Information-based Dynamic Range:

Measuring camera performance over a wide range of illumination from a single image

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Abstract

We present a new method for measuring a camera's Dynamic Range (DR) and low light performance, both of which are derived from C_4 information capacity [2,3], which is measured directly from ISO 12233-standard 4:1 contrast slanted edges [1].

The method uses a new test chart that consists of groups of squares in a compact arrangement, where each square differs in transmittance or reflectance from its neighbors by a factor of 4, so that all edges between adjacent squares in a group have 4:1 contrast ratio (a density step of 0.602).

The major advantage of C_4 is that it completely characterizes the performance of cameras for objects with 4:1 contrast, whereas the traditional metrics, signal amplitude, sharpness, and noise, each of which contributes to information capacity, do not individually constitute complete camera performance metrics.

Because the new technique uses the difference in Digital Numbers (DNs) across an edge as the signal for calculating C_4, it avoids a measurement issue with simple flat patches, where stray light can be misinterpreted as improved Signal-to-Noise Ratio (SNR), distorting the measurements. It does, however, require that the test chart be well-focused. (The old technique was tolerant of moderate misfocus.)

Finally, we examine a new plot of C_4 as a function of exposure, which is a superior representation of camera performance over a wide range of illumination.

Introduction

We review the concept of information capacity, which is calculated from measured signal power, noise power, and bandwidth from ISO 12233-standard slanted edges, and we stress how information capacity is a *complete* performance metric, unlike traditional metrics, especially sharpness (Modulation Transfer Function, *MTF*, which is synonymous with Spatial Frequency Response, *SFR*) and noise or Signal-to-Noise Ratio (*SNR*), which are used to calculate information capacity, but don't fully characterize performance at the pixel level.

Next, we summarize the methods for calculating noise power (and hence information capacity) from slanted-edge (e-SFR) test patterns [1], focusing on the method that uses minimally or uniformly-processed images to obtain the most accurate and detailed results.

We describe the design of the new test charts, which come in several variants, each of which consists of groups of slanted squares that have a wide range of densities, where each square differs from its neighbors by the same 4:1 contrast ratio. We show how the new charts overcome several of the performance limitations of prior-art charts.

Finally, we show key results, especially the plot of C_4 information capacity as a function of illumination, which provides a particularly good indication of camera performance over a wide range of illumination.

Information capacity— Summary

Claude Shannon's ground-breaking work on information theory [4-5] is the basis for the calculation of information capacity and related metrics from the familiar and widely-used slanted-edge test pattern, described in recent papers [2-3].

In electronic communications systems, channel (information) capacity, C, defines the maximum rate in bits per second that information can be transmitted through a channel without error. For additive white gaussian noise, it is given by the deceptively simple Shannon-Hartley equation.

$$C = W \log_2\left(1+\frac{S}{N}\right) = \int_0^W \log_2\left(1+\frac{S(f)}{N(f)}\right) \qquad (1)$$

In imaging systems, C has units of bits/pixel. $S(f) = \left((V_{light} - V_{dark})\ SFR(f)\right)^2/12$ is the mean signal power, where (V_{light} - V_{dark}) is the difference between the mean Digital Numbers of the two sides of the slanted edge, *SFR* is the spatial frequency response derived from the edge, and 12 scales $S(f)$ to be the mean value of signal power, for a normal distribution of amplitudes between V_{light} and V_{dark}.

Calculating Signal power, $S(f)$, from slanted edges has always been straightforward, but noise power, $N(f)$, was traditionally calculated separately, in flat regions, which was cumbersome and error-prone.

The important thing to note is that information capacity C is a function of contrast, (V_{light}-V_{dark}), sharpness, ($SFR(f)$), and noise, $N(f)$, making it a *complete* image quality metric with units of information bits per pixel, in distinction to contrast, sharpness, and noise considered separately, which are *partial* metrics. [Please note that the partial/complete dichotomy applies only to metrics that affect information capacity; it does not apply to metrics such as color and optical distortion that can be corrected in software, and have no direct effect on information capacity.]

References [1-2] describe newly-developed techniques for calculating *N*(*f*) and *S*(*f*) from the *same* location, making the calculations fast and robust. The first step is to enable the calculation of spatially-dependent noise by finding the sum of the squares of each appropriately shifted scan line (in addition to the simple sum). The second step is to find the noise image, using a process of inverse binning of the slanted edges. This enables the calculation of the Noise Power Spectrum and several additional metrics such as *SNRi* (Ideal observer SNR), which allows the quality of object detection to be predicted.

These calculations work best with minimally or uniformly processed images. They are less accurate for most JPEG images acquired from consumer cameras, most of which have been bilateral (nonuniformly) filtered [8].

Test charts and their limitations

Two broad classes of test chart have traditionally been used for testing cameras.

1. Charts with high spatial detail, designed to fill the frame and measure sharpness (*SFR*) over the image surface. The chart shown below is an enhanced version of the Edge SFR chart illustrated in the ISO 12233 document that has extra slanted squares for improved spatial detail.

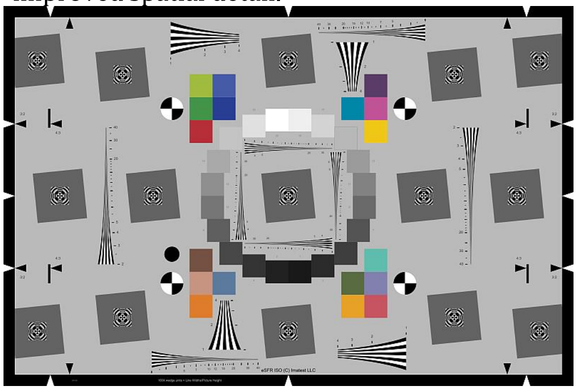

Figure 1. *Edge SFR chart with high spatial resolution*

   All the slanted edges on these charts have the same densities (with 4:1 contrast ratio), and the grayscale patterns tend to have insufficient maximum density (D_{max}) for Dynamic Range measurements. Additional features (colors, wedges) are added as space allows for customer convenience.

2. Charts with high tonal detail, such as 36-patch dynamic range charts, shown in the example below. These charts measure tonal response, noise, and *SNR* over a wide tonal range, but they have several drawbacks. Stray light, often originating from the lightest patches, fogs darker parts of the image, increasing the signal amplitude (Digital Number, DN). This results in a false improvement in *SNR* measurements. Another limitation: Depending on the chart, information capacity can be measured in at most at one level.

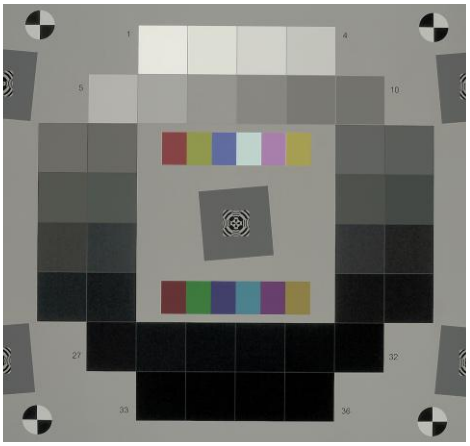

Figure 2. *Dynamic range chart with high tonal resolution*

C_4 information capacity

The original ISO 12233 standard called for a minimum of 50:1 contrast, but it was soon discovered that 50:1 contrast was too high to produce reliable results because images frequently saturated, i.e., reached their maximum allowable level (typically 255 for 8-bit files or 65535 for 16-bit files), creating sharp corners at the onset of saturation that erroneously boosted high frequency response and hence *SFR*. 10:1 was appealing because it looked similar to 50:1, but it was still somewhat susceptible to saturation. 2:1 rarely saturated, but *SNR* was lower than optimum for noisy images.

4:1 contrast ratio was a compromise — and in our view, it remains an excellent compromise. Most real-world objects that need to be recognized, for example cars on gray pavement, are not extremely high contrast. Because 4:1 contrast objects tend to stay in the linear operating region of well-exposed images, they work well for characterizing cameras. Because of this linearity, performance at different contrast levels, for example 2:1, where low *SNR* would make measurements difficult, can be estimated reliably.

C_4 information capacity (which we often abbreviate as C_4) is the amount of information in bits per pixel that can be contained in an object with 4:1 contrast ratio (Density difference of 0.602), assuming a uniform distribution of Digital Numbers (which results in the maximum capacity).

New test chart design

The goal of the new design, which we call InfoDR for Information-based Dynamic Range, is to measure C_4 over a wide range of illumination in a compact area, where sharpness (*SFR*) is likely to be reasonably consistent. It should have a high density of slanted-edges in both near-vertical and near-horizontal orientation. Although neighboring edges have 4:1 contrast ratio (Density step = 0.602), the density increment in the overall pattern must be smaller in order to achieve good tonal resolution.

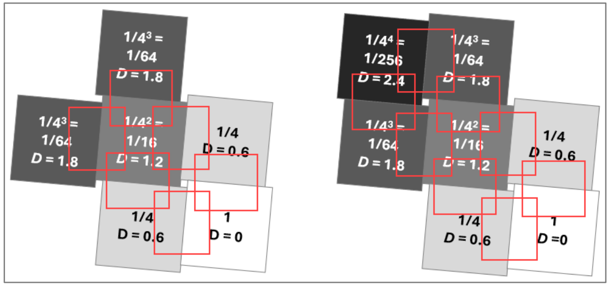

Figure 3. *Building blocks of the new test chart design*

In Figure 3, the lightest patch (reflectance ρ or transmittance τ=1; density D = 0 relative to the base density) is shown on the lower right of each pattern. The two neighboring patches (to the left and above) ρ or τ = 1/4, i.e., densities = 0.6. The single patch adjacent to previous two patches has ρ or τ = 1/16 = $1/4^2$, i.e., D = 1.2. The next two patches have ρ or τ = 1/64 = $1/4^3$, i.e., density = 1.8. This progression of {1, 2, 1, 2…} patches continues as long as needed. Note that the contrast ratio between adjacent patches is always 4:1, equivalent to density steps = ΔD = 0.602 or Michelson contrast = $(\rho_n - \rho_{n-1})/(\rho_n + \rho_{n-1})$ = 0.6.

The 4:1 density steps of the building blocks shown above are coarser than ideal for measuring camera performance over a range of illumination. To obtain finer steps, we designed charts with several regions (called quadrants where there are four), where the density of each region is offset from its neighbor by a fixed amount that allows small steps throughout the chart's tonal range.

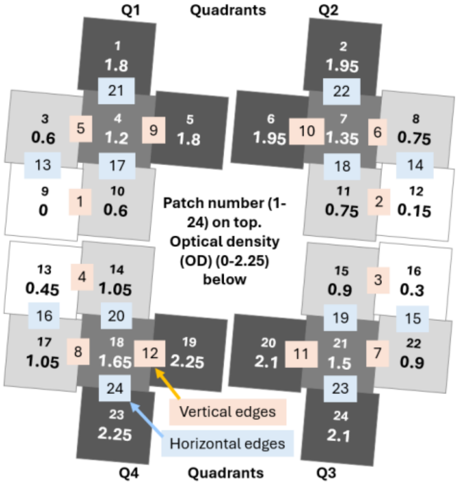

Figure 4. *Layout of four-quadrant reflective chart*

The example in Figure 4 is for the reflective chart, which has four quadrants, each with 6 patches. With this arrangement, the density offset of quadrants Q1 to Q4 relative to their neighbors is ΔD = 0.15 (half an f-stop), resulting in chart densities from 0 to 2.25 in steps of 0.15. Near-vertical edges are shown as rectangles with cream background; near-horizontal edges are shown as rectangles with light blue backgrounds.

Reflective charts, such as the one in Figure 4, have limited density ranges: $D_{max} \cong 1.5$ for matte media and 2.0 to 2.3 for semigloss or glossy media. For this reason, they are poorly suited for Dynamic Range or low light measurements.

Transmissive charts, which have sufficient density range for Dynamic Range measurements, differ in details: the 2-layer film chart shown in Figure 5 has six regions with ΔD = 0.20. It has 42 patches (7 in each section) and 48 slanted edges (8 in each section; 24 near-horizontal and 24 near-vertical) total. The patches on the bottom half of the chart are covered with film with uniform density (including the film base) = 2.4 The total patch density range is 5.2 (104 dB). The range of mean edge densities is lower by a factor of 0.6: it is 4.6 (92 dB), which is sufficient for the great majority of cameras, even High Dynamic Range (HDR) cameras, where sensors can have up to 150 dB dynamic range, but the practical dynamic range limited by reflections in the air-to-glass (or plastic) surfaces of lenses to under 100 dB.

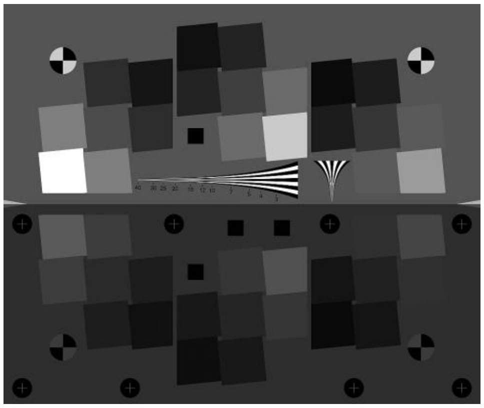

Figure 5. *Two-layer film chart, consisting of six regions, each offset by D = 0.2 from its neighbors. Bottom half shown lightened for the sake of illustration.*

The results in the remainder of this paper are from the 2-layer InfoDR film chart.

Working with the InfoDR chart

The most important thing to remember when preparing to photograph the InfoDR chart is

The InfoDR chart is not designed to fill the image (at least not in medium to high resolution cameras).

It is

sufficient if the active area of the chart fills 600-1000 pixels. Fewer pixels may reduce measurement consistency. Anything more is unnecessary, and even worse, increases the likelihood that the outer edges may be in regions of the image with reduced *SFR*. The compact chart design is intended to minimize this possibility.

Dynamic Range and low-light measurements should be made with transmissive versions of the chart, and should be photographed in darkened rooms, taking care to minimize reflections from the environment back to the chart.

For accurate Dynamic Range results, the exposure should be adjusted so the brightest patch is just below saturation.

Illumination

For camera tests in general, lighting should be as uniform as possible and free of glare (specular reflections) where analysis is to be performed. Matte surfaces, which have no specular reflections, may be needed for wide angle reflective charts.

In the past, relative illumination measurements were considered sufficient, even for measuring Dynamic Range, but knowledge of the absolute illumination level is required for meaningful low-light performance measurements. Our measurement procedures have been influenced by the excellent explanation of radiometry and photometry by Jenkin and Zhao [6].

Two types of illumination are available, depending on the chart type.

1. Reflective charts, which can be printed very large, but have a limited tonal range (about 50:1 for matte surfaces; 100:1 to 150:1 for semigloss or glossy surfaces), require reflective lighting. Illuminance E is measured in units of Lux using illuminance (incident light) meters. For Lambertian surfaces (which reflect light equally in all directions), the luminance L of a patch with reflectivity ρ is $L = \rho E/\pi$. Since transmissive charts are preferred for Dynamic Range and low-light measurements, we won't discuss reflective charts further.
2. Transmissive charts have relatively large density ranges: 1000:1 (Optical density OD = 3) for photographic film or OD = 4 for photomask media, and must be backlit with a lightbox. Lightboxes come in a variety of sizes and maximum luminances, ranging from 1,000 to 100,000 candelas per meter^2 (cd/m^2).

Measuring luminance— Transmissive charts have no illuminance because they are used in darkened environments, i.e., all illumination comes from the lightbox behind the chart. Luminance (reflected light) meters have limited fields of view for measuring the source (lightbox) luminance, L_{source}, (with the chart removed from the lightbox) or patch luminance, L_{patch}. The relationship between the two is $L_{source} = L_{patch}\, 10^{Dpatch}$, where D_{patch} is the patch density obtained from the density reference file.

A luminance meter can be held very close to the chart (even in contact) since shading isn't an issue.

Edge contrast adjustment

The nominal edge contrast for measuring C_4 is 4:1 ($\Delta D = 0.6$). However actual chart densities, and hence edge contrasts, vary because transmissive charts cannot be manufactured with perfect consistency. For that reason, transmissive charts are supplied with individually-measured density files.

The density increment of edge i is the difference between the adjacent patch densities, i.e., $\Delta D_i = D_j - D_k$. for adjacent patches j and k. To correctly represent the edge signal for the C_4 calculation, replace measured $\Delta V_i = \left(V_{light} - V_{dark}\right)$ with

$$\Delta V_{i-corrected} = \Delta V_i\, 10^{(\mathrm{mean}(\Delta D) - \Delta D_i)} \qquad (2)$$

Where $\mathrm{mean}(\Delta D) \cong 0.6$ is the mean measured patch density difference for calculating C_4.

Results

Tests were performed on a number of adjustable consumer cameras that had raw output. Obtaining raw or minimally-processed output can be challenging with some development systems. You may need to dig deeply into the documentation or even lobby the manufacturers for the feature.

The figures below are the most significant results from the InfoDR chart. The upper plot in each figure is C_4 as a function of exposure. The lower plot is the logarithm of the normalized digital number, $\log_{10}(DN/DN_{max})$, for each patch, equivalent to the classic film characteristic curve.

The x-axis in the figures below, Log$_{10}$(Exposure H in Lux-seconds), is the exposure at the focal plane for each patch, derived from ISO standard 12232:2019, Annex B [9]. The approximate equation is

$$H \cong \frac{0.65\, L\, t}{A^2} \qquad (3)$$

where A is the aperture (the lens f-number), t is exposure time in seconds, and L is the patch luminance in candelas per meter2 (cd/m^2). A and t are often available from EXIF metadata. The equation involves several approximations, most notably, lens transmission factor T = 0.9. T is easy to find for cinema lenses, but is rarely available and difficult to measure for still camera lenses. Since it can vary from about 0.85 to 0.95, depending on the number of lens surfaces and the quality of the coatings, the 0.9 approximation should be adequate for most applications. The standard has a more precise equation for close distances (image distance < 10∗lens focal length) or when T is known.

Note that $\mathrm{Log}_{10}(H)$ is used as the x-axis for characteristic curves in photographic film datasheets.

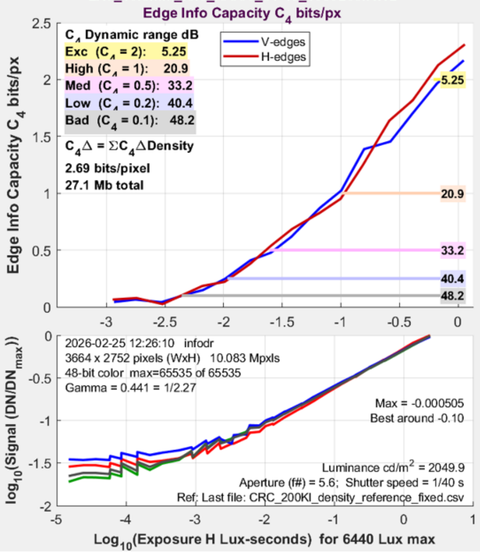

Figure 6. *Edge information capacity C_4 and tonal response for a 10-megapixel compact consumer camera with 2.14 µm pixel size and an excellent Leica-branded zoom lens.*

$C_4\Delta$, shown on the left of the upper plot, is a preliminary heuristic figure of merit that combines C_4 and dynamic range. It correlates well with the perceptual quality of cameras we've tested, which range from the compact camera in Figure 6 to the high-end heavyweight in Figure 7. $C_4\Delta$ is calculated from a simple summation,

$$C_4\Delta = \sum C_4(x)\Delta x \tag{4}$$

where $x = \log_{10}(\text{Exposure } H \text{ in Lux-seconds})$ and Δx is the x-axis increment = 0.2 OD (Optical Density units) for the 2-layer InfoDR film chart. Note that even though Figures 6 and 7 look similar, the x and y-axes of the two C_4 plots are very different. $C_4\Delta$ in Figure 7 is over 10x higher than Figure 6: not unexpected given the difference in the price and weight of the cameras. (Sometimes, you get what you pay for.)

Although the $C_4\Delta$ figure of merit should be of interest for consumers and engineers tasked with selecting cameras, the detailed plots of C_4 as a function of Exposure H should prove especially useful for camera designers who need to quantify low light performance.

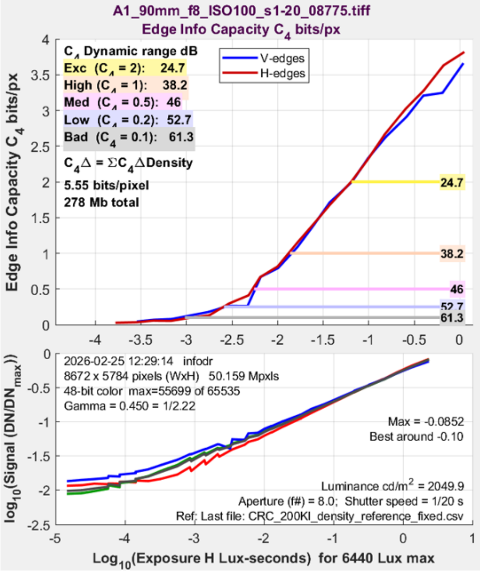

Figure 7. *Edge information capacity C_4 and tonal response for a 50.1-megapixel professional-grade camera with 4.16 µm stacked sensor pixel size and an excellent 90mm macro lens.*

Deeper exploration

The new InfoDR chart can be used for all standard slanted-edge measurements (SFR, etc.) as well as traditional *SNR* and slope-based Dynamic Range (DR) measurement (Figure 8), which we regard as inferior to C_4 because *SNR* does not fully characterize performance. The results in Figures 7 and 8 are closer than we expected. The new C_4-based measurements often show lower dynamic range.

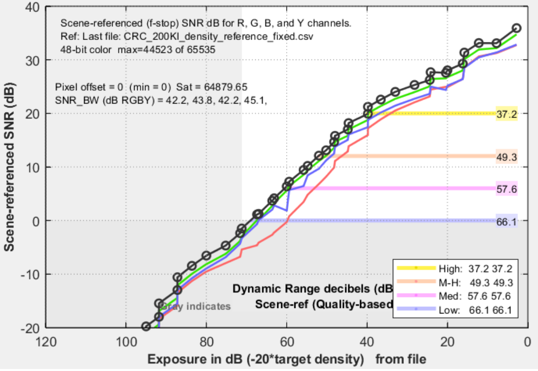

Figure 8. *Scene-referenced noise and Dynamic Range for the 50.1 megapixel camera with 4.16 µm pixel size in Figure 7.*

Results can sometimes be surprising. For example, a peak in spatial noise [2,3] can indicate the presence of bilateral filtering [8], which is a form of edge-preserving noise reduction that smooths low contrast regions while maintaining sharpness near contrasty features such as edges. It is almost universal in JPEG files from cameras, but we've never seen it in raw images — except for one case, the iPhone 15, which appears to have noise reduction but no sharpening. When it is present, information capacity is estimated using the amplitude of the smoothed peak noise instead of the mean noise. Even with noise reduction, the iPhone 15 had impressive performance.

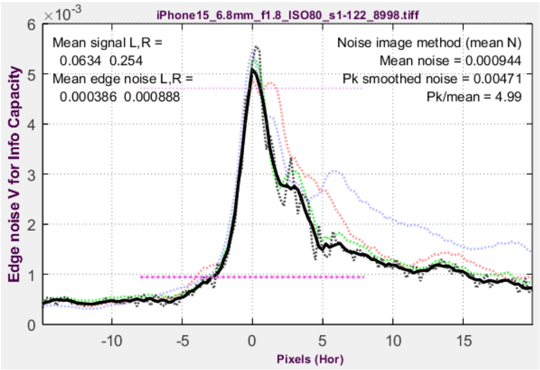

Figure 9. *Spatially dependent noise for the iPhone 15, rarely seen in (converted) raw images.*

Summary

We have introduced the new InfoDR test chart that allows C_4 information capacity— the amount of information that can be contained in an object with a 4:1 contrast ratio— to be measured over a wide illumination range (92 dB for the two-layer film chart). It is a significant advance over previous test charts, which either allow sharpness and C_4 to be measured at a single exposure level or allow noise and SNR (but not sharpness or C_4) to be measured over a wide illumination range. When combined with a chart with good spatial detail, like Checkerboard or eSFR charts (Figure 1), a camera's information-related performance metrics can be very well characterized.

DR results are comparable to traditional measurements in cameras where stray light is well-controlled. Customers need to be aware that camera DR is normally limited by reflections from lens surfaces, rather than image sensors, which can have extraordinarily high DR specifications (up to 150 dB) that are unattainable in real cameras with lenses.

We again emphasize that C_4 information capacity is a *complete* pixel-level performance metric, i.e., it can answer the question, "How good is the pixel or camera?" Sharpness (SFR), and noise or SNR are *partial* performance metrics that are entered into the Shannon-Hartley equation (1) for information capacity.

C_4 can also be used to calculate additional information metrics such as Ideal Observer SNR ($SNRi$) [3,10-12], which quantifies how well an object of a given size can be detected.

Imatest is actively working on ISO 23654, "Digital imaging — Image information metrics," which will describe the calculations of information capacity and related metrics, including C_4, in detail.

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Norman Koren became interested in photography while growing up near the George Eastman Museum in Rochester, NY. He received his BA in physics from Brown University (1965) and his Masters in physics from Wayne State University (1969), then worked in the computer storage industry simulating digital magnetic recording systems and channels. He founded Imatest LLC in 2003 to develop software, test charts, and lab hardware for measuring the quality of digital imaging systems. Since 2021 he has been obsessed with applying information theory to image quality measurement.