Imaging Performance Taxonomy

Don Williams, Image Science Associates
Peter D. Burns, Carestream Health, Inc.
Larry Scarff, Vistapoint Technologies

ABSTRACT

A significant challenge in the adoption of today's digital imaging standards is a clear connection to how they relate to today's vernacular digital imaging vocabulary. Commonly used terms like resolution, dynamic range, delta E, white balance, exposure, or depth of focus are mistakenly considered measurements in their own right and are frequently depicted as a disconnected shopping list of individual metrics with little common foundation. In fact many of these are simple summary measures derived from more fundamental imaging science/engineering metrics, adopted in existing standard protocols.

Four important underlying imaging performance metrics are; Spatial Frequency Response (SFR), Opto-Electronic Conversion Function (OECF), Noise Power Spectrum (NPS), and Spatial Distortion. We propose an imaging performance taxonomy. With a primary focus on image capture performance, our objective is to indicate connections between related imaging characteristics, and provides context for the array of commonly used terms. Starting with the concepts of Signal and Noise, the above imaging performance metrics are related to several simple measures that are compatible with testing for design verification, manufacturing quality assurance, and technology selection evaluation.

Keywords: Standards, Imaging Performance, Image Quality

1. INTRODUCTION

George: The sea was angry that day, my friends - like an old man trying to send back soup in a deli. I got about fifty feet out and suddenly the great beast appeared before me. I tell you he was ten stories high if he was a foot. As if sensing my presence, he let out a great bellow. I said, "Easy, big fella!" And then, as I watched him struggling, I realized that something was obstructing its breathing. From where I was standing, I could see directly into the eye of the great fish.
Jerry: Mammal.
George: Whatever.

'Seinfeld, The Marine Biologist (1994)[1]
George Costanza describing his efforts to save a whale.

As a comic mechanism, George's indifference to accepted terminology for a whale works well. What makes it funny though is the obvious language dichotomy that we have all engaged in at one time or other. We are George. Who among us, at some point, have not mistakenly referred to a whale as a fish, cyan as blue, or resolution as Megapixels? We all do it and in casual café conversations it is acceptable. Indeed we, as scientists and engineers, all silently say, 'whatever', whenever we recognize mistaken usage in digital imaging. There is this fraternal and invisible nod and wink that makes it OK. We are so cool within our cliques. It needs to stop there though.

Pedagogically it is unsound. Economically it is insidious. Rather than creating a basic understanding of the science, it sustains image illiteracy and confusion for the greater population. The consequences? Device manufacturers are presented with ill-conceived imaging specifications that yield needless product rejection. Mass digitization efforts are organized based on a capability list not a performance report, requiring costly redone work. Corporate collaborations are frustrated by a sea of misunderstood idioms. And it is all unnecessary.

Just as the Swedish botanist, Carolus Linnaeus, proposed a botanical taxonomy [2] to organize plant names, we propose one for imaging performance evaluation. The purpose is more than just a nomenclature translator, or glossary. It is a hierarchical framework for understanding the landscape of digital capture performance and its related standards, be they sanctioned or *de facto*. The fundamental classes are Signal and Noise. For each of these we identify primary imaging performance measures. These primary measures for signal capture attributes are the Opto-Electronic Conversion Function (OECF), Spatial Frequency Response (SFR). Similarly, noise is classified as a distortion, being either spatial or radiometric in nature. From these four divisions more commonly used terms such as resolution, gamma, fixed pattern noise, or lateral chromatic error are related.

Our primary objective here is to indicate the relationship between common imaging performance measures and methods. We do this with an eye to the development of practical, economical, standard approaches that can simplify communication and facilitate negotiation in this area. In ISO parlance, we consider this taxonomy to be a working draft that can change and expand as required. Certainly, Linnaeus's did. While this paper focuses on digital capture for still images it may serve as a model for motion imaging as well as rendering and printing too.

1.1. Why Imaging Performance?

Before we address how measures of imaging performance can be organized, it is helpful to discuss why someone might be interested in imaging performance and image quality. To some extent the meaning of image quality will depend on who is asking and why. The most general definition of image quality is the set of perceptions of the overall degree of excellence or value of an image. While this definition is useful, it may appear vague to someone who is interested in specifying acceptable design or production tolerances for a particular imaging technology, or choosing between products.

Those charged with specifying and designing, or choosing an imaging subsystem, whether it is a lens, detector, supporting electronics, or a printer, need to understand the technical requirements imposed by the rest of the system. In addition, if system image quality goals are defined in terms of individual perceptual attributes they need to be related to the physical parameters of any particular design. Often it is important to have a physical imaging model that relates a desired objective image quality measure with design parameters and their variation.

An imaging service provider who is working, e.g., in photofinishing or image archiving, may be interested in controlling variation in performance, rather than setting image quality goals. Here the need is for standardized testing procedures and tools, whose results are credible in the general imaging community. In addition, corrective actions need to be identified prior the observation of unacceptable variation in imaging performance. Image quality assurance is the goal.

A framework for relating system and subsystem imaging design and performance is addressed by Engeldrum in the form of an Image Quality Circle.[3] This is shown in Fig. 1, where a product design, expressed in terms of technology variables, can be related to customer perceptions via several physical image parameters. In this paper we address imaging performance as evaluated by primarily physical or statistical image parameters, and as used in international and industry standards for evaluating and comparing system and subsystem performance. Our performance evaluation methods and measures sit in the lower box of Fig. 1, between Customer Perceptions, such as sharpness, and Technology Variables, such as detector size or optical design. We hope to show how these imaging performance evaluation methods can satisfy the requirements of system and subsystem design *and* statistical process control for manufacturing or service providers.

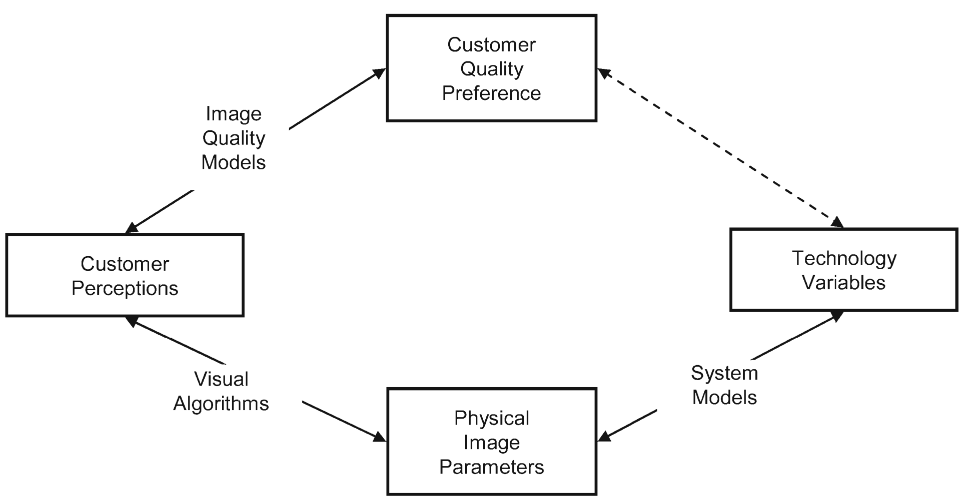

Figure 1: The Image Quality Circle of Ref. 3

2. SIGNAL AND NOISE

Categorizing imaging performance attributes as either Signal or Noise is much like debating whether certain plants are considered desirable flowers or invasive weeds. It all depends on ones perspective. No matter where one draws the line though, it is unarguable that Signal and Noise are considered the foundation ideas from which all others are derived. Without regard to imaging, *per se*, we offer the following definitions;

Signal: Any response that provides valued information

Noise: Any response that detracts from a desired signal

Imaging is distinctly spatio-radiometric. The hierarchy of Table 1 reflects this by separating signal and noise into predominantly spatial and radiometric attributes. For signals we suggest, two primary metrics. The Opto-Electronic Conversion Function (OECF) [4] is an ISO-standard measure of the capture tone-reproduction, or signal encoding. The OECF measures large-area image signal capture. The second primary metric is the Spatial Frequency Response (SFR). [5]

<table>
<tr><td>Foundation Attributes</td><td colspan="11">Signal</td><td rowspan="2">Signal-to-Noise Ratio</td><td colspan="11">Noise</td></tr>
<tr><td>Primary Metrics</td><td colspan="5">OECF
(Opto-Electronic Conversion Function)</td><td colspan="6">SFR
(Spatial Frequency Response)</td><td colspan="6">Radiometric Distortion
NPS (Noise Power Spectrum)</td><td colspan="5">Spatial Distortion</td></tr>
<tr><td rowspan="3">Secondary Metrics</td><td rowspan="3">Linearity</td><td rowspan="3">Sensitivity, Quantum efficiency</td><td rowspan="3">Tone, Exposure</td><td rowspan="3">White Balance/ Neutrality</td><td rowspan="3">Color Rendering or Encoding Accuracy</td><td rowspan="3">Sampling Rate</td><td rowspan="3">Resolution, sampling efficiency</td><td rowspan="3">Sharpening</td><td rowspan="3">Acutance</td><td rowspan="3">Flare</td><td rowspan="3">Depth of Focus</td><td rowspan="3">Dynamic Range
DQE, NEQ, Information capacity</td><td colspan="4">Total Noise</td><td colspan="2" rowspan="2">Chroma Noise</td><td rowspan="3">Micro (deterministic)</td><td rowspan="3">Color Misregistration (deterministic)</td><td rowspan="3">Aliasing (deterministic)</td><td rowspan="3">Spatial SFR Uniformity (deterministic)</td><td rowspan="3">Pincushion/Barrel (deterministic)</td></tr>
<tr><td>Temp-oral</td><td colspan="3">Fixed pattern</td></tr>
<tr><td>Random (stochastic)</td><td>Banding/Streaking (deterministic)</td><td>Defects (stochastic)</td><td>Vignetting or Shading (deterministic)</td><td>Color Uniformity (deterministic)</td><td>Color SFR Uniformity (deterministic)</td></tr>
</table>

Table 1: Proposed Imaging Performance Hierarchy

From each of these primary signal measures, one can derive several secondary metrics, suitable as simplified evaluation for, e.g., quality assurance testing. The OECF-secondary metrics are based on the mean responses for relatively large regions of interest (ROI). If these metrics have any spatial frequency identity at all, it is at zero-frequency. Linearity, speed, exposure, and many color related metrics fall into this category.

The SFR provides a measurement of the capture of image spatial detail and is related to the Modulation Transfer Function (MTF) commonly used to describe optical and photographic systems. While radiometry is certainly required for SFR calculations, its role is of a relative nature. In other words, the SFR ordinal response is always calculated as a relative radiometric response not an absolute one. One can interpret the SFR as characterizing the spatial interaction of neighboring signals whether they are in remote (low frequency) or close (high frequency) proximity.

The right-hand side of Table 1 addresses the noise attributes. Noise is cast as a distortion, i.e. variation from ideal, be it radiometric or spatial. Consistent with the definition of noise above, it is much more than the random stochastic pixel-to-pixel fluctuations associated with grainy film scans. On the radiometric side it also includes fixed-pattern forms such as streaking and pixel defects. [6] We have also included an increasingly common form of low frequency chroma noise due to chief ray angle (CRA) mismatch often found in cell phone cameras. With some imagination and the prudent use of frequency based tools, such as the Noise Power Spectrum (NPS), [7] these behaviors may be characterized in terms of their unique or differential signatures, just as the SFR is used for signal analysis. To aid the reader in our noise classification system, we have labeled the listed noise sources as either deterministic or stochastic in nature. Deterministic degradations occur in accordance with some pre-specified model. Stochastic ones are probabilistic or random in nature. An example of a deterministic distortion is that observed due to optical vignetting.

The spatial side of the noise category was largely inspired by spatial distortions of compact digital cameras designs like those of cell phone cameras. These distortions detract from a desired rectilinear reproduction aim, free of lateral color error and optical aberrations, and as such fit our definition of noise well. Pincushion, barrel, and lateral chromatic error distortions can all be derived from optical field diagrams. Micro distortions of the type found in linear array scanners, and aliasing may need specialized methods for measuring these types of errors.

Finally, there is the combined signal-to-noise ratio attribute. This combination of primary metrics is essential for understanding and measuring signal detection capability. The noise-based dynamic range metrics falls into this category. For systems where absolute scene exposure is at a premium, or needs to be limited, the detective quantum efficiency (DQE) is used in standards for image capture.[8] Discussion of DQE and the related metric, Noise Equivalent Quantum exposure, will not be presented here.

Table 1 is the beginning of our imaging performance taxonomy. To make it practical, however, requires more definition and connection to everyday usage. Fulfilling that is the purpose of the subsequent section, which addressees the Signal portion Table 1. We will restrict our presentation to this area with the understanding that the corresponding Noise/Distortion portion can be addressed in the future, following discussion and feedback on our basic approach.

3. SIGNAL – OECF FAMILY OF MEASURES

Table 2 presents a proposed breakdown of commonly used measures that can be derived from OECF protocols in ISO 14545. In keeping with our goal of a logical and useful taxonomy, we have listed similar terms and associated standards for each where appropriate. For instance, depending on ones preference, terms such as Tone Transfer Function (TTF) or Tone Reproduction Curve (TRC) are commonly used to describe the same measurement. Since OECF is ISO terminology, its use is preferred. The second row provides the secondary metrics. All of these result from calculating mean signal values over several relatively large ROIs, using similar protocols to those described in ISO 14545. The way these mean values are combined or analyzed within and across color channels, makes each different. The essence of the measurement is common. Some, like noise-based speed, even combine measurements from other portions of the classification system.

Depending on the imaging application, a number of performance criteria within each secondary metric can be calculated. We offer some suggestions. For instance, under sensitivity, a number of single valued performance metrics can be calculated under ISO 12232. They are all sensitivity metrics. However, some are more appropriate for certain uses than others. To help prioritize their use in this taxonomy, we have indicated several to be of primary, secondary, or tertiary importance. In other areas, such as linearity, we welcome comments. Finally, to connect each metric with vernacular usage, we offer a ‘related descriptive terminology’ row at the bottom. This is intended as a means to associate common descriptive terms of imaging failures or phenomena with the appropriate secondary metric. For example, descriptions of over or under exposure are often connected with tone or exposure controls driven by the OECF shape and radiometric position.

Primary Metric	OECF – Opto Electronic Conversion Function (ISO 14545) *TTF – Tone Transfer Function* *TRC – Tone Reproduction Curve* Mean large area characteristic response of an electronic imaging device to light stimuli				
Secondary Metric	<u>Linearity</u> The extent to which a sensor's native magnitude response is linearly related to the input stimuli magnitude	<u>Sensitivity</u> (ISO 12232) The reciprocal of the amount of light necessary to achieve a desired output response.	<u>Tone and Exposure</u> Characteristic behavior of large area digital output responses (count value) to spectrally neutral input stimuli	<u>White Balance</u> Equivalence of large area color channel output responses to a range of spectrally neutral input stimuli	<u>Color Rendering or Encoding Accuracy</u> The difference between selected physically measured input color coordinates and their intended signals (encoding)
Performance Criteria ●=Primary ◒=Secondary ○=tertiary	*TBD*	●: Saturation based speed ◒: Noise based speed ○: Exposure Index, Standard Output Sensitivity	●: Deviation from aim for neutral patches of interest. ◒: Deviation from an aim OECF, camera gamma value	●: Deviation from aim between color channels (R-G, R-B, G-B) for neutral patches of interest.	●: Deviation from aim signal value for chromatic patches of interest
Related descriptive terms	*TBD*	- Responsivity - High or low ISO setting	− Too dark/light − Under/over exposed − No shadow/ highlight detail − Clipping − Too little(flat) or too much (snap) contrast -gamma	− Color cast. - Too red, blue, or green	− Over/under saturated colors − Color balance is wrong − Memory colors are not correct - Color accuracy

Table 2: OECF Family of Imaging Performance Measures

4. SIGNAL – SFR FAMILY OF METRICS

Table 3 provides a map for the variety of imaging performance metrics that can be associated with or derived from the SFR. The SFR is often referred to as the Modulation Transfer Function (MTF), though there are differences between them. The SFR is measurement of the effective system MTF relative to the test object feature used. It is commonly measured using slanted-edge and sinusoidal test features. There are a number of ISO standards that have adopted nearly identical protocols for measurement of the SFR. Several are listed in the top row of Table 3.

Limiting resolution and its many offspring are perhaps of highest interest. For example, limiting resolution is frequently calculated by identifying the spatial frequency associated with the 10% SFR level. This definition is consistent with the Rayleigh resolution criterion used in optical design. A number of other single-valued criteria are also used depending on preference or measurement resilience. When such a simplified evaluation of the capture of image detail or sharpness is required, the sampling efficiency [9] can be computed from the SFR.

Such summary measures are often used in form of a control chart. An example of this is shown in Fig. 3. The set of daily SFR measurement were made during a digitization project using a digital copy-stand. Both the actual image sampling rate on the object, and the limiting resolution (as measured by the 10% SFR value) vary due to lens zoom-position and focus. Reference 10 describes similar applications of imaging performance measures to statistical process control (SPC). Frequency referred metrics are also used. Instead of selecting a spatial frequency associated with a given response level, the response at a particular frequency is often adopted. Note that all such metrics are SFR-based and can be classified as a common form of single valued resolution measure.

Acutance and depth of focus should be brought into the fold of SFR based measurements. The objective formulas used for acutance measurement[11, 12] can be seen as integrated, weighted SFR values. Even the Strehl ratio, an integrated MTF ratio used in optical design, falls into this category. Instead of referring to depth of focus in terms like 'circle of confusion' or 'blur circle' we recommend using measures based on either SFR or MTF protocols already in place. By selecting SFR limits that define unacceptable blur levels, depth of focus can be objectively quantified. Flare and sharpening also fall into this category. With the proper measurements, the extreme low frequency responses of the SFR can be used for flare measurement.[13] Sharpening operators of many common types can also be uniquely described with their SFR signatures.[14]

Primary Metric	SFR – Spatial Frequency Response – (ISO 12233, ISO 16067-1, ISO 16067-2, ISO 15524) *MTF – Modulation Transfer Response* A spatial frequency descriptor of an imaging system's ability to capture or maintain the relative radiometric contrast of increasingly finely space signals					
Secondary Metrics	Sampling Rate The spatial frequency of the digital sampling. The reciprocal of the center-to-center distance between closest adjacent pixels	Resolution An imaging system's ability to resolve finely spaced detail. The level of spatial detail that can resolved in an image	Sharpening Artificial amplification of the SFR to achieve sharper appearing images	Acutance An objective SFR based metric that is used as a correlate to perceived image sharpness.	Flare a skirty or wide spreading of light.	Depth of Focus The distance along the optical axis that remains within acceptable focus.
Performance Criteria ●=Primary ◒=Secondary ○=tertiary	●: Dots or Pixels per inch (DPI or PPI) ◒: Sensor Pitch	◒: Response level at Nyq./2 or Nyq./4 (frequency referred)	●: Max SFR gain	●: SQF – Subjective Quality Factor	*TBD*	◒: distance along the optical axis
		●: 10% sampling efficiency based on Luminance SFR	◒: Sign of SFR slope	●: SQRI – Square Root Integral		
		●: Frequency at 10% or 50% Luminance SFR (response referred)	◒: Normalized area under the SFR			
Related descriptive term	- Megapixels	− Blurred − Soft − Sharp − Focus − Spherical aberration − Coma - Rayleigh criterion	− Haloing − Garish looking edges − Over sharpening − Edgy − Sharp − Edge Enhancement	- Sharpness - Strehl ratio (optics)	− Low contrast − Hazy − Soft	- Depth of field - Circle of confusion

Table 3: SFR Family of Imaging Performance Metric

5. CONCLUSIONS

A proposal has been offered for organizing the terminology and methods used to evaluate several aspects of imaging performance for capture systems. We have attempted to show the connections between various measures, and how several of these have common technical origins. By starting from the simple general engineering concepts of signal and noise (or distortion) we aimed at facilitating common communication of image performance information. Our discussion of the common elements of noise/distortion measures awaits comments on this approach, and will likely be reported on in the future. Feedback and suggestions on the taxonomy can be made via e-mail to: info@imagescienceassociates.com

ACKNOWLEDGEMENT

The authors wish to thank Michael Stelmach of the Library of Congress, Office of Strategic Initiatives for the encouragement and helpful suggestions in populating the different families of performance metrics in an understandable and useful manner for everyday imaging practices.

REFERENCES

[1] The Marine Biologist, *'Seinfeld,'* 1994, *The Internet Movie Database*, http://www.imdb.com

[2] C. Linnaeus, *Systema naturae per regna tria naturae : secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis.*, (1758)

[3] P. G. Engeldrum, Psychometric scaling: a toolkit for imaging systems development, Winchester, Mass., Imcotek Press, USA (2000)

[4] ISO 14524, Photography - electronic still picture cameras - Methods for measuring opto-electronic conversion functions (OECFs), ISO 1999.

[5] ISO 12233, Photography – Electronic still picture cameras – Resolution measurements, ISO, 1998

[6] P. D. Burns and D. Williams, Identification of Image Noise Sources in Digital Scanner Evaluation, *Proc. SPIE-IS&T Electronic Imaging Symposium*, SPIE vol. **5294**, 114-123, 2004

[7] C. J. Dainty and R. Shaw, Image Science, Academic, NY, 1974, ch. 7

[8] IEC 62220-1, 'Medical electrical equipment – Characteristics of digital X-ray imaging devices – part 1: determination of the detective quantum efficiency', (2003).

[9] P. D. Burns and D. Williams, Sampling Efficiency in Digital Camera Performance Standards, *Proc. SPIE-IS&T Electronic Imaging Symposium*, SPIE vol. **6808**, 680805, 2008

[10] R. Murray, Managing a Quality Digitization Practice in Cultural Heritage Institutions: Statistical Quality Control Tools and Techniques, Proc. IS&T Archiving Conference, (2006)

[11] E. M. Granger and K. N. Cupery, An Optical Merit Function (SQF), Which Correlates with Subjective Image Judgments, *Photographic Science and Engineering*, vol. 16, pp. 221-230, 1973

[12] P. G. J. Barten, "Evaluation of subjective image quality with the square-root integral method," J. Opt. Soc. Am. A **7**, 2024-2031 (1990)

[13] D. Williams and P. D. Burns, Low-frequency MTF Estimation for Digital Imaging Devices Using Slanted Edge Analysis, *Proc. SPIE-IS&T Electronic Imaging Symposium*, SPIE vol. **5294**, 93-101, 2004

[14] D. Williams and P. D. Burns,, Measuring and Managing Digital Image Sharpening, Proc. IS&T Archiving Conference, pp. 89-93 ,(2008)