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Extending the Utility of Noise Equivalent Quanta (NEQ) for Dynamic Range Measurement in Imaging Systems

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Abstract

This paper investigates the application of Noise Equivalent Quanta (NEQ) as a comprehensive metric for assessing dynamic range in imaging systems. Building on previous work that demonstrated NEQ's utility in characterizing noise and resolution trade-offs in imaging systems using the Dead Leaves technique, this study seeks to validate the use of NEQ for dynamic range characterization, especially in high-dynamic-range (HDR) systems where conventional metrics may fall short.

This paper makes use of previous work [1] [2] [3] [4] that showed the possibility to measure noise and NEQ on the dead leaves pattern which is otherwise typically used for the measurement of the loss of low contrast fine details, also called texture loss [5]. This shall now be used to improve the measurement of the dynamic range.

Dynamic Range

Dynamic range (DR) is a fundamental property of imaging systems, describing the ratio between the highest and lowest luminance levels that a system can reliably capture and reproduce. Conventionally, dynamic range is defined as:

$$DR = \frac{L_{max}}{L_{min}} \quad (1)$$

where L_{max} represents the luminance level at which the system saturates (maximum reproducible signal), and L_{min} corresponds to the lowest luminance at which a meaningful signal can still be distinguished from noise. Often, L_{min} is defined as the luminance level where the signal-to-noise ratio (SNR) reaches 1. This definition is used in standards such as ISO 15739 and EMVA 1288.

While simple and reproducible, this classical definition presents several limitations in practice:

Object contrast consideration

While the Dynamic range defines the extreme limits of the image signal, it does not take the object contrast into account. An object that forms a high contrast in the image will suffer from contrast reduction in a smaller range than an object with lower contrast. So the actual dynamic range is depending on the object contrast.

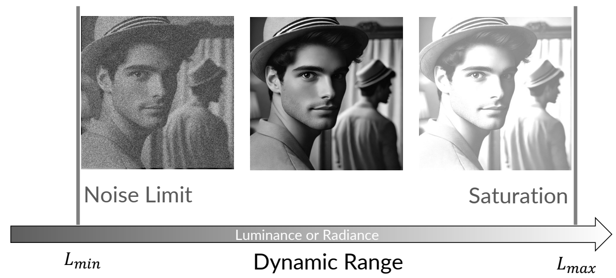

***Figure 1**: Illustration of object contrast within the dynamic range*

Flat Patch Limitation

Most conventional DR measurements are performed using flat gray patches at different intensity levels. This approach does not account for the spatial structure of real-world scenes and fails to capture the interaction between signal fidelity and image content such as edges or textures.

***Figure 2** Detail of IS15739 test target. The noise increases significantly close to the edge, showing that the flat gray area is processed differently*

Influence of Noise Reduction and Processing

Modern image processing pipelines often apply aggressive noise reduction, compression, or tone mapping—especially in high-dynamic-range (HDR) systems. These operations can artificially suppress noise in flat patches while simultaneously degrading fine detail. As a result, measurements based on flat patches may report high SNR values and thus a wide dynamic range, despite a noticeable loss of useful information in textured regions.

Non-Linear behavior in HDR systems

HDR systems typically combine multiple exposures or apply non-linear tone curves to expand the perceived dynamic range. These processes can introduce non-monotonic noise behavior or "SNR holes," where certain exposure levels produce unexpectedly poor signal fidelity. Traditional DR measurements do not detect these artifacts.

Over-reliance on a Single SNR Threshold

The use of a fixed SNR=1 threshold to define Lmin oversimplifies the relationship between noise and (perceptual) image quality. In many applications, such as surveillance or automotive vision, a higher SNR may be required to ensure reliable object detection or recognition. Consequently, the reported dynamic range may not align with actual system usability.

These limitations underline the need for a more comprehensive and application-relevant approach to dynamic range assessment. A metric that accounts for spatial frequency response, local contrast preservation, and noise characteristics across the full luminance range is essential to be able to differentiate between the theoretical maximum dynamic range and the actual usable dynamic range.

NEQ based on Dead Leaves

The NEQ-based method addresses these issues by combining resolution and noise performance into a single frequency-dependent metric. When evaluated across a range of exposure levels using a textured target like the dead leaves pattern, NEQ provides a richer and more realistic characterization of dynamic range as it not just based on saturation and noise.
Noise Equivalent Quanta (NEQ) is a critical metric for assessing the performance of imaging systems. It unifies information on resolution and noise, reflecting how well a system preserves image fidelity across spatial frequencies. Mathematically, NEQ is defined as:

$$NEQ(f) = \frac{SFR(f)^2}{NPS(f)/\mu^2} \quad (3)$$

where SFR(f) is the Spatial Frequency Response at spatial frequency f, NPS(f) is the Noise Power Spectrum, and μ is the mean signal level. This expression quantifies the system's ability to transfer information at various spatial frequencies, weighted by its noise characteristics.

Principles of the Method

Traditionally, measuring NEQ requires separate experiments to estimate the SFR and NPS. However, the dead leaves pattern provides a unified and practical method to derive both quantities from a single test chart. Originally proposed for texture loss analysis and resolution measurement, the dead leaves method has evolved to support objective NEQ estimation as well.

The dead leaves pattern is composed of randomly distributed overlapping disks with known contrast and statistical properties. Because it contains fine textures across a broad range of spatial frequencies, it mimics real-world content more effectively than flat-field targets. This makes it ideal for examining the impact of image processing such as noise reduction or compression, especially in HDR and ISP-processed data.

Estimating SFR Using Dead Leaves

The derivation of SFR from the dead leaves pattern is based on frequency-domain analysis, employing a cross-power spectral approach. A known reference image (the input pattern) is compared against the captured image (the output of the imaging system). The key quantity is the system's complex transfer function, H(f), defined as:

$$H(f) = \frac{\phi_{YX}(f)}{\phi_{XX}(f)} \quad (2)$$

where $\phi_{YX}(f)$ is the cross-power spectrum between the input and output, and $\phi_{XX}(f)$ is the power spectrum of the input. From the complex H(f), the magnitude provides the SFR. To simplify analysis and improve robustness, the 2D frequency response is rotationally averaged over rings of equal spatial frequency, resulting in a 1D SFR curve.

This method is detailed in ISO 19567-2 and its derivatives and is widely used in texture analysis.

Estimating NPS Using Dead Leaves

Estimating the NPS using the same dead leaves target is less conventional but highly effective. The captured image is assumed to be a combination of a blurred version of the target and added noise. By applying the previously derived system transfer function H(f) to the input pattern in the frequency domain, a simulated "blurred reference" image can be constructed. Subtracting this from the actual captured image yields a residual that represents the noise component. The NPS is then derived from this noise image using 2D power spectral analysis and subsequent rotational averaging.

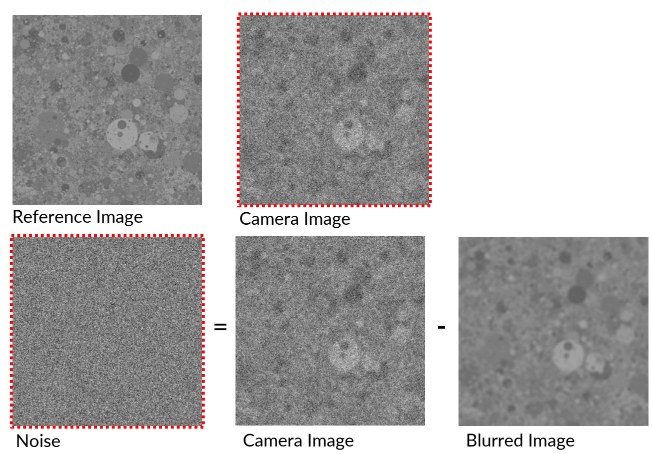

***Figure 3** Different intermediate images used to obtain the noise image. The blurred image is created from the reference and the measured SFR, then subtracted from the camera image.*

This approach assumes that geometric distortions and tone reproduction can be compensated. Gray patches surrounding the dead leaves pattern assist in linearization of the signal response, and image registration algorithms align the captured image with the reference pattern. These preprocessing steps are standard in SFR estimation workflows and are reused here.

Advantages of the Unified NEQ Measurement

One of the strongest arguments for this methodology is that both SFR and NPS are computed from the same scene, under identical exposure and processing conditions. This ensures that NEQ reflects the true trade-offs made by the imaging system or ISP, including those stemming from dynamic range compression, tone mapping, or denoising algorithms.

Simulations in the 2024 study confirmed that NEQ is invariant to linear image processing, such as Gaussian filtering. The MTF drop introduced by such filters is counterbalanced by the corresponding decrease in noise power, leaving NEQ unaffected. Conversely, non-linear processes like median filtering alter the frequency structure of noise in a way that reduces NEQ, aligning with the intuitive notion that these changes are not easily reversible

Dynamic Range based on NEQ

To derive dynamic range from NEQ, a sequence of images captured at varying exposure levels is analyzed. This method goes beyond traditional DR measurements by considering the spatial frequency response and noise characteristics at each intensity level. The process leverages the NEQ metric, which unifies resolution and noise performance, allowing for a nuanced evaluation of an imaging system’s ability to preserve information across a wide luminance range.

The measurement process begins with capturing a dead leaves target under a controlled intensity sweep. This can be implemented using a transmissive dead leaves chart with 100 logarithmically spaced steps of illumination. For each intensity step, the captured image is used to compute three key metrics: Spatial Frequency Response (SFR), Noise Power Spectrum (NPS), and NEQ.
By repeating this analysis for each exposure level, we create a 2D representation of NEQ across luminance and frequency. This data is visualized as a series of curves or a 3D NEQ volume, illustrating how well the system captures detail across the intensity range.

Figure 4 shows the SFR plotted depending on spatial frequency and luminance of the backlight lightsource behind the transparent test target (see Figure 8 that shows the setup). This is the SFR measured as specified in ISO19567 including the normalization on a very low spatial frequency. During the data analysis is became obvious, that this normalization might mitigate the influence of contrast loss due to tone scaling. Figure 7 shows an effect that was observed with the used automotive sensor and ISP combination which resulted in significant contrast loss at some intensities, most likely an artifact of HDR generation. As this was hidden by the normalization, an alternative method that omits the normalization was implemented, this results in the SFR as shown in Figure 5. This indicates that to skip the normalization has the potential to combine contrast behavior and spatial frequency response into one measurement. Further investigation is needed.

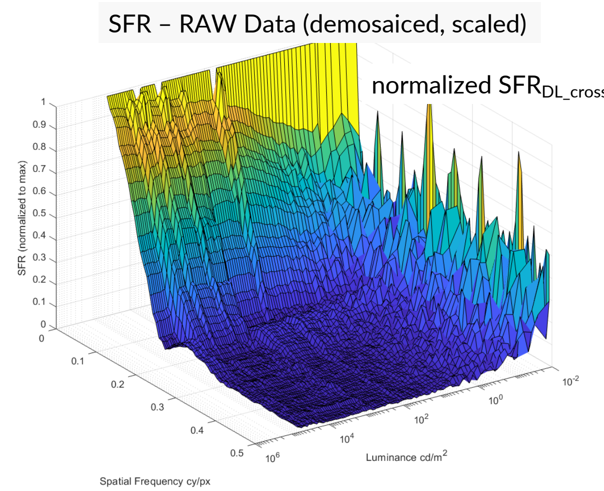

***Figure 4** SFR measured over an intensity sweep of the dead leaves target - including standardized (ISO19567) normalization*

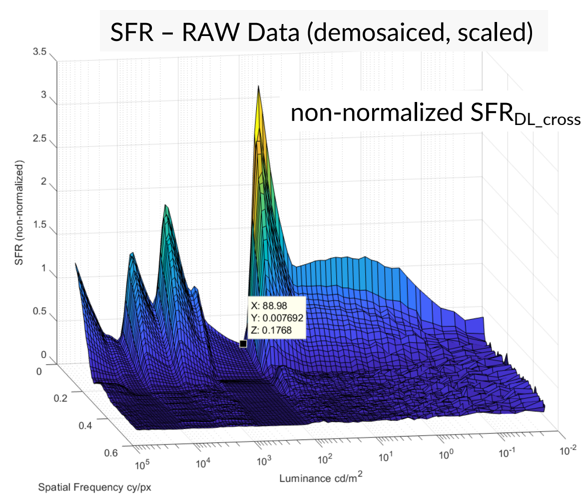

***Figure 5** SFR measured over an intensity sweep of the dead leaves target*

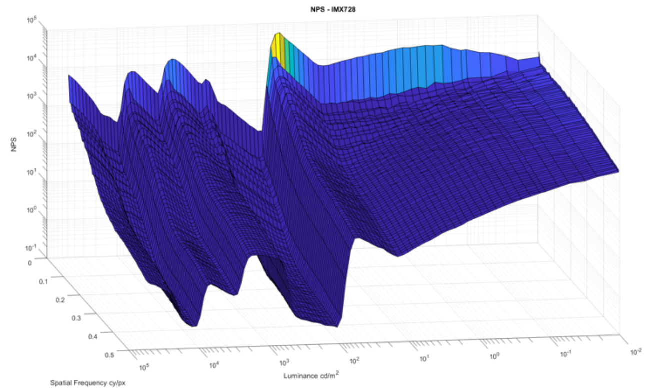

Figure 6 *NPS measured over an intensity sweep of the dead leaves target*

The derives NPS from the used dataset is shown in Figure 6, combined with the SFR this results in the NEQ.

Figure 9 show the NEQ values extracted from image data across various luminance levels. These plots reveal not just where the signal is detectable, but where it retains spatial integrity across relevant frequencies. This insight enables the definition of a dynamic range that aligns more closely with actual image utility, rather than a simplified threshold-based estimate.

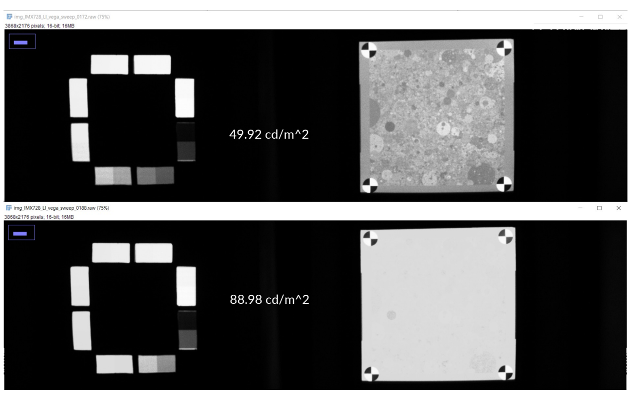

Figure 7 *Comparing images of different intensities using an automative grade sensor with non-optimized soft ISP, resulting in significant contrast loss in some intensity regions*

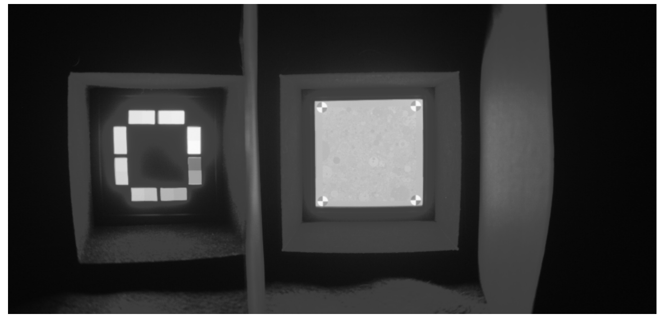

Figure 8 *Test setup used for measurement; adjusted to 8bit for visualization* ***Left:*** *grayscale target* ***Right:*** *dead leaves target* ***Both:*** *back illuminated with changing intensity*

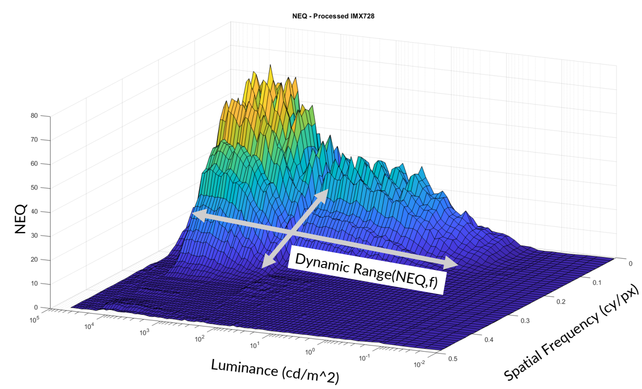

Figure 9 *NEQ based dynamic range measurement, resulting in a volume defined by spatial frequency, object contrast and the measured NEQ*

Conclusion

This paper extends the application of Noise Equivalent Quanta (NEQ) from a static quality metric to a dynamic range assessment tool. By leveraging a dead leaves intensity sweep, we demonstrated how NEQ can be measured across exposure levels, providing a more realistic and informative representation of usable dynamic range in imaging systems.
The proposed method captures the trade-offs between resolution and noise under varying luminance. Unlike traditional approaches, it evaluates dynamic range based on actual image content, not just flat patches.

Future work will focus on defining standardized NEQ thresholds for specific applications, automating volume-based DR extraction, and extending the method to SNRi-based object detectability for practical use-case definitions.

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Author Biography

Uwe Artmann studied Photo Technology at the University of Applied Sciences in Cologne following an apprenticeship as a photographer and finished with the German 'Diploma Engineer'. He is the CTO at Image Engineering, an independent test lab for imaging devices and manufacturer of all kinds of test and calibration equipment for these devices. He is also the head of the standards department within VCX-Forum e.V. and member of various international workgroups regarding standardization of image quality measurement including IEEE and EMVA.

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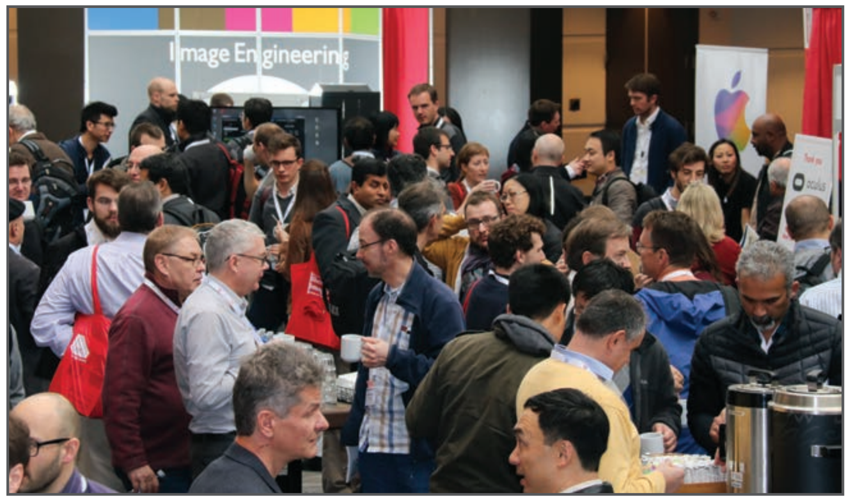

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