

TRANSMITTANCE OR DENSITY – A QUESTION OF BITS?

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ABSTRACT:

The question of radiometric resolution is an important one in connection with the introduction of digital systems. The number of available bits is generally given with the note that the achieved radiometric resolution is much superior to that of photographic emulsions. In this comparison it is usually overlooked that film records densities, i.e. logarithmic values, while CCDs record transmittance or reflectance, i.e. linear values. To be able to derive from transmittance or reflectance densities reaching from 0 to 3 with an 8 bit resolution ~13 bits of resolution are needed for transmittances or reflectances. The paper presents results for a black-and-white digital image recorded using 12 bits which was recalculated from the recorded reflectances to densities assuming different exposures and film emulsion properties defined by the Standards characteristic curve for black-and-white negative silver-based film. It is shown that film, when properly exposed and processed, is able to reproduce the information present in a digital image recorded with 12 bit radiometric resolution.

KURZFASSUNG:

Die Frage der radiometrischen Auflösung ist im Zusammenhang mit der Einführung digitaler Systeme wichtig. Die Angabe der Anzahl der zur Aufzeichnung zur Verfügung stehenden Bits wird im allgemeinen mit dem Hinweis verbunden, dass die radiometrische Auflösung digitaler Systeme (unter Verwendung von CCDs) wesentlich besser ist als die von photographischem Film. Dabei wird in der Regel übersehen, dass Film (logarithmischen) Dichtewerte aufzeichnet, und dass zur Aufzeichnung von (linearen) Transmittanz- oder Reflektanzwerten mit gleicher Auflösung in Bereichen hoher Dichte bis zu ~ 13 Bits benötigt werden. Es werden Ergebnisse für ein digitales, mit 12 Bit aufgezeichnetes Bild berichtet. Dieses wurde zunächst aus linearen in logarithmische Objektmfangswerte umgerechnet, die dann unter Annahme unterschiedlicher Belichtung und einer Normschwärzungskurve in Dichtewerte für eine photographische Aufnahme umgerechnet wurden. Es zeigt sich, dass bei richtiger Belichtung alle im digitalen Bild vorhandenen Informationen auch im photographischen Bild vorhanden ist.

1. INTRODUCTION

This paper summarizes a number of sensitometric concepts and reviews the relationship between density and transmittance. It discusses density considerations valid for analogue photogrammetric images and leads from there to characteristics of digitized and digital images. An image taken with a digital aerial camera and recorded using 12 bits has been transformed from linear values obtained as output from a CCD (representing transmittances in the case of scanning an image and reflectances in the case of taking an image with a digital camera) to logarithmic (density) values and investigated in regard of its detail in shadow areas.

2. SENSITOMETRY, DENSITOMETRY AND CHARACTERISTIC CURVE

Sensitometry is the science of measuring the sensitivity of photographic materials; it is used to control the operations of exposing and processing photographic materials. The sensitivity or photographic speed refers to the response of a photographic material to incident light. In practice, it is the amount of light exposure required to get a certain density in the processed photographic material as determined with a sensitometer,

Figure 1. The sensitivity of a photographic material depends on the emulsion type and the development conditions.

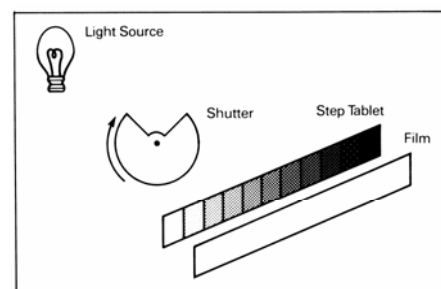


Figure 1. Schematic presentation of a sensitometer

A sensitometer consists of the three major parts shown in Figure 1: (1) a suitable light source calibrated to produce a precise illumination at a standard colour temperature, (2) a calibrated shutter and (3) a transparent step wedge covering a density range from 0 to 3 in equal density increments. The sensitometer should be used with settings simulating actual aerial photographic conditions.

The light source should be chosen to produce light of the spectral characteristics (expressed by means of its colour temperature) of the air-photo daylight (~5500 – 6500 K). Since the normally used tungsten bulb (~ 2800 K) does not meet this requirement, an adapter filter is necessary. This filter may also be used to modify the light further for the transmission characteristics of the photogrammetric lens in order that the illumination for the exposure of the step wedge resembles that reaching the image plane of a photogrammetric camera. The shutter of a sensitometer is usually a sector disk operated by a synchronous motor at a fairly high speed in a repeatable fashion.

The **step wedge** is a series of calibrated filters with uniform density increments. It converts a single level of light produced by lamp, filter and shutter into many different levels or illuminances; this simulates the condition in photography were many different illuminances reach the image plane. Step wedges for sensitometry need to be spectrally neutral, i.e. their transmittance must not vary as a function of wavelength; such step wedges can not be produced photographically but are made by incorporating carbon particles in gelatine and copying them onto film base. Step wedges are produced with different density ranges and increments. Common in photogrammetry is the use of tablets covering a range of 3.0 between maximum density and the density of clear film (having an uncoated density in the order of 0.05 to 0.10); this range is then divided into increments of 0.15. Since densities are logarithmic values (see section 4), the illuminances reaching the image plane have a logarithmic range of 3.0 representing an illuminance ratio of 1000:1, and a density decrease of 0.3 results in a doubling of the illuminance in the image plane. – The density range of 3.0 is far greater than that typically desirable for aerial images.

Densitometry is the measurement of transmission or reflection characteristics of objects and photographic images. While sensitometry assures that an exposure will be correct, the task of densitometry consists of checking whether the exposure was correct: the exposures taken with a sensitometer will be measured with a densitometer and evaluated. Hence, densitometry is the last step in a sensitometric process.

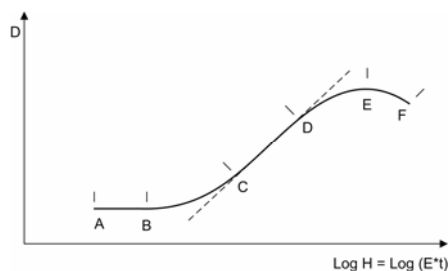


Figure 2. Characteristic curve for a monochrome negative emulsion

The **characteristic curve** for photographic materials, Figure 2, also called sensitometric, HD- or D logH-curve, shows the relationship between the exposure of the material and the resulting density of a photographic image. It may be assumed to have the shape of a stretched S with the following parts:

- A: minimum density or base-plus-fog,
- B-C: toe of the curve,
- C-D: straight-line section of the curve,
- D-E: shoulder of the curve,
- E: maximum density, and
- E-F: area of solarization.

The slope of the characteristic curve at any given point is equal to the slope of the tangent at this point. The slope α of a curve at any given point is called the gradient and it varies along the curve. The maximum gradient of the characteristic curve is called "gamma" and corresponds with the slope of the straight-line portion, hence: $\gamma = \tan \alpha_{\max}$.

When an unexposed photographic emulsion is processed, there will always be a certain amount of silver formed, i.e. the film gets slightly darker. In addition, even the clear film used as support is not completely clear. The sum of both effects should not increase beyond $D = 0.2$ if the photographic material has been handled correctly.

The entire toe of the curve is often considered to be the area of underexposure, however, there are indications that this is not valid for all the range between B and C. For example, the point of minimum useful density may be defined by placing a tangent with a gradient of 0.2 at the characteristic curve in the toe section or by defining its gradient as a fraction of γ , e.g. 30%.

The straight-line section (C-D) is of particular significance since γ is used e.g. in datasheets to show the effects of changes in development conditions in the form of a γ /time curve. It is sometimes also referred to as the contrast area because of the constant ratio between logH-difference and density difference, and γ as contrast factor.

The shoulder of the curve is often considered to be the area of overexposure, however, there are indications that this is not valid for all of the range between D and E; the point of maximum useful density could be found using a tangent parallel to the for defining that of the minimum useful density.

Increasing exposure increases density until a maximum density is reached. Extreme overexposure can result in solarization, a reversal of gradation in heavily exposed areas. The degree of solarization depends on the particular emulsion and on the developer used.

Color films have three separate emulsion parts (B-G-R- or G-R-IR-sensitive). Each of these needs to be described with a separate characteristic curve; however, the curves need to be practically identical for films where the original images are used for evaluation (usually reversal films) and at least parallel for films where copies are made under the utilization of filters. Non-parallel curves will result in unwanted color changes with density changes; such changes occur with color-infrared emulsions.

3. DIGITAL SENSORS FOR PHOTOGRAMMETRY

Digital sensors used in photogrammetric applications today are CCDs (Charge-Coupled Devices) made in a dedicated semiconductor process. Semiconductors can conduct electrical current under certain circumstances.

Solid-state imaging is based on the physical principle of converting light (photons) into a measurable quantity (electrical voltage, electrical current, density for photographic emulsions). The link between the photons at the input of an imager and the output of the device (voltages, metallic silver or colour dyes) are the electrons. The collection and transport of those electrons is of great importance in this chain. It is almost impossible to transport a single electron to an output stage and to convert it into a measurable quantity because its energy content is much

too small. This problem can be avoided by integrating: instead of transferring each single electron, the charge-carriers are integrated locally over a certain period of time into a charge packet creating energy large enough to be easily detectable as output. The next link in the imaging chain is the transport of the integrated charge packets from the integrating sites towards the output of the device.

CCDs, silver-halide crystals in photographic emulsions and even the human eye are "photon counters". While CCDs are regular arrays of receptors of identical size, photographic emulsions consist of a random three-dimensional arrangement of receptors in size significantly smaller than CCD cells. In practical applications, CCD images can be built up one-dimensionally (line-scanner) or two-dimensionally; all cells in the light-sensitive part of a CCD are biased in the integrating mode. A camera based on the full-frame CCD imager will be making use of a mechanical (or LCD) shutter. After opening this shutter, impinging photons will generate charges which are collected until the shutter is closed. Next, the charge packets are transferred first to a CCD output register and then to the output stage where they can be converted to an electrical voltage. In the case of photography integration of the effect on a larger number of exposed and processed crystals by means of a scanning aperture is necessary.

Research is continuing to increase the performance of solid-state image sensors. Improving fabrication technology, optimizing design and creating new device architectures, all have the same goal: increasing the signal-to-noise (S/N) ratio of the sensor for a given application or a given resolution. The number of signal electrons can be specified in terms of the number of photons impinging on the sensor ε , the receptor area $A_{receptor}$, the quantum efficiency η and the integration time T_{int} :

$$\#_{\text{signal electrons}} = \varepsilon \times A_{receptor} \times \eta \times T_{int}$$

The performance of imaging systems can be compared by means of the detective quantum efficiency (DQE) which is derived from the signal-to-noise ratios of the image input and output processes:

$$DQE = (S/N)_{\text{out}}^2 / (S/N)_{\text{in}}^2$$

The number of noise electrons for CCDs can be split up into three main noise sources:

- photon shot noise, equal to the square root of the number of signal electrons, given by the equation above,
- noise electrons generated in the CCD channels (e.g. incomplete transfer, shot noise on dark current, fixed-pattern noise, ...), all summed in n_{sens} ,
- output amplifier noise n_{out} .

and written as:

$$\#_{\text{noisel electrons}} = \sqrt{(\#_{\text{noisel electrons}} + n_{\text{sens}}^2 + n_{\text{out}}^2)}$$

Amplifier noise and sensor noise are independent of the input signal; they are, however, strongly dependent on readout frequency, chip temperature and integration time. Another important noise source is the light fixed-pattern noise; this noise is static and is related to the non-uniformities between the various pixels of the imager, and it is proportional to the light input; a typical value for this noise source is 1%. In addition to the various noise sources in the imaging part of the sensor itself, another important noise source is the output amplifier. The small analog circuitry used to convert the electrons into a voltage and to buffer the output voltage towards the outside world, adds some uncertainty to the signals in the form of noise electrons.

Photographic emulsions are very effective in recording information. Only four electrons are needed to form a latent image spot on silver-halide crystals of an estimated average size of $(0.5 \mu\text{m})^3$ a magnification factor of 25000000 results per crystal. The DQE can be estimated as

$$DQE = SNR^2 = (\text{signal} / \text{density variation})^2 = \Delta D^2 / \sigma_D^2 = (0.434^2 \times \gamma^2) / (H \times A \times \sigma_D^2)$$

Typical values for the density variation σ_D within an aperture A are 0.02 to 0.03, γ is the gradient of the straight-line section of the applicable characteristic curve and H is the exposure in ergs/cm².

DQE values for the three different types of sensors all are in the area around 1%. Optimum exposure levels vary as does the range of exposure levels which is most limited in the case of photographic emulsions. One way of increasing the DQE is to optimize the light sensitivity of the devices. At extremely small light inputs, however, the detection limit of any signal is determined by the remaining noise floor. The dynamic range is also partly defined by the noise level of the imager and the output amplifier. Further reducing the various noise sources is just as important as increasing the light sensitivity of the devices. Since most noise sources have different origins, it is not possible to tackle them all at once; several mechanisms are technology related, others have to do with the design of the device, some can be minimized by the processing of the video signal, and others cannot.

4. REFLECTANCE, TRANSMITTANCE AND DENSITY

The concepts of transmittance and reflectance are very similar as will be shown shortly. In the case of scanning a transparent photo, the amount of energy transmitted will be measured. In the case of digitally recording an image, the amount of energy reflected at the scene will be recorded. While we speak mostly of transmittance, we mean also reflectance. **Reflectance** ρ is defined as the ratio of flux reflected from the sample (Φ_o) and that reflected from the reference surface (Φ_i):

$$\rho = \Phi_o / \Phi_i$$

Similarly, **transmittance** τ is defined as the ratio of flux transmitted through the sample (Φ_o) and that incident onto the sample (Φ_i):

$$\tau = \Phi_o / \Phi_i$$

Consider a piece of material of a thickness d which passes half of the incident light: $\tau = 0,5$. If several pieces of the same material were placed on top of each other, on would observe that with a doubling of the thickness half of the transmittance would be obtained. The inverse of the transmittance is called opacity O , and it would double with a doubled thickness as shown in Table 1.

Table 1. Thickness of material, transmittance and opacity

d	τ	O
1	0,5	2
2	0,25	4
4	0,0625	16

A human observer would see decreases in brightness not corresponding to the geometric progression of opacity but proportional to the thickness; the latter is obtained by introducing the transmission **density** D as the logarithm of the opacity (or of the inverse transmittance):

$$D = \log O = \log(1/\tau)$$

The proportionality of thickness and density can be seen in the Table 2.

Table 2. Thickness of material, transmittance, opacity and density.

<i>d</i>	τ	O	D
1	0,5	2	0,3
2	0,25	4	0,6
3	0,125	8	0,9
4	0,0625	16	1,2
5	0,03125	32	1,5
6	0,015625	64	1,8
7	0,0078125	128	2,1
8	0,00390625	256	2,4
9	0,001953125	512	2,7
10	0,0009765625	1024	3,0

Reflection density is derived analogously as

$$D = \log(1/\rho).$$

Assuming that a monitor is able to present linearly a density range of 3,0, i.e. that realized by means of a step wedge, the normal 1-byte or 8-bit presentation spreads the density range over the values 0 to 255; in increment of 1 corresponds therefore to a density change of ~ 0.0118. The 8-bit density values presented by a step wedge with density increments of 0.15, a clear material of density 0.5 and a maximum density of 3.05 are shown in the following Table 3; also shown the corresponding transmittance values assuming 8-bit, 9-bit, 10-bit, 11-bit, 12-bit, 13-bit and 14-bit presentation.

Table 3. Transmittance in several quantizations and 8-bit density values for a steptablet.

D	D (8)	τ (8)	τ (9)	τ (10)	τ (11)	τ (12)	τ (13)	τ (14)
3.05	0	0	0	1	2	4	7	15
2.90	12	0	1	1	3	5	10	21
2.75	25	0	1	2	4	7	15	29
2.60	38	1	1	3	5	10	21	41
2.45	50	1	2	4	7	15	29	58
2.30	63	1	3	5	10	21	41	82
2.15	75	2	4	7	14	29	56	116
2.00	88	3	5	10	20	41	82	164
1.85	100	4	7	14	29	58	116	231
1.70	113	5	10	20	41	82	163	327
1.55	125	7	14	29	58	115	231	462
1.40	138	10	20	41	81	163	326	652
1.25	150	14	29	58	115	230	461	921
1.10	163	20	41	81	163	325	651	1301
0.95	176	29	57	115	230	459	919	1838
0.80	188	40	81	162	324	649	1298	2597
0.65	201	57	114	229	458	917	1834	3668
0.50	213	81	162	324	647	1295	2590	5181
0.35	226	114	228	457	914	1829	3656	7318
0.20	238	161	322	645	1292	2584	5168	10337
0.05	251	227	455	912	1824	3650	7300	14601
0	255	255	511	1023	2047	4095	8191	16383

While the density values are evenly spread over the available range, the transmittance values are clearly not. In order to achieve similar resolution in the densest part of the step wedge, 13 to 14 bits of transmittance are needed.

Density requirements vary to some extent from country to country depending upon the type of terrain, the type of used film and the processing facilities available. They are determined by two main considerations: (1) best resolution is achieved at densities in the order of 0.8 to 1.0, and (2) the illumination used in the plotter should not generate heat, i.e. be

not intense. Analogue monochrome contact or contrast-adjusted diapositives are most commonly used in plotters, while negatives or contrast-adjusted diapositives are scanned to obtain digital image data for the use in digital evaluation equipment.

Exposure and processing of monochrome aerial film shall be such that, using density values above base plus fog and read on land detail at least 5 mm in extent, the minimum density is not below 0.2 or over 0.6 within a 10 cm radius from the image centre. The density shall not be less than 0.1 anywhere within the image outside of this area. The maximum density shall not exceed a value of (minimum density + 1.0); in very-high-brightness-range scenes such as mountain snowfields it may reach a value of 2.0, and it may exceed this value for images of extremely bright spots such as specular reflections of the sun.

An average gradient of development shall be chosen such that the negative density range is as close to 1.0 as possible. This aim density range can be obtained with low-contrast processing for high-brightness range terrain and with high-contrast processing for low-brightness range terrain. The requirements are considered not to be met if the density range of a roll of film is less than 0.7 and its average gradient less than 1.3, or if the density range of a roll of film is more than 1.4 and its average gradient less than 1.0.

If densities exceeding 2.0 are disregarded, only ~ 11 bits are needed for the transmittance values to achieve a separation similar to that of the density values for the allowed maximum density of 2.0, and the 10 bits permit a clear separation. It is noteworthy at this point, that the scanner available to the authors uses 10 bits and can only meaningfully scan a density range of ~ 1.9. Therefore, all photographs are measured in a densitometer before they are to be scanned, and the scanner is than set such that the available dynamic range is applied to the density range to be determined.

5. EXPERIMENTS

In order to demonstrate the dynamic range of photographic emulsions compared to that of a CCD used in a digital camera, a digital colour image (RGB) available with 12-bit radiometric resolution was converted to an intensity-hue-saturation image (HIS). The black-and-white intensity image was then converted from recorded (reflectance) values to densities to obtain logH subject values and transformed using a characteristic film curve to reflect the process of photographically recording the image. The latter process simulated several exposures to explore the possible loss of detail as a result of underexposure. The resulting images were visually investigated in regard to information loss within deep-shadow areas. All computations were carried out using PCI's Geomatica software.

The investigation was based on a section (Figure 3) of a single DMC image available on a demo CD "Digital Mapping Camera (DMC) Operational Flight Data", Version B, from September 2003. The image was taken on 2003-MAI-24 from 1700m and shows castle Neuschwanstein. Sunny skies causing shadows and forest areas helped generate an image with a large subject range.



Figure 3. DMC image section used in the investigation

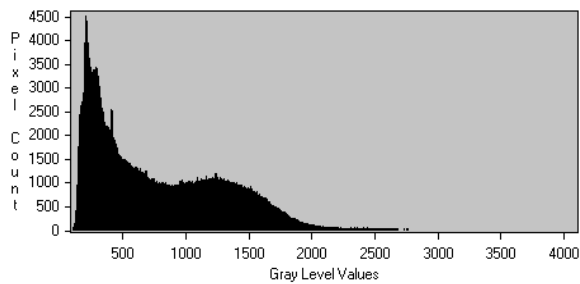


Figure 4. Histogram of the initial intensity image

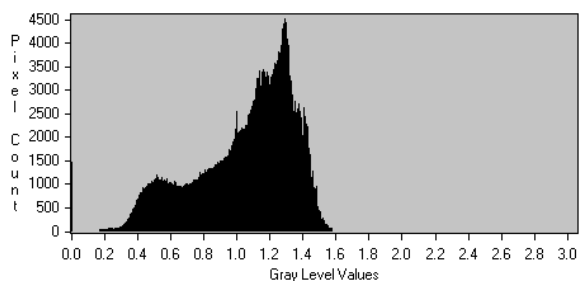


Figure 5. Histogram of the derived negative density image

The effect of the conversion from reflectance values assuming a subject range of 1000:1 as used for high-contrast resolution targets and transmission density step tablets is seen on the histograms for the original intensity image (Figure 4) and the resulting density image (Figure 5). The bar labelled 1 in Figure 6 shows the subject range for the used image section in densities.

The values in Figure 4 range from 4095 to 91; this corresponds to reflectances from 1.0 to 0.0222. The derived densities range from 0.0 to 1.653. Using the DlogH curve used to define the sensitometric characteristics of black-and-white negative film

(Figure 6) these densities were transformed to include the effect of photographic film; seven different exposure increasing by a factor of 1.585 ($\log = 0.2$) and represented by the seven bars in Figure 6 were simulated to investigate the information loss in shadow areas comprised of densities between 0.2 and 0.6.

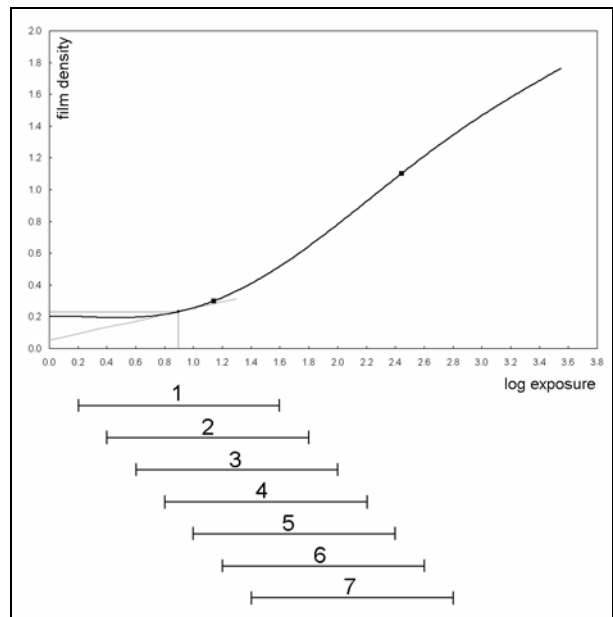


Figure 6. Original subject range (#1), standard D-logH curve for black-and-white negative film and seven exposures (#1-7) used to derive densities for simulated images on film.

Figure 7 presents the histograms for the seven simulated photographic images; these were derived from densities obtained when the subject-range values shown on the abscissa are converted to image densities shown on the ordinate. As a larger part of image 1 includes the base-plus-fog (B+F) range, a compressed histogram results. The increase in exposure first reduces the part of the subject range falling into the B+F range and spreads the histogram (images 2 to 4) and then simply moves the histogram (images 5 to 7). It should further be noted, that the density range for the latter images does not exceed ~ 1.0 as required for aerial negatives.

Inspection of the same magnified shadow area in the seven images for subject-range densities between 0.2 and 0.6 located for exposure 1 and 2 below the of the "first useful point" located where $\tan \alpha = 0.2$ suggests for exposure 1 a total replacement of image content through noise whereas in image 2 the image content can already be recognized; it becomes clearer in images 3 to 7. This result indicates that the first useful point on the characteristic curve could be located where $\tan \alpha \approx 0.15$.

With a density range of ~ 1.0 there is danger of loss of information in the highlight areas of the image.

6. CONCLUSIONS

The paper attempted to demonstrate that photographic emulsions are able to image a large subject range without loss of information if properly exposed. Certain aspects were not considered such as the exposure-difference variations within the image format resulting from loss of illumination with an increasing imaging angle, or the apparent noise in photographically recorded areas of uniform appearance.

Experiences gained when scanning transmission step tablets have resulted in a decision to scan photographs in density mode using the density range determined for the photographs through densitometer measurements. This approach yields good results for all kind of transparent images including contrast reversal without the need to subject the digital data to a modification based on histogram manipulation. The simulated data obtained in this investigation confirmed our experiences gained when scanning photographic images.

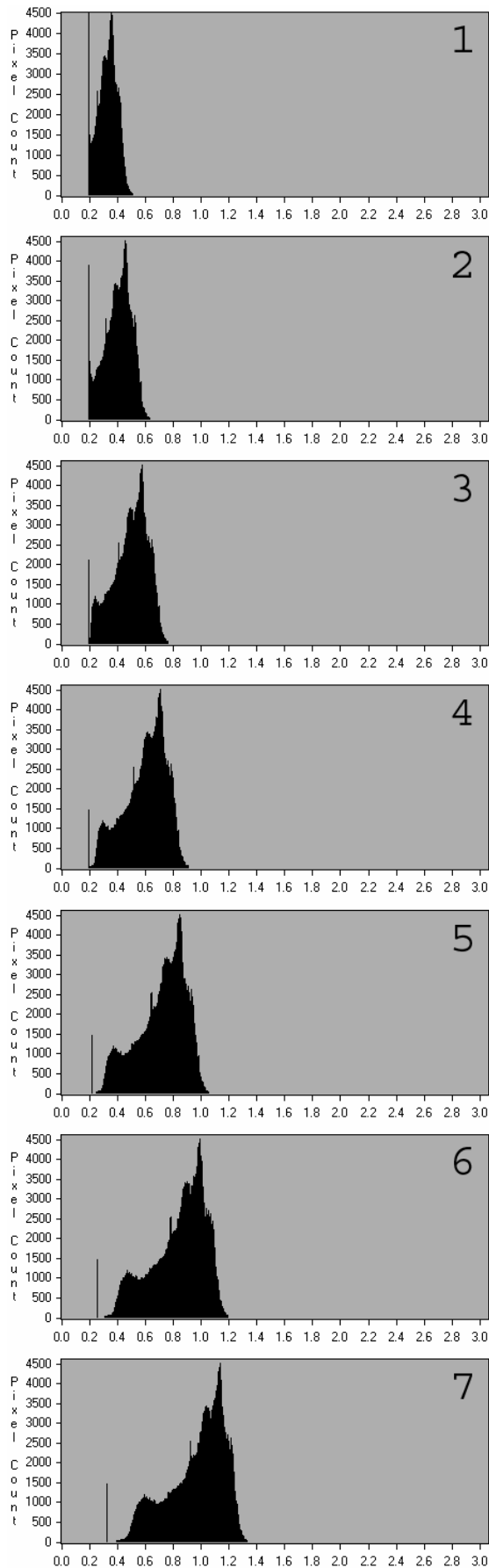


Figure 7. Histograms for the seven simulated images derived for the subject ranges 1 to 7 from Figure 6.