Sampling Efficiency in Digital Camera Performance Standards

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ABSTRACT

One of the first ISO digital camera standards to address image microstructure was ISO 12233, which introduced the SFR, spatial frequency response, based on the analysis of edge features in digital images. The SFR, whether derived from edges or periodic signals, describes the capture of image detail as a function of spatial frequency. Often during camera testing, however, there is an interest in distilling SFR results down to a single value that can be compared with acceptable tolerances. As a measure of limiting resolution, it has been suggested that the frequency at which the SFR falls to, e.g., 10%, can be used. We use this limiting resolution to introduce a sampling efficiency measure, being considered under the current ISO 12233 standard revision effort. The measure is the ratio of limiting resolution frequency to that implied by the image (sensor) sampling alone. The rationale and details of this measure are described, as are example measurements. One-dimensional sampling efficiency calculations for multiple directions are included in a two-dimensional analysis.

Keywords: camera resolution, SFR, MTF, limiting resolution, sampling efficiency, effective megapixel

1. INTRODUCTION

Along with the development and adoption of standard methods for evaluating digital camera imaging performance has come the need for a simple interpretation of the results. ISO 12233 was one of the first to address digital camera performance. It introduced the spatial frequency response (SFR), based on analysis of an edge feature in the digital image. The SFR, whether derived from edge analysis or periodic signals, describes the capture of image detail as a function of spatial frequency. Often during camera testing, however, there is an interest in distilling SFR results down to a single value that can be compared with acceptable tolerances. A measure of limiting resolution is often sought, and it has been suggested that the frequency at which the SFR falls to, e.g., 10%, can serve this purpose.

The use of limiting resolution is well established and is usually measured by visual examination of periodic image features such as high contrast lines. The method currently being considered in the ISO 12233 standard revision effort, however, is an extension of the methods established in the current digital camera resolution standard. A limiting resolution value is one measure of the ability of an image capture system to record image detail information. This measure is acknowledged as providing an incomplete description of image sharpness or image quality. It is, nevertheless, natural to compare the limiting *image* resolution with that implied by the *sampling* resolution. The sampling resolution, sometimes referred to as the addressable resolution or sampling rate, is based on the digital image sampling. It is the comparison of the measured limiting resolution with the sampling resolution that can be expressed as a “sampling efficiency.”

Before proceeding with the development of the proposed sampling efficiency measure, it is useful to discuss several terms that we will be using. The visual impression of spatial detail in a displayed image is often described by its apparent sharpness for pictorial scene content. The term “resolution” can also used to indicate the visual impression of image-spatial detail. ISO 12233, however, defines resolution as, “a measure of the ability of a digital image capture system, or a component of a digital image capture system, to distinguish picture detail.”[1] We will follow this usage with the observation that the standard then proceeds to define the particular measure of resolution as the “spatial frequency response.”

Limiting resolution, also called the minimum resolvable distance, is the minimum separation distance between two objects (often lines) so that they can be *seen* as distinct. Given that we are concerned with measurements based on image data, we will use the term “limiting resolution” to mean an indirect measure (or estimate) of this distance, expressed as a

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corresponding spatial frequency. In this paper, since any measure of limiting resolution will be based on automated analysis, we can interpret it as a surrogate for the value that might be derived from a visual evaluation of that image, if it were displayed. Sampling resolution is that implied by the sampling (or size) of the delivered image file. When expressed in terms of pixels, the sampling interval is one pixel. The corresponding spatial frequency is the half-sampling, or Nyquist, frequency of 0.5 cycles/pixel.

1.1 Camera Resolution – ISO 12233

The ISO method,[1, 2] based on the analysis of slanted-edge image features, is a special case of edge-gradient analysis. The analysis is performed on a digital image containing a high-quality edge feature. From this edge, one needs to estimate an edge-spread function for the image transition (edge profile). From this edge profile, a sampled line-spread function is found by estimating the first derivative. The modulus of the computed discrete Fourier transform of this line-spread function, after scaling, is the measured, normalized signal-modulation function of spatial frequency. This is the measured spatial frequency response (SFR) called for in the standard.

In cases where the objective is to characterize the performance limited by lens, sensor and readout electronics, it is often recommended that some camera features, such as spatial image processing, be disabled during testing. Often this is not easy, but also has the disadvantage that device-testing conditions will then differ from normal usage. Here, we will assume that a *system* test is to be undertaken, which includes all normal digital camera settings. As we will see, this can influence the measured SFR, when digital image sharpening (or blurring) is present.

Figure 1 shows the measured SFR for a digital camera set at two lens positions. One test image was acquired with the camera focused on the test target and the other with the lens set to be out of focus. The spatial frequency axis is shown in terms of cycles/pixel rather than cycles/mm on a test target. The value of 0.5 cy/pixel is the half-sampling frequency and is often taken as the upper limit for unambiguous capture of scene spatial information. We are not addressing artifacts such aliasing that result from image sampling in this paper, so we will simply take 0.5 cy/pixel as the upper frequency of interest. Note that the rise in SFR near 0.1 cy/pixel for the focused image indicates that digital image sharpening has been applied. This is also applied in the second image path, but the effect is reduced by the optical defocus.

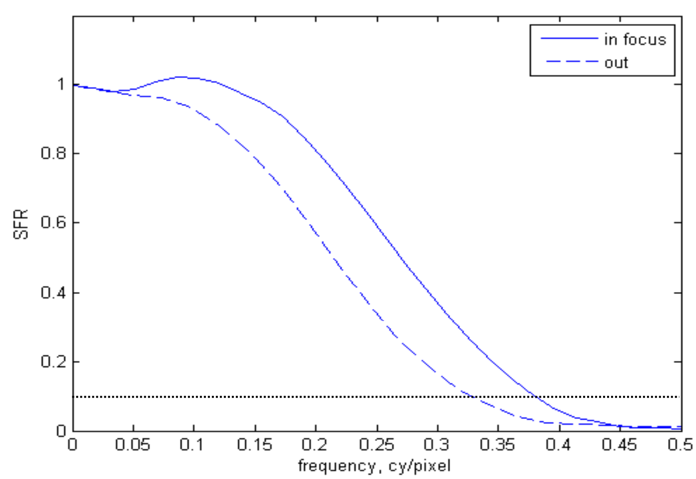

Figure 1. SFR measurement results for a digital camera with two lens focus positions.

An additional method for digital camera SFR evaluation that is likely to be included in the second edition of the ISO 12233 standard is based on polar sinewave image features (Siemens star).[3] Either the edge (E-SFR) or sinewave SFR (S-SFR)could serve as the basis for the limiting resolution and sampling efficiency. For completeness we note that a third, non-SFR based, approach is being considered for inclusion in the revised standard. This *visual resolution* metric[4] is adopted from a Camera and Imaging Products Association (CIPA) standard, and is correlated with the edge-based 10% SFR measure described in this paper. The reader is referred Ref. 5 in these proceedings for more information.

2. LIMITING RESOLUTION BASED ON SFR

The rationale for deriving a measure of limiting resolution from the SFR comes from the optics community. For continuous optical systems, the frequency associated with the 10% MTF response point can generally be interpreted as a summary resolution value consistent with the Rayleigh criterion.[6] If we interpret a measured SFR data set as an estimate of the digital camera's effective (sample) MTF, then it is natural to apply a similar rule. While the idea is simple to express, two points of caution are worth noting. The empirical Rayleigh criterion was derived for visual instruments such as telescopes. The viewing of digital images of continuous scene information may approximate this condition but not if significant artifacts such as aliasing or contouring are present. In addition, image noise introduced during image capture is not accounted for when using this approach. While it is possible to measure a 10% SFR frequency for various cameras, the correspondence of these values to visual limiting resolution data may vary with image noise level.

Figure 2 outlines the steps in the procedure. We start with a digital image test file containing the edge feature used in the SFR evaluation. In addition, the critical value of 0.1 is used. Given that the measured SFR is a vector representing the sampled function, it is likely that the frequency where the SFR falls to 0.1 can be interpolated from nearby data. The results of this analysis for a near-horizontal edge from a digital camera image are shown in Fig. 3. In this case, the limiting resolution was found to be 0.44 cy/pixel. If we compare this with sampling resolution as defined by the half-sampling frequency, 0.5 cy/pixel, then the one-dimensional vertical sampling efficiency is,

$$E_v = \frac{\text{limiting res}}{\text{sampling res}} = \frac{0.44 cy / pixel}{0.5 cy / pixel} = 88\% \qquad (1)$$

Note that we can calculate sampling efficiency values for the two SFR results shown in Fig. 1. The 10% limiting resolution values are 0.38 and 0.33 for the focused and defocused cases, respectively. The corresponding sampling efficiency values are 0.76 and 0.66, respectively.

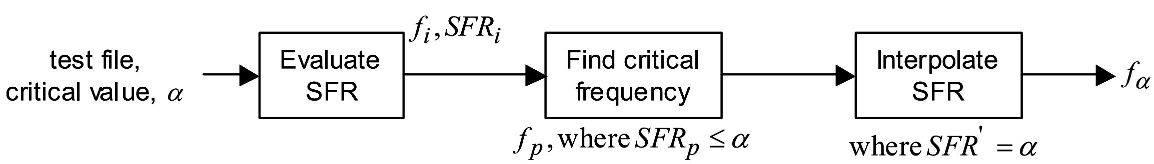

Figure 2. Calculation of limiting resolution (frequency) from SFR.

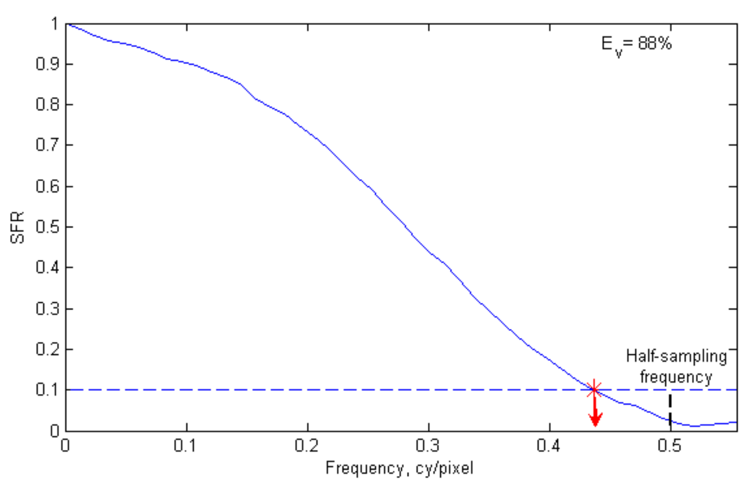

Figure 3. Results of 10% SFR calculation as in Fig. 2.

3. TWO-DIMENSIONAL SAMPLING EFFICIENCY

Although the above one-dimensional sampling efficiency value may be useful, it fails to account for differences in performance that often occur as a function of angular direction across a digital image. This calls for some form of two-dimensional sampling efficiency, which would also facilitate comparison with a camera's total image pixels ("megapixel" value). The proposed two-dimensional sampling efficiency measure under consideration for ISO 12233 revision calls for the following steps:

1. SFR measurement in three principal directions: vertical, horizontal, and diagonal.
2. Estimation of limiting resolution frequency and sampling efficiency in each direction: E_v, E_h, E_d . Note that the diagonal sampling efficiency calculation uses the same sampling resolution frequency, 0.5 cy/pixel, as for the horizontal and vertical directions, rather than the extended range of frequency support, [0-0.707 cy/pixel] of the sampled signal spectrum.
3. Calculation of the sampling resolution rating E_s as the product of E_v and the average of E_v and E_h:

$$Es = \frac{100 E_d \left(E_v + E_h\right)}{2} \% \qquad (2)$$

A rotationally symmetrical SFR surface is shown in Fig. 4, with its 0.1 and 0.5 value contours. In this case, the 10% limiting resolution frequency is 0.5 cy/pixel for the vertical, horizontal, and diagonal directions. So by Eq. 2, the two-dimensional sampling efficiency is 100%.

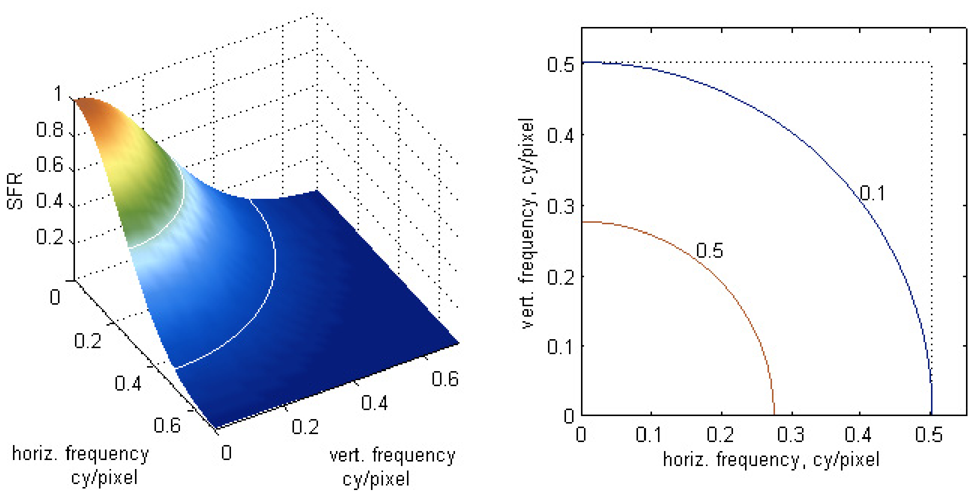

Figure 4. Example of two-dimensional symmetric SFR and corresponding 50% and 10% response contours.

For some digital systems, the acquisition SFR or MTF can be assumed to be separable so that,

$$MTF(u,v) = M_h(u) M_v(v) \qquad (3)$$

where $M_h(u)$ and $M_v(v)$ are the one-dimensional horizontal and vertical MTFs, respectively, and u and v are the corresponding spatial frequency coordinates. In this case, the diagonal sampling efficiency is computed from the array

$$SFR_d(u) = SFR_h(u) SFR_v(u) . \qquad (4)$$

CONCLUSIONS

A sampling efficiency measure is introduced as an extension of the current ISO 12233 standard revision effort. The measure is based on the ratio of a 10% SFR-spatial frequency bandwidth to the bandwidth implied by the image sampling alone, for a digital camera under test. While this measure is not intended to include the influence of sampling artifacts and image noise, it can provide guidance when considering the level of image signal detail likely to be delivered by a camera. In addition, it can be used to select between camera operating conditions, e.g., file size selection for an imaging task. The measured sampling efficiency provides a convenient factor for the adjustment of advertised values to yield an *effective megapixel* value.

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