A Short Image Quality Model Taxonomy*

Peter G. Engeldrum✦
Imcotek, Winchester, Massachusetts, USA

A short taxonomy of image quality models is proposed. Although the taxonomy includes medical and security image quality, its primary focus is commercial imaging, where the image quality judgment by the user is often cast as a "beauty contest" selection from images produced by competing products. By taking a broad view of "image quality models," it seems possible to arrange them into categories based on how they are applied in practice. This taxonomy illustrates and clarifies an array image of image quality models applicable to many practical applications.

Journal of Imaging Science and Technology 48: 160–165 (2004)

Introduction

Image quality, as a specific area of study is only a few decades old. In the photographic industry image quality does not appear as an index topic until the 3rd edition of Mees' and James' *Theory of the Photographic Process* (1966).[1] It is absent in James' and Higgins' *Fundamentals of Photographic Theory*[2] (1960), and *Neblette's Photography: Its Materials and Processes* (1962).[3] The concept of "the visual quality of an image" has been around in an optical context, though, for well over a century. For as long as humans have been making images, via drawing, painting or other means, there has always been an interest in the quality of the image in some context.

As with any new idea or concept, there are fits and starts before there is a congealing of ideas and terminology. Perhaps the most important aspect or attribute of an image is its image quality. Yet, the term has no accepted standard definition, and quality means different things to different people. This is a major reason why there is much confusion with both the topic and the terminology. Confusion hampers scientific progress and thwarts communication among those who are designing and evaluating imaging products and systems. The goal of this paper is to clarify ideas, concepts, measures, and notions about image quality, and to suggest a structure or taxonomy for classifying image quality models. This effort is seen as an early step toward a taxonomy, rather than the last word on this elusive topic.

The references and examples that are cited here to describe the taxonomy are simply illustrative of areas discussed. No attempt has been made to provide a comprehensive listing of the literature for each topical area, simply because it would be almost impossible to do it justice.

Original manuscript received February 11, 2003

✦ IS&T Fellow

pge@imcotek.com

*An early version of this image quality taxonomy was presented orally at PICS 1999.

Image Quality

Although some attempts have been made, so far as is known, there is no widely accepted formal or de facto definition of image quality. Lacking an alternative, the following is proposed:

Image quality is the integrated perception of the overall degree of excellence of an image.

Image quality, as defined here, is not intended to describe an image's "fitness for purpose," or utility for potential applications of the image. Further, there are no connotations about the observers who view the image or the context of the image-making process. The definition presented here does integrate component attributes that comprise image quality. The sole thrust is how good does the image look in the sense of a "beauty contest," as the quality judgment has often been described.

The major focus of this image quality definition is commercial imaging systems or devices, where the image is intended to be viewed by "non-experts." In medical imaging, for example, the "quality" of the image has a lot to do with the ability of expert observers to detect and recognize pathology to support a diagnosis. Medical image quality is, therefore, evaluated with a different set of tools, such as signal detection theory.[4] Users of such systems nonetheless express their personal preferences, so "beauty contests" still come into play.

There have been other proposed definitions for image quality. Janssen and Blommaert[5] have suggested that "*the quality of an image to be the degree to which the image is both useful and natural. The usefulness of an image [is defined] to be the precision of the visual representation of the image, and the naturalness of an image [is defined] as the degree of correspondence between the visual repre-*

sentation of the image and knowledge of reality as stored in memory."[5] This concept assigns to image quality two perceptual attributes: usefulness and naturalness. To use such a definition in the context of this discussion unnecessarily restricts the concept of image quality to two "nesses," or perceptual attributes, dimensions that may, in fact, be functions of other "ness" dimensions. With the Janssen and Blommaert definition, it is unclear where synthetic or abstract images fit in. For example, how does one characterize the quality of a synthetic image that is not at all "natural," but is still useful?

Keelan takes a different tack and proposes a definition that considers the image making context[6]: "*The quality of an image is defined to be an impression of its merit or excellence, as perceived by an observer neither associated with the act of photography, nor closely involved with the subject matter depicted*." According to this definition, image quality is not, apparently, in the eye of the photographer, the art director, the advertising executive, the producer, director, or a "soccer mom," to name just a few. Although Keelan[6] makes an interesting case for his definition, the requirements that the observer be distant from the imaging industry and not be involved with the subject of the image are needless and unrealistic complications.

When we speak of image quality, it is implicit that the image quality value is determined by some appropriate response from human observers. The desired response is, of course, the purchase of the product. But, we can attempt to elicit other observer responses using suitable psychometric scaling techniques.[7] Two useful responses obtainable from an observer are, judgments, and, preferences or choices. These are two entirely different concepts and are quite often confused. When asking an observer for a judgment we assume the observer is acting "objectively," like a measuring device. (Most of psychophysics is based upon judgement-like responses.) A preference, on the other hand, is an opinion, such as acceptability, satisfaction, utility and value that an image has in some context. In this author's experience it is typical for "expert" and "non-expert" observers to agree on image quality, or other attribute, judgments but have entirely different preferences for, say, acceptability. Image quality judgments and preferences are not necessarily mutually exclusive. One way to combine the two is to use the judgment data to define the psychometric image quality scale and measure preferences in terms of this scale. In a sense preferences are overlaid onto the image quality judgment scale.

Since preferences vary widely among observers and observer groups, basing an image quality taxonomy on these would not engender stability of the structure and interpretation. For this reason when image quality is used here, it is understood to be a judgment of image quality and not an image quality preference or preference related quantity.

Image Quality Models

The purpose of the image quality model is to connect these image quality judgments to other aspects of the imaging system. Our purpose here is not to define or describe a specific set of constructs or computations that define an image quality model. Rather, the goal is to suggest a basic idea or concept of what an image quality model consists.

Image quality is an outcome of many complex processes that may involve, among other things, software algorithms, chemistry, physics, and the psychology of human judgment. In conventional practice, the image quality value is used as a summary measure, or index, to describe the resulting "output" of an imaging system or product. In this sense, image quality is the catchall "bucket" that, in a single concept, encompasses a critically important aspect of the imaging system.

What is an "image quality model?" In many practical applications of the image quality concept, some computation is performed on some set of system parameters, attributes, subsystems, components, algorithms, or measurements obtained from images or image data files. The output of this computation is a numerical value that is monotonically related to the human judgment of image quality. For the purposes of this discussion, we call an image quality model the process of taking image or imaging system related inputs, performing calculations, and deriving index values. Terms such as *objective image quality, subjective image quality, image quality evaluation, and image quality assessment* have been also been used to describe various aspects of this process.

Generally, the model can be related to a preference or choice by human observers, or to some diagnostic performance measure, but this is not a fundamental requirement of the model.

Three M's Confusion–Measures, Metrics and Models

Image quality terminology has been a particularly knotty problem, so it seems worthwhile to try and bring some order to the chaos. In constructing taxonomy, a balance has to be struck between precision and generality. The attempt, at this stage, is to be most general and to span a wider set of applications of image quality models. To this end, a discussion of some commonly used terms referring to image quality models is needed.

Many terms have used to describe the relationship of image quality to other aspects of an imaging system. Some of these terms are: *image quality measures*,[8-10] *image quality metrics*,[11-14] *image quality models*,[15] *quality scale*,[16] *image quality criteria*,[17] and *image quality equation*.[18] Such an array of terms to describe one concept does not assist in increasing the communication and consensus about what image quality is and is not.

Since some of these image quality terms have counterparts in mathematics, it seems reasonable to use the existing mathematical framework.[19] In this context, the following definitions of the various image quality models are proposed:

Image Quality Measure

A signed scalar value of image quality, perhaps associated with a vector, indicating magnitude and sense, but not orientation, in any multidimensional image quality representation. Most, if not all, widely used image quality models are really image quality measures. They have a magnitude, value, and a sense, sign, but not typically an orientation.

Image Quality Metrics

These posses the properties of a distance function and satisfy the triangle inequality. Image quality measures that have metric properties qualify as image quality metrics. Metrics are useful constructs if the fundamental components of image quality are viewed as the axes of a multidimensional perceptual attribute space.

Some image quality model formalisms can be interpreted as metrics, and are often called Minkowski distance metrics.[20] However, the same mathematics can also be interpreted as a generalized weighted mean, so

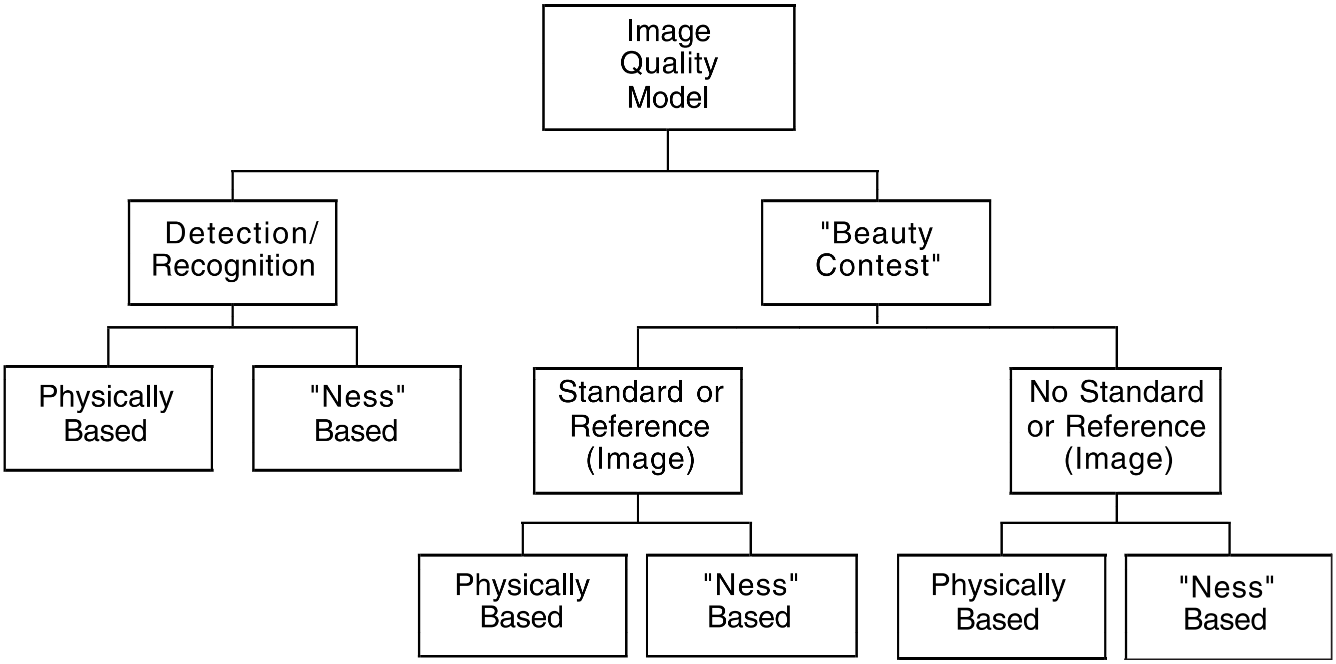

Figure 1. Image Quality Model Taxonomy

the metric property of image quality model will depend on the specifics of the model components.[15] Most so-called "image quality metrics" are properly called image quality measures in this taxonomy.

Image Quality Model

An image quality model is a mathematical model of image quality perception and judgment. It is possible that it may be a small fragment of a larger, global, model of human perception, visual, tactile, or other. One type of image quality model enables the prediction of image quality from the component image quality attributes. Some image quality perceptual attributes are also termed the "nesses"[7] that are most often but not exclusively visual. These "nesses," or attributes, contribute to the judgment of image quality, including such well-known visual perceptual attributes as sharpness, noisiness, graininess, and colorfulness.

These three terms–metric, measures, and models–are not unique and are not mutually exclusive with respect to one another. For example, an image quality model, using the above definition, can have metric properties, which are possessed by one of the more successful formulations.[15] The components of the image quality model can be measures of the underlying image quality attributes, or "nesses." This may be a special case, but it is the case embodied in the Image Quality Circle.[7]

Image Quality Model Taxonomy

With some of the foundation laid, we can now take up the task of constructing an image quality model taxonomy. Taxonomy is the science of classification. It is reasonable to ask whether image quality models, as defined here, can even *be* classified. Naturally, we believe that a schema of image quality models can be developed, at least according to the basis presented here. In fact, given the mysteries surrounding the topic, an attempt at classification is needed. What is offered is a taxonomy of image quality models that is largely based on the contemporary and historical usage of such models.

Figure 1 is a diagram of the proposed Image Quality Model Taxonomy. In this arrangement, image quality models are broken into two major subgroups, "*beauty contest*" models and *detection / recognition* models. These two categories seem to cover the majority of practical image quality model applications.

Beauty Contest

The term "beauty contest" stems from the notion that in a competitive marketplace, customers often make purchase decisions on the basis of how "beautiful" the images are compared to images from competing products. At present, this is a rather loose criterion when compared to the more quantitative criteria associated with detection/recognition. An alternative categorization might be "quantitative" and "non-quantitative," except that "non-quantitative" implies that "beauty contest" judgments cannot be put on a rational quantitative basis, which is incorrect.[7]

Detection/Recognition

The detection/recognition image quality model category is most applicable to medical, reconnaissance, and security imaging. Models in this category usually have a specific set of parameters that enable the detection and recognition of various objects, features or elements within the image.

Medical imaging is partially "ness"-based in the sense that the ultimate evaluation of the image is by a human observer. If and when the evaluation of medical images becomes fully automated, then it will become more physically based. However, the usual image quality model, the theory that measures the performance of the observer (signal detection theory), is rigorously quantitative.[4] Observer performance is often measured as the probability of a "correct" decision, given some description of the image or imaging system "signal-to-noise ratio." Signal detection theory quantitatively combines these two aspects of the imaging system and is often the image quality model of choice.[4]

For reconnaissance imaging, the image quality model can be a combination of both physically and "ness"-based.[8,10,22] Likewise, the image quality model of a security imaging system might be both physically based and "ness"-based. For example, identifying unique facial features from typical face images can be physically (computer) based, but the image quality model of the same facial image for general identification is usually "ness"-based.

Since our image quality emphasis is on commercial imaging, not medical, security or reconnaissance imaging, detection/recognition models will not be explored further. However, it should be clear that certain features of the "beauty contest" branch of the taxonomy can also have their equivalencies on the detection/recognition branch.[23]

Standard or Reference

The "beauty contest" image quality model category can be partitioned into two subcategories: "Standard or Reference" and "No Standard or Reference." For suitable partitioning, a description of a standard or reference is in order. The following items can serve, in this context, as a suitable reference image:

a) An actual image, or image data, such as an arbitrary "standard" image in the sense of an internationally standardized test image or chart. The actual image need not be a recognized standard. Any suitable image will serve. The new ISO 22028 Standard further subdivides this idea, for color image data, into four "referred image states": (1) *original*, which references a two-dimensional hard or soft copy image, (2) *output*, where the reference is some output device, (3) *picture*, a two-dimensional representation that can be referenced to both original and output, and, finally (4) scene, which can be either a real or synthetic "scene."[24]

b) A reference or standard system, which is an imaging system with specific defined characteristics. Television systems are based on specific standards. The Digital TV, NTSC, and PAL systems are examples of standard systems, in that they have a detailed set of specifications and thus a level of "standard" image quality. In some cases, the standard or reference is in fact the upper bound in image quality that the system can deliver.

c) An upper bound fundamentally defined by physics. A lens that is limited only by the diffraction of light produces a limiting image quality for the particular lens parameters. For example, the lens f/number and the wavelength of light determine the smallest image of a point of light and the maximum of its optical transfer function formed by a diffraction limited lens.

The standard or reference image is typically taken as the criterion point in applications where the imaging subsystem transmits or stores an image. The transmission or storage system may compress the image data or signal, to minimize storage or transmission bandwidth requirements. Image compression algorithms are almost universally assessed against the image quality of the "original" image, which comprises the reference. The reference or standard is often taken as the highest level of image quality and subsequent processes are viewed in terms of a decrease in image quality. This has spawned the "demerit" or "impairment scale" concept[25,26] that rates the degree to which the image quality has been impaired, or degraded.

The standard or reference is not necessarily tied to the impairment concept in a negative sense. It is common practice today to provide software whose goal is to improve image quality above some reference or standard. So, in fact, impairments are only the negative side of an image quality scale about the reference, with "improvements" or "enhancements" being the positive part of the axis.

Physical or "Ness"-Based

The next subdivision of the taxonomy includes physically based or "ness"-based image quality models. Equivalent terms for physically-based models found in the literature are *objective* image quality measures and *objective image evaluation*.

Physically based image quality models are models that have physical image parameters–numbers, values or functions that describe one or more physical aspects of the image or imaging system–as the model inputs. This approach to image quality modeling is more than a century old, and consequently has the largest body of literature.

"Ness"-based is a newer term for what has been called *subjective* image quality or image evaluation. A "ness" approach is based on using human perceptions, or perceptual attributes, as the basic independent variables of the image quality model. Of course, at some point the numerical values for these "nesses" can be generated from physical image parameters, but these are not the primary input for the "ness" based category of models.

Standard – Physically Based

The physically based image quality model comes in a wide range of complexity and sophistication, but the common denominator is some physical measure of deviation or "distance" from the original or reference image.

The concept of a deviation from a reference for image quality goes back at least 100 years to the development of the Strehl intensity ratio[27] which is used in optical engineering to this day. This ratio is a measure of the amount of light in the central core of the lens-spread function compared to the amount in a diffraction-limited lens. In the 1950s, Linfoot[28] developed the physically based optical image quality measures of *fidelity defect*, *relative structural content*, and *correlation quality* and showed how they are all related. In the same period, Otto Schade[29] who, in a series of papers that are probably one of the earliest documented examples of imaging systems engineering, developed a similar measure the *equivalent passband*. Schade's papers provided the basis for the more modern image quality models that are widely used in image coding and processing.[9,12,30-33]

A complete, but somewhat dated, review of physically based image quality models can be found in Chapter 4 of Tannas[30] and a summary of the predictive performance of popularly used measures can be found in Eskicioglu, et. al.[9] Recent reviews of image quality models used in image processing have been offered by Nadenau, et. al.[32] and Eckert and Bradley.[34] A broader view of the physically based approach that includes some properties of the human visual system can be found in Watson.[31]

Although not exactly physically based, the role of the human contrast-sensitivity function plays a key role in both No-Standard and Standard-based image quality models. Barten[33] provides a good summary of this important visual characteristic.

Standard – "Ness"-Based

In application areas where the physically based method is used, the use of a standard or reference in a "ness" based image quality model does not seem to be very common. There may be a very practical reason for this. In order to apply the "ness" based image quality models to, say, the optimization of a compression algorithm, the relevant "nesses," or artifacts, that are generated by the algorithm need to be identified. But this is only the first step. Once the "nesses" are identified, they need to be measured on an appropriate psychometric scale. Identifying and measuring the relevant "nesses" may be the most difficult part, requiring suitable realizations of the "ness" artifacts by the algorithm and some sort of multidimensional scaling to elicit the number of psychological or "ness" dimensions and scale values. Using the multidimensional scaling dimensions to identify the specific "nesses" artifacts can be quite challenging. What is more, once the appropriate "nesses" are identified, some form of visual algorithm or computational scheme using physical image parameters to predict the algorithm-generated "nesses" needs to be developed. These are neither quick nor simple tasks.

Although the "ness" artifact approach requires more effort, a major advantage is that the image processing algorithm can be optimized directly in terms of what human observers see. One would expect that such an approach would be more robust, since the focus is on the perceptual attributes comprising image quality. No scheme is a panacea, though. The potential troublesome area for any given algorithm is that the actual "nesses" may change as a function of both the image structure and algorithm parameters. In this sense, the resulting "nesses" are not stable; i.e., the relevant "nesses" upon which the observer makes an image quality judgment can vary considerably.

No Standard or Reference

There are important cases where there is no standard or reference for image quality. These tend to be associated with imaging processes, with silver halide photography and electrophotography being the most notable examples. In neither case is there an inherent reference or standard of image quality for the process. This contrasts with the standard or reference case, where the standard is inherent in the selected system or image. In principle, if there was complete understanding of the imaging process, a standard in the form of an upper bound could be described. However, in practice, such complex systems are almost never completely understood.

When there is no reference, we can think of image quality being "built up," as opposed to being decreased or impaired by the imaging process or system. These are quite different ideas from the point of view of imaging system design. The absence of an inherent reference or standard does indeed give the imaging system designer flexibility, but at the cost of a clear image quality goal. The output image quality value, index, or measure in this situation does not have an upper bound, a more difficult position from the system design and assessment point of view. Clearly, at some point, an empirical image quality criterion or standard must be established to determine if the product meets the requirements, but this is not an inherent aspect of this class of image quality models. The image quality model values are just arbitrary points on the image quality scale describing the imaging process.

No Standard – Physically Based

Physically based image quality models with no standard, often called objective image evaluation, have long been associated with photographic, electrophotographic, and television imaging.[35-38] Historical physical image parameters such as *resolving power* (resolution), *tone reproduction*, and *granularity* (noise) have helped guide the image quality development of these processes over the past century.[1,2]

Information theory concepts have also been employed as image quality models[35,36,39-41] with various degrees of success. Typically, these sorts of models are applied to imaging channels and imaging systems.

No Standard – "Ness"-based

There are a few key "nesses" that are associated with almost all imaging systems and technologies. Examples include sharpness, noisiness (graininess), lightness, brightness, colorfulness, and contrast(ness). Most of these "nesses" have been part of image evaluation vocabulary for over three quarters of a century. However, despite various attempts,[17,42] the first practically successful image quality model that was completely based on "nesses" was suggested by Bartleson in 1982.[43] Bartleson's and similar image quality models are based on the so-called Minkowski metric. The Minkowski metric has been applied to coding impairments by de Ridder[20,44] and to imaging system evaluation by Nihenhuis, et. al.[45,46] Engeldrum[15] has shown that the Minkowski-like formalism can also be interpreted as a generalized weighted mean, which implies that the image quality value is some sort of averaging of the component "nesses."

Summary

A short taxonomy of image quality models has been proposed. The taxonomy focuses more on commercial imaging, where the image quality judgment by the user is cast as a "beauty contest" selection between images produced by competing products. By taking a broad view, it seems possible to arrange image quality models into categories based on how they have been applied in practice.

Defining image quality as the judgment of the excellence of an image, independent of any application, utility or preference, seems to offer stability for taxonomy construction. A series of definitions of image quality model terms has been proposed that will help clarify image quality model usage.

This is by no means proposed as a complete taxonomy of image quality models. Nor is this taxonomy a prescription for the selection of the "correct" image quality model to use in a given engineering application. However, the value of the Image Quality Model Taxonomy is in helping to classify image quality models presently in use, and suggest other possible image quality models. This taxonomy is only a starting point upon which other workers can build.

References

1. T. H James, Ed., *The Theory of the Photographic Process, 3rd ed.,* Macmillan, New York, NY, 1966.
2. T. H James and G. C. Higgins, *Fundamentals of Photographic Theory,* 2nd ed., Morgan & Morgan, New York, NY, 1960.
3. C. B. Neblette, *Photography Its Materials and Processes*, 6th ed., D. Van Nostrand Co., Princeton, NJ, 1962.
4. J. A. Swets, *Signal detection theory and ROC analysis in psychology and diagnostics*, Erlbaum, Mahwah, NJ, 1996, ISBN 0805818340.
5. T. J. W. M Janssen and F. J. J. Blommaert, Image quality semantics, *J. Imaging Sci. Technol.* **41,** 555 (1997).
6. B. W. Keelan, *Handbook of Image Quality*, Marcel-Dekker Inc., New York, NY, 2002, Chapter 1, ISBN 0824707702.
7. P. G. Engeldrum, *Psychometric Scaling: A Toolkit for Imaging System Development*, Imcotek Press, Winchester, MA, 2000, ISBN 0967870607.
8. N. B Nill and B. H. Bouzas, Objective image quality measure derived from digital image power spectra, *Opt. Eng.* **31,** 803 (1992).

9. A. Eskicioglu and P. S. Fisher, Image quality measures and their performance, *IEEE Trans. Comm.* **322,** 959 (1995).
10. F. Scott, The search for a summary measure of image quality-a progress report, *Photogr. Sci. Eng.* **12,** 154 (1968).
11. R. J. Beaton, R. W. Monty and H. L. Snyder, An evaluation of system quality metrics from hard-copy and soft-copy displays of digital imagery, *Proc. SPIE* **432,** 320 (1983).
12. A. J. Ahumada, Computational image quality metrics: A review, *SID Digest* **24,** 305 (1993).
13. R. E. Jacobson, An evaluation of image quality metrics, *J. Photogr. Sci.* **43,** 7 (1995).
14. R. T. Brigantic, M. C. Roggerman, K. W. Bauer, and B. M. Welsh, Image-quality metrics for characterizing adaptive optics system performance, *Appl. Optics* **36,** 6583 (1997).
15. P. G. Engeldrum, A framework for image quality models, *J. Imaging Sci. Technol.* **39,** 312 (1995).
16. K. Miyahara, Objective picture quality scale (PQS) for image coding, *IEEE Trans. Comm.* **46,** 1215 (1998).
17. G. C. Higgins, Image Quality Criteria, *J. Appl. Photogr. Eng.* **3,** 53 (1977).
18. J. C. Leachtenauer, W. Malila, J. Irvine, L. Colburn and N. Salvaggio, General image-quality equation: GIQE, *Appl. Optics* **36,** 8322 (1997).
19. E. J. Borowski and J. M. Borwein, *The HarperCollins Dictionary of Mathematics*, Harper Perennial, Harper Collins, New York, NY, 1991, ISBN 0064610195.
20. H. de Ridder, Minkowski-metrics as a combination rule for digital-image-coding impairments, *Proc. SPIE* **1666,** 16 (1992).
21. P. G. Engeldrum, Image quality modeling: where are we?, *Proc. IS&T PICS Conference*, IS&T, Springfield, VA, 1999, p. 251, ISBN 0892082151.
22. G. C. Brock, *Image Evaluation for Aerial Photography*, The Focal Press, New York, 1970, ISBN 0240507169.
23. B. Escalante-Ramirez, J-B Martens AND H. deRidder, Multidimensional characterization of the perceptual quality of noise-reduced computed tomography images, *J. Vis. Comm. Image Representation* **6,** 317 (1995).
24. DIS ISO 22028-1:2003(E), *Photography and graphic technology—Extended colour encodings for digital image storage, manipulation and interchange—Part 1: Architecture and requirements*.
25. *Methology for the subjective assessment of the quality of television pictures*, Recommendation ITU-R BT.500-7.
26. J. W. Allnatt, *Transmitted-Picture Assessment*, J. Wiley and Sons, Chichester, UK, 1983, ISBN 047190113X.
27. K. Strehl, *Z. fur Instrumentenkunde* **22,** 213 (1902)
28. E. H. Linfoot, *Fourier Methods in Optical Image Evaluation*, The Focal Press, London, 1964.
29. a) O. Schade, Image gradation, graininess and sharpness in television and motion picture systems - Part I: Image structure and transfer characteristics, *J. SMPTE* **56,** 137 (1951);
b) O. Schade, Image gradation, graininess and sharpness in television and motion picture systems - Part II: The grain structure of motion picture images - an analysis of deviations and fluctuations of the sample number, *J. SMPTE* **58,** 181 (1952);
c) O. Schade, Image gradation, graininess and sharpness in television and motion picture systems - Part III: The grain structure of television images *J. SMPTE* **61,** 97 (1953);
d) O. Schade, Image gradation, graininess and sharpness in television and motion picture systems - Part IV: Image analysis in photographic and televisions systems (definition and sharpness) *J. SMPTE* **64,** 593 (1955);
e) O. Schade, An Evaluation of Photographic Image Quality and Resolving Power, *J. SMPTE* **73,** 81 (1964).
30. H. Snyder, Lawrence E. Tannas, Ed., Flat-panel displays and CRTs, Image Quality: Measures and visual performance, Chapter 4, Van Nostrand Reinhold Co. NY, 1985, ISBN 0442282508.
31. A. B. Watson, Ed., *Digital images and human vision*, MIT Press, Cambridge, MA, 1993, ISBN 0262231719.
32. M. Nadenau, S. Winkler, D. Alleysson, and M. Kunt, *Human vision models for perceptually optimized image processing - A review*, http://dewww.epfl.ch/~nadenau/Research/Paper/HVS_Review_Final.pdf.
33. P. G. J. Barten, *Contrast sensitivity of the human eye and its effects on image quality,* SPIE Optical Engineering Press, Bellingham, WA, 1999, ISBN 0819434965.
34. M. P. Eckert and A. P Bradley, Perceptual quality metrics applied to still image compression, *Signal Processing* **70,** 177 (1998).
35. J. C. Dainty and R. Shaw, *Image Science*, Academic Press, London, 1974 ISBN 0122008502.
36. T. H. James, Ed., *The theory of the photographic process*, 4th ed., Macmillian, NY, 1977, ISBN 0023601906.
37. J. H. Dessauer, and H. E. Clark, *Xerography and related processes*, The Focal Press, London, NY 1965.
38. M. Scharfe, *Electrophotography principles and optimization*, Research Studies Press, Hertfordshire, England, 1984, ISBN 0863800092.
39. H. J. Metz, Comparison of image quality and information capacity for different model imaging systems, *J. Photogr. Sci.* **26,** 229 (1978)
40. P. Oittinen and H. Saarelma, Average mutual information as a quality measure in imaging processes, *J. Opt. Soc. Amer. A.* **3,** 897 (1986)
41. K. R. Scheuter and R. Hradezky, Objective print quality evaluation based on information theory, *Proc. TAGA* 222 (1978).
43. C. J. Bartleson, The combined influence of sharpness and graininess on the quality of colour prints, *J. Photogr. Sci.* **30,** 33 (1982).
44. H. de Ridder, Subjective evaluation of scale-space image coding, *Proc. SPIE* **1453,** 31 (1991).
45. M. R. N. Nijenhuis, & F. J. J. Blommaert, Perceptual error measures for sampled and interpolated images, *J. Imaging Sci.* **41,** 249 (1997)
46. M. R. N. Nijenhuis, & F. J. J .Blommaert, Perceptual-error measure and its application to sampled and interpolated single-edge images, *J. Opt. Soc. Amer. A* **14,** 2111 (1997).
42. J. F. Sawyer, Effect of graininess and sharpness on perceived print quality, in *Photographic Image Quality*, Royal Photographic Society, Bath, UK, 1980, pp. 222-231.