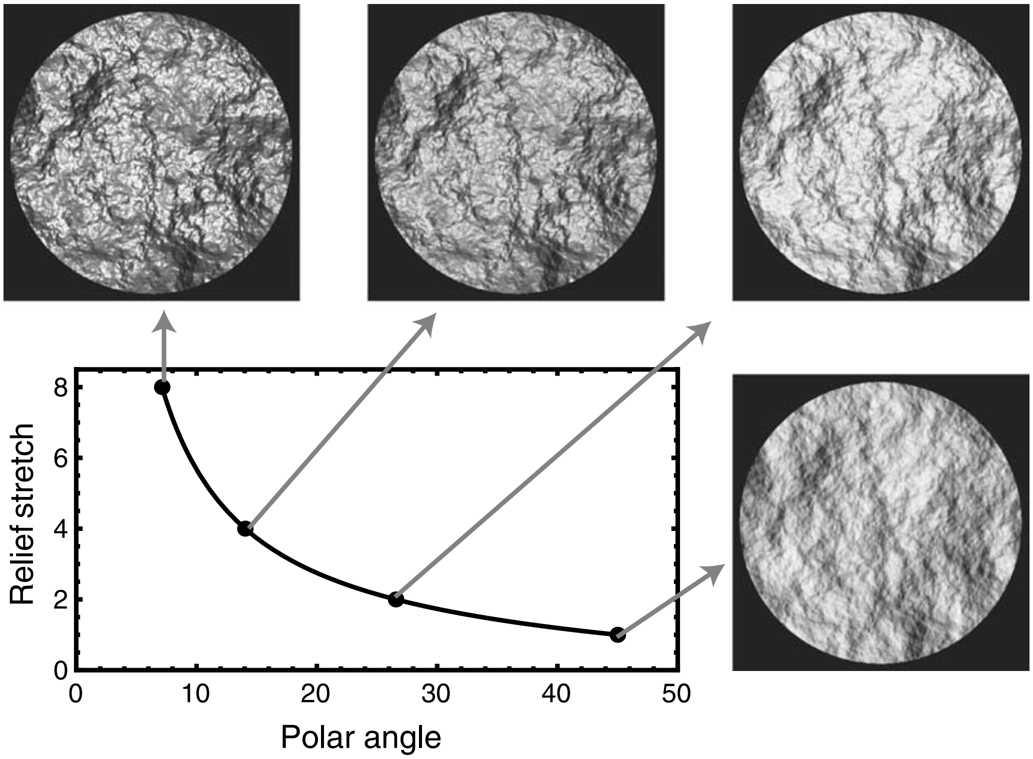


Figure 6. Four renderings on the bas-relief characteristic which should leave the image intact up to an albedo correction. No albedo correction was applied which resulted in illusory gloss for the high reliefs.

The (unit) illumination vector can be written as a function of the polar angle σ and the azimuthal angle θ:

$$\mathbf{L} = (\cos\theta \sin\sigma, \sin\theta \sin\sigma, \cos\sigma). \tag{A2}$$

The surface normal vectors can be written as a function of the partial derivatives of the surface relief $z(x, y)$:

$$\mathbf{n} = \frac{(-z_x, -z_y, 1)}{\sqrt{z_x^2 + z_y^2 + 1}}, \tag{A3}$$

where z_x and z_y denote the partial derivatives $(\frac{\partial z}{\partial x})$ and $(\frac{\partial z}{\partial y})$, respectively.

We want to understand the influence of a relief stretch on the image, i.e. given a surface transformation $\tilde{z}_\lambda(z) = \lambda z$, where λ is a positive scalar, what is the associated image transformation $\tilde{I}_\lambda(I)$? Importantly, we are looking for a solution in which the shape information ($z(x, y)$ and its derivatives) can be eliminated. If this is possible the image transform will be a generic, shape independent transform. Since the surface is isotropic we can set $\theta = 0$ without loss of generality. The original and transformed image can now be written according to Equation A1:

$$I(x, y) = \frac{\cos\sigma - z_x \sin\sigma}{\sqrt{z_x^2 + z_y^2 + 1}}, \tag{A4}$$

$$\tilde{I}_\lambda(x, y) = \frac{\cos\sigma - \lambda z_x \sin\sigma}{\sqrt{\lambda^2(z_x^2 + z_y^2) + 1}}. \tag{A5}$$

A simple case for which Equations A4–A5 can lead directly to the desired $\tilde{z}_\lambda(z) = \lambda z$ relation is to take the illumination in frontal direction, i.e. $\sigma = 0$. This leads to

$$I(x, y) = \frac{1}{\sqrt{f(x, y) + 1}}, \tag{A6}$$

$$\tilde{I}(x, y) = \frac{1}{\sqrt{\lambda^2 f(x, y) + 1}}, \tag{A7}$$

with $f(x, y) = z_x^2 + z_y^2$, which contains the shape information of the surface. The shape information can be eliminated, which leads to the desired image transform

$$\tilde{I}_\lambda(I) = \sqrt{\frac{I^2}{I^2 + \lambda^2(1 - I^2)}}. \tag{A8}$$

Nonzero polar angle

The more generic case for arbitrary illumination polar angle σ is more complicated, and can only be found numerically. The only way to eliminate the shape information from Equations A4–A5 is to set either z_x or z_y to zero. This means that in one of these directions the shape is constant. Since we chose the illumination in the x-direction ($\theta = 0$), the variation in this direction should be non-zero. Therefore, we set $z_y = 0$. This resulting shape is some (irregular) grating. We have illustrated this for the case of Brownian surfaces in Figure A1. As can be seen in the axes of the figure, the illumination is directed perpendicular with respect to the grating direction.

Now it becomes possible to eliminate z_x from both Equations A4–A5 as follows:

$$z_x = \frac{\sin\sigma\cos\sigma \pm \tilde{I}\sqrt{1 - \tilde{I}^2}}{\lambda(\sin^2\sigma - \tilde{I}^2)} = \frac{\sin\sigma\cos\sigma \pm I\sqrt{1 - I^2}}{\sin^2\sigma - I^2}. \tag{A9}$$

This equation cannot be solved analytically for the transformed image intensity, $\tilde{I}_{\lambda,\sigma}(I)$. Nevertheless, the equation can be numerically solved. The results of this solution are presented in the main text.

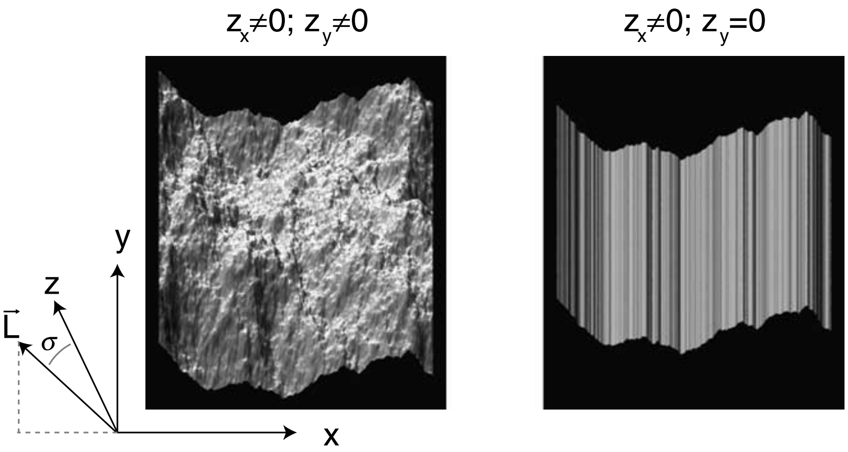


Figure A1. Illustration of $z_y = 0$.