# Applying and Extending ISO/TC42 Digital Camera Resolution Standards to Mobile Imaging Products

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## ABSTRACT

There are no fundamental differences between today's mobile telephone cameras and consumer digital still cameras that suggest many existing ISO imaging performance standards do not apply. To the extent that they have lenses, color filter arrays, detectors, apertures, image processing, and are hand held, there really are no operational or architectural differences. Despite this, there are currently differences in the levels of imaging performance. These are driven by physical and economic constraints, and image-capture conditions. Several ISO standards for resolution, well established for digital consumer digital cameras, require care when applied to the current generation of cell phone cameras. In particular, accommodation of optical flare, shading non-uniformity and distortion are recommended. We offer proposals for the application of existing ISO imaging resolution performance standards to mobile imaging products, and suggestions for extending performance standards to the characteristic behavior of camera phones.

**Keywords:** camera phone, cell phone camera, ISO 12233, image quality, SFR

## 1. INTRODUCTION

The convenience and low incremental cost of today's mobile-telephone cameras have lead to their rapid adoption by consumers. The current imaging performance, however, is far below that of a digital still camera (DSC) due to several factors such as lens size, flash power and image compression. In addition, perhaps due to this, consumer usage patterns for the two types of product differ. For example a cell phone image, while adequate when displayed on the unit, can appear as relatively low quality when downloaded to a computer and viewed there or printed. Since we expect the difference in performance to diminish as mobile cameras improve, the need arises for industry standards for the evaluation and comparison of image quality for mobile imaging. The existing image resolution standard for digital cameras (ISO 12233) is a good starting point for such an effort since resolution can be a significant factor influencing image quality.

Standards DSC imaging performance have evolved over the last decade. Based on years of practical engineering experience, they have proven to be useful for both product evaluation and subsystem design analysis. The architecture of the measurement protocols for resolution, noise, speed, and color remains resilient despite the gauntlet of complex image processing algorithms they have faced over the years. And while there are a few chinks in the armor they are frequently remedied in subsequent revisions of the standards.

The market for today's picture taking has changed dramatically from when the camera resolution standard was introduced. Developed with the growth of consumer and professional grade DSCs, the standard's recommendations reflects, perhaps unwittingly, the picture taking habits and camera technologies of the time. That design paradigm was one of shared personal memory images from a firmly gripped palm-sized point-and-shoot CCD-based (4-6 μm) camera, or its larger sibling, the digital single lens reflex (SLR) camera dedicated to picture taking on special occasions. Compare that with typical cell phone camera usage; spontaneous ephemeral images taken by unstable one-handed shutter actuation of a CMOS based (1-2 μm) camera, with miniaturized optics that have taken a back-seat to higher priority text and audio communication needs. In addition, the pictures are usually taken under low light conditions with limited flash units. While the usage has clearly changed, the existing standards are often resilient enough to accommodate them, albeit with some adjustments.

Currently many standards have a decidedly engineering spin to their methods. By suggesting in some cases that image-processing features be disabled, the implied goal is to deduce the intrinsic capabilities of the camera as opposed to the delivered and finished file. There is an increasingly accepted opinion in the camera community that this unprocessed file philosophy needs to be reconsidered in favor of the latter; for both practical and consumption reasons. In many ways it is challenge of relevance. Perhaps the most significant challenge for these standards with respect to cell phone usage is a migration from a capability-based philosophy to one of delivered performance. That is, moving from metrology under fixed, often optimal, laboratory conditions (e.g., single subject distance, on-axis, tripod mounted conditions) to more realistic usage conditions that reflect spatial, temporal, or environmental variables.

In this paper we describe several areas where the current digital cameras resolution standard is likely to be adapted and applied to the mobile-telephone cameras. While doing so we also describe areas where extensions to the standard may be needed. We limit our attention to device imaging performance and the components that relate to image quality, and will not address the larger field of telecommunications.

### 1.1. Field-Dependent Performance Testing

Given the constraints on the space available for the optical elements of a phone camera, it is not surprising that we observe considerable image variation across the digital image. Typical performance in center-to-edge mean signal uniformity, sharpness and noise is often similar to the widest setting of a zoom lens for a DSC. Figure 1 shows an example from a uniform exposure and current cell phone camera. As a general rule then, we suggest that imaging performance standards explicitly address this variation.

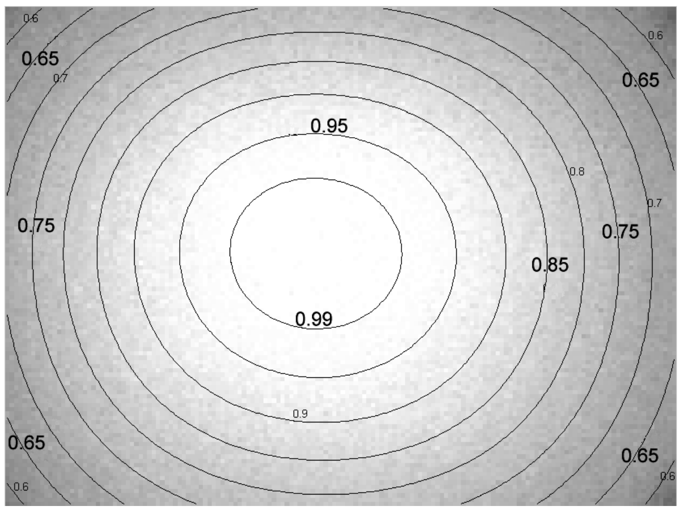


*Figure 1: Example of cell phone camera (green-record) image due to a uniform field. The contour labels show the fractional level in the saved file, where the reference value was 246.3 (8-bit encoding).*

This example also serves to illustrate the connection between hardware and software in the delivery of imaging performance. Since it is not possible to have control over subsystem settings for these imaging products, we can only observe net effect. Consider a camera with the optical falloff characteristics of Fig.1. There are already products that compensate for predictable characteristics such as this in the image processing prior to saving the digital image file. The compensation, however, is in the form of a position-dependent compensation gain, or correction matrix, applied to the detected image data. With this compensation, however, comes an amplification of the pixel-to-pixel image noise in the delivered image, especially where corrected aggressively. The effect represents a special case of error propagation[1, 2]. If $x$ is the input image array ($N$ x $M$), and $g$ is the compensating gain matrix, the uniformity correction can be written,

$$y_{ij} = g_{i,j} x_{i,j}, \text{ where } i = 1, \ldots, N \text{ and } j = 1, \ldots, M \,. \tag{1}$$

The image noise, as described by the pixel-to-pixel standard deviation for a nominally uniform exposure, is transformed

$$\sigma_y = g_{i,j} \sigma_x \,, \tag{2}$$

where $\sigma_x, \sigma_y$ describe the image noise at or near location (*i*, *j*). In this case the compensation calls for a correction gain, *g* = 1.66 (1/0.6) near the edge of the frame, which amplifies the image noise by the same factor. This example serves to illustrate how certain types of in-camera image processing can be expected to introduce intra-image variation that needs to be incorporated into imaging performance standards for cell phone cameras.

## 2. SPATIAL RESOLUTION – ISO 12233

Issued in 1998, the first edition of ISO 12233 for measuring camera resolution is an example of how an effort at standardization can be incrementally refined through software improvements, field usage, and frank user feedback from industry practitioners. Several changes from the first edition, particularly in the target design, are now better-suited to the 'delivered file' of cell phone cameras. We expect these improvements to be adopted in the next revision of the standard, currently at ISO draft stage. Software improvement will also add flexibility and tend to mitigate constraints imposed by cell phone camera designs such as noise, lighting non-uniformity, and limited file sizes. To understand the development of this standard we first discuss the technical background of the analysis method, and how it has been applied since first developed.

The ISO method,[3, 4] based on analysis of slanted-edge image features, is a special case of edge-gradient analysis. The basic steps for edge-gradient methods are shown in Fig. 2, where the input is the system response to a high quality edge feature. For a digital camera or scanner, this would be the digital image of a printed test target of an edge or scene object. From an edge image, one needs to estimate an edge-spread function for the image transition. From this edge profile, a line-spread function is found by estimating the first derivative. The modulus of the computed Fourier transform of this function, after scaling, is the measured normalized signal modulation function of spatial frequency. This is the Spatial Frequency Response (SFR) called for in the standard.

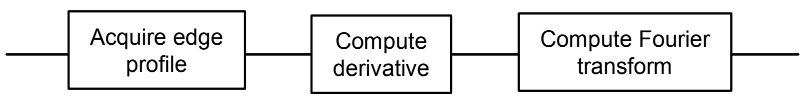


*Figure 2: Steps in edge-gradient analysis*

Often the output modulation (SFR) is divided by the corresponding input edge (test target) modulation, frequency-by-frequency, to yield the measured system MTF. When no account is taken of the input edge modulation, the measured modulus can still provide a useful measurement relative to the input target edge and other relevant operating conditions. We will refer to the single output modulation, normalized to unity at zero frequency, as the spatial frequency response (SFR), consistent with the standard. The ratio will be called the estimated or measured MTF. Since this compensation for the input target modulation was not required by the standard, it does not refer to the SFR as the MTF. The distinction on this point, however, is generally more important for scanners than for digital cameras.

A second reason to distinguish between the SFR and MTF is because there are several established methods for MTF measurement. The MTF has long been used to describe image signal transfer in, e.g., optical and photographic systems.[5] Several measurement methods have been developed, based on edges features, periodic signals, random noise, and other signals. Each of these methods may, in theory, yield the same results. Practical aspects of digital imaging technology, including image sampling, signal quantization and image processing, however, result in differences between results from various methods. Details of each method and sources of measurement variation are beyond this treatment, but each method can be said to provide an *estimate* of the MTF. We use this term in the same way that the common *sample mean* is used to estimate the *mean value* (parameter) of a population. That is, the sample mean approaches the mean value for a stationary stochastic process when sufficient data are gathered. When viewed in this (statistical) way, we concluded that several measurement methods provide useful SFR evaluation, but none provides *the* MTF.

The above situation is a fairly common reason for the adoption of international standards that specify test methods, definition of terms and analysis procedures in detail. Such was the case when ISO 12233 specified a particular method for evaluation for digital camera resolution based on SFR analysis of a slanted-edge feature. Current work on a revision of the standards, however, makes it likely that additional methods for camera resolution evaluation will be included. Since these will be applied to cell phone cameras, we include a brief description of one method.

### 2.1 Sinewave SFR

Unless stated otherwise, we view standards-based efforts for image quality evaluation of camera phone as aimed at the system or product evaluation. Since image-processing steps applied before the digital image are displayed or downloaded are part of the product, these will influence the delivered image quality and the characteristics of image features used in testing. Consider the case of image sharpening operations that are used in most digital cameras. For the most common types of image sharpening, such as simple convolution and unsharp masking with fixed parameters, we would expect the edge- and sinewave-SFR results to be similar. This may not be the case for sharpening operations whose characteristics vary on or near edge features in the image. Here a measured SFR based on a slanted-edge can yield different results that a corresponding SFR based on other image features. Another example of adaptive image processing occurs as part of image noise reduction methods, which may adapt to local features such as flat area and edges, in the detected digital image.

Wueller[6] introduces an SFR method based on a polar sinewave image features (Siemens star) that is likely to be included in the next revision of the ISO 12233 standard. While claims are made that this method results in a result closer to 'the MTF',[*] as discussed above, it results in a different SFR (S-SFR), by reducing the influence of edge-adaptive sharpening and noise-cleaning operations. As with the previous edge-SFR (E-SFR) method, the adoption of this S-SFR technique will be helped by the availability of simple, reliable analysis software.

### 2.2 Resolution Targets - Low Contrast and OECF Feature Combination

Previous target designs had several resolution features that, while visually and instinctively appealing, offered little to enable automated and robust camera evaluation. The predominance of high contrast features, lack of *in situ* neutral gray patches, absence of machine-vision registration features, and unnecessary complexity were, in retrospect, seen as design flaws. Such critiques are welcome though, and moderation is likely to prevail in the second edition that makes the adoption for cell phone camera usage easier.

Figure 3 is an illustration of the proposed target design for the slanted-edge SFR of the second revision of ISO 12233. The low contrast edge features are perhaps the single greatest improvement. High contrast edge features in the original target often delivered clipped image files resulting in inaccurate and ill-behaved SFR measurements. Even when the image signals were not clipped, correction for the Opto-Electronic Conversion Function (OECF) non-linearity was sometimes required.[7] Without neutral patches for OECF characterization, these corrections were difficult or often impossible to reliably accomplish because a separate OECF target exposure was required. Auto-exposure camera operations can often not be disabled, especially in cell phone cameras. In this case the separate exposure for OECF can result in a variation in the (input-referred) mapping to an effective exposure image signal. An OECF and clipping resistant-SFR methodology was in order. Low contrast edge features allow this and their utility was demonstrated in work by Burns and supported through experiences with scanner resolution protocols of ISO 16067-1

The lower contrast features with moderate average values not only make signal clipping less likely but allow one to make a piecewise linear assumption of the OECF response over the edge transition range, thus avoiding the need for an OECF correction. As insurance against this assumption, OECF enablement is still built in to the target to avoid OECF variability due to separate frame captures and allows more efficient testing by eliminating the need for a separate OECF capture when required. Moderated edge contrast values are also more consistent with natural scene features by which sharpness of delivered image files are judged.

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[*] Meaning the SFR based on the characteristics of camera lens and detector and less influenced by adaptive image processing

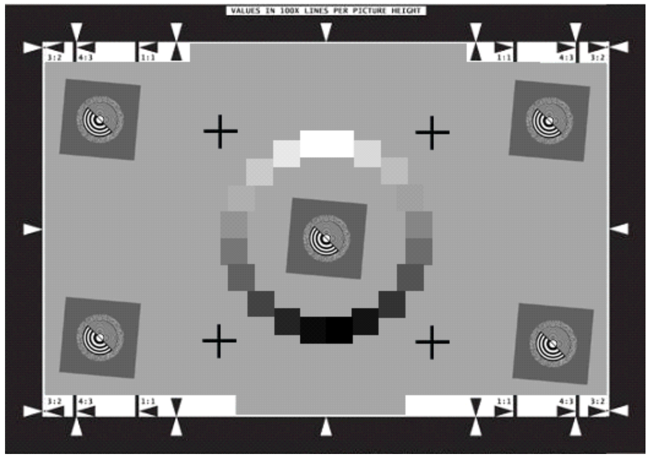



*Figure 3: Proposed test target design for revised ISO 12233 standard with duplicate slanted-edge features*

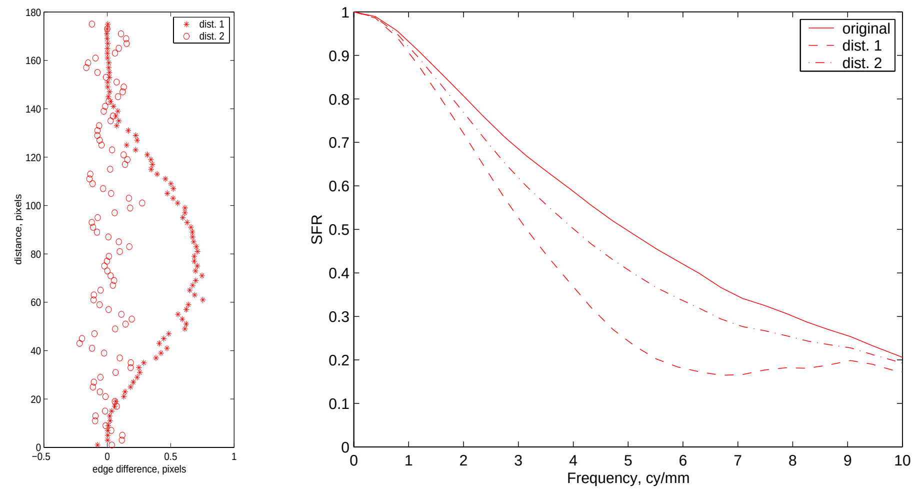
### 2.3 Resolution Targets -Field of View Feature Distribution

Limitations on the space available for the optics in cell phone cameras result in performance concessions. These compromises typically manifest themselves with decreasing average signal (Fig. 1) and SFR performance at off-axis field positions. Using duplicate slanted-edge features in the new test target design, shown in Fig. 3, helps in the evaluation of such intra-image variation. These features enable monitoring of location-dependent SFR performance for better image quality management, especially for cell phones. The uncluttered design is intended to provide ample space for adding customized features or annotations at the user's discretion.

Another reason to use methods based on small test features, such as edges, is that many techniques rely on locally stable imaging characteristics to perform the analysis. As an example, we considered the case of spatial distortion as a source of bias-error in slanted-edge analysis. [4] In this case the method requires the use of a straight edge image feature, however, spatial distortion during image capture can result in a curved feature in the digital image. This introduces a bias error in to the resulting SFR. Figure 4 from Ref. 4 indicates the reduction in SFR due to two types of spatial distortion. Although edge distortion is a source of bias error for the SFR, the slanted-edge analysis lends itself to simple diagnosis of the problem. Just as the intermediate finding of the edge location has been used to detect color misregistration,[8] residual errors for this fit can be used to detect and measure edge distortion.

### 2.4 Field-Dependent SFR

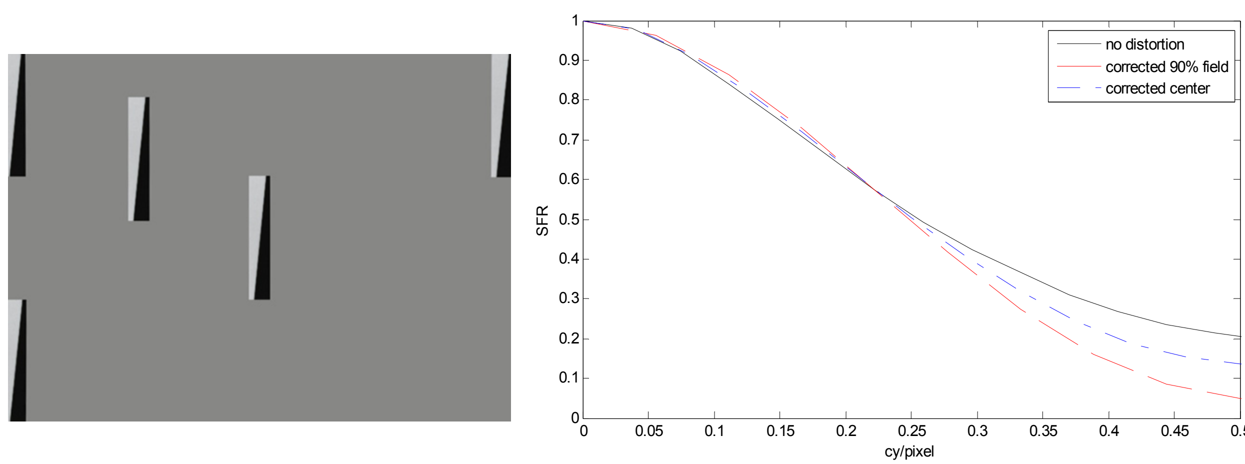
The above is an example of image distortion introducing a bias error into the measured SFR. As described above for optical falloff, image processing aimed at compensating for field-dependent variation, can result in the introduction of other (field-dependent) characteristics. In other cases, this shading correction can improve the SFR estimation by reducing noise in the intermediate estimate of the Line-Spread function.[9] A similar situation can occur when a digital image is corrected for barrel or pincushion distortion. Simply put, this form of optical distortion results in a non-uniform sampling of the correctly projected scene in the digital image. Alternatively, we can think of the camera lens as having a variable optical magnification (object-to-image) at the sensor. The solution is to resample the image array in a way that compensates for the non-uniform sampling. Image non-integer resampling, however, requires interpolation and therefore loss of spatial information.




*(a)* *(b)*

*Figure 4: Example of the influence of optical distortion of camera edge-SFR measurements, from ref. 4. (a) Edge displacement observed because of barrel lens (1) and (2) ripple type distortion. (b) Measured SFR for undistorted edge. Sampling is at 400 ppi.*

To simulate this effect, a scanned edge feature was placed in a larger digital image array at the center and corners, as shown in Fig. 5(a). Barrel distortion was introduced in software, with 5% effective optical distortion at the corners. This distorted image array was then corrected using the same software, so as to invert the first operation. Since both the original edge and the corrected edges where straight, the primarily differences are due to the image resampling which used bilinear interpolation. Note that the degree of loss in image detail, as indicated by a lower SFR in Fig. 5(b), is greater at the corner, as expected based on a larger effective interpolation ratio.




*(a)* *(b)*

*Figure 5: SFR results for a digital image before and after the barrel distortion correction (a) test image, (b) SFR results*

### 2.5 Software

The first version of ISO 12233 listed the source code for the SFR analysis, which also was the basis for plugin-software for Adobe PhotoShop. A standalone Windows program was also generated from this source code. While useful as a demonstration, these had several limitations. The currently available Matlab code[10] is not based on the original source code and, while following the intent of the standard, differs in several ways. The original software did not compute the

SFR for all color-records of a color image. This is now done, as is the calculation of color misregistration described in ref. 8. In addition, a two-pass estimation of the edge slope is now performed. This makes the analysis more resilient to varying location of the edge within the selected region of interest. As part of the analysis intermediate results are tested so that non-fatal warnings can be reported. For example, data clipping, low-contrast edges and missing data at the binning step are all reported. The current Matlab version tends to be more resilient to image noise.

## 3. EXPANDED METROLOGY

Below are examples of how the existing resolution standard can be extended or applied, as is, to image performance issues that tend to be associated more with cell phone cameras than their more mature cousin, the digital still camera.

### 3.1 Flare

One of the optical quality compromises imposed by space and cost constraints of cell phones cameras is increased flare. For capture, the conventional wisdom is that flare can be treated as a global or zero spatial frequency metric of contrast reduction that limits dynamic range. Targets for measuring flare are often characterized by a low luminance neutral patch in a much larger high luminance neutral background. The luminance of the dark patch in the bright surround is compared to the same dark patch in a dark surround. The difference in measured dark patch luminance relative to the bright surround is taken as a measure of flare. A problem with this procedure is that the answers are dependent on not only the dark patch size, but also the region-of-interest (ROI) used to measure the patch.

This spatial reliance of contrast differences or modulation supports the notion that, for image capture, flare can be characterized in a more fundamental way by an SFR measurement. Such an approach has been demonstrated [11] using ISO slanted edge protocols but with extended ROIs for extracting low frequency spatial frequency signatures for flare. A theoretically satisfying outcome of the work showed that the results were independent of feature contrast. An example of how flare manifests itself at low frequencies of an SFR is illustrated in Fig. 6. Edge targets are especially suited to flare measurement because their spatial extent can be expanded, thus enabling very low frequency spatial measurement.

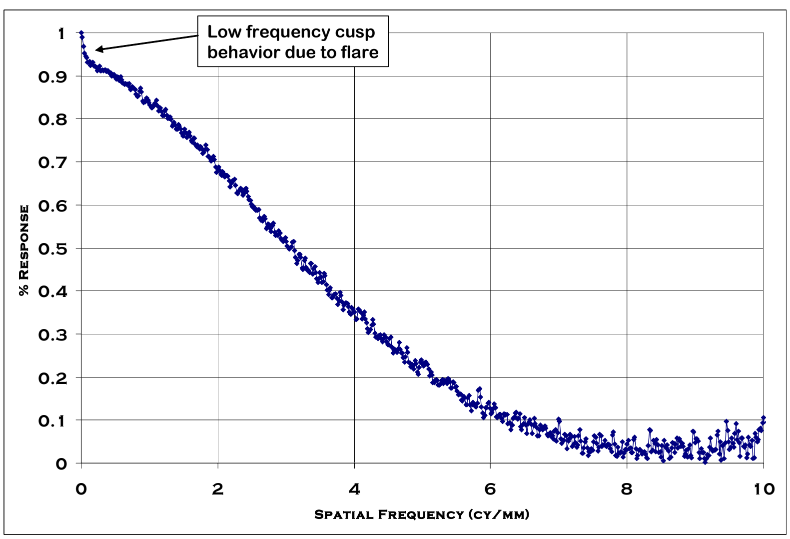



*Figure 6: SFR response with flare behavior shape*

### 3.2 Over-sharpening

To compensate for poor intrinsic SFR response, digital image sharpening operators are almost always used to enhance the image quality of the delivered file. The amount of sharpening should be chosen carefully though, or the results can be garish, cartoon-like images with heavy edge ringing that make images appear unnatural. Such over-sharpening behavior can be easily monitored through SFR measurement and is identified by SFR values above 1.0, especially in the low to mid spatial frequencies. Subjective studies[12] have been performed that provide insight on SFR bounds in order to maintain natural looking delivered images. Keelan[13] provides a framework for interpreting image quality loss due to oversharpening in the context of other quality attributes.

### 3.3 Image Stabilization

The difference between technology capability and actual performance can be significant in cameras without image stabilization features. While able to yield high quality images under optimal conditions, many designs are not resilient enough to provide the same under realistic field usage. Camera motion due to mechanics (size, shutter and lens placement), environment, and user expertise are all factors that introduce image degradation by way of motion blur into the delivered image file. These items can be especially influential for cell phone cameras and small DSCs and is a good reason why image stabilization is often considered for such devices. Regardless of the nature of the blur, the net effect on sharpness or resolution can be measured with existing methods of ISO 12233 by way of SFR. A missing item is a guideline for consistently and accurately reproducing realistic camera motion during testing. Wueller[6, 14] has already demonstrated a programmable device to simulate such motion. Once in place the existing resolution protocols can be easily applied to image stabilization testing.

### 3.4 Interpretation - Summary Metrics and Results Presentation

The good news about using SFR as a measurement tool is its potential as a source of rich spatial information. However, when presented with an SFR curve (whether from edges or sinewaves), it can be somewhat intimidating to understand, especially when the shapes are not classical low-pass functions. This is likely to be the reason for some practitioners to abandon it in favor of less reliable, but easily interpreted resolution methods involving repetitive high contrast bar features. So if SFR were used for determining resolution for cell phone cameras, it would be wise to offer simple rules or distillation methods to arrive at simpler resolution metrics. For instance, the frequency associated with the 10% SFR response point can generally be interpreted as a summary resolution value consistent with the Rayleigh criteria in the optical sciences. Such a number could be a good indicator for text or barcode imaging tasks. Multiple limiting resolution values for different directions can also be combined in a simple efficiency metric that enables users to more easily judge Megapixel claims.

Single valued acutance values can also be easily calculated from SFR curves to arrive at a sharpness measure, however, most previous studies, [15-17] addressed camera lenses and printed images with little or no digital image processing. The application and verification of these single-channel distortion metrics[18] rely on the weighting of visual contrast sensitivity function. Applying these methods to cell phone camera image quality calls for a detailed understanding of the image path, influence of over-sharpening, device use and viewing conditions. For electronic image display, this is particularly important, since rarely if ever is a consumer viewing a full-resolution digital image. A displayed image array is effectively subsampled even for current cell phone LCD displays. While digital image simulation can provide insight into the introduction of artifacts and loss of image detail, caution should be used when using simple continuous-tone metrics to predict image quality for this application.

## 4. CONCLUSIONS

While it is likely that a revised version of the ISO 12233 standard will be applied to cell phone camera image resolution, testing will need to be specified for various image field and operating conditions. Measurement of camera performance will include the influence of several image-processing steps, more common than in digital still cameras. The evaluation methods will address product performance, including these operations, rather than subsystem design. However, the proposed alternative methods, e.g., based on analysis of sinewaves and lines, may provide additional insight about the influence of adaptive image processing on measured results.

Another development to be considered is the introduction of summary measures based on SFR results, such as 10% limiting resolution. While these, and other frequency-weighted measures, need to be interpreted in the context of image viewing, they can simplify the presentation of characteristics that vary with imaging parameters and signal processing, etc. There are no suggestions in the current standards on how to do this, but a simple plot of limiting resolution vs. field position, or zoom position may be adopted.

## ACKNOWLEDGEMENTS

It is a pleasure to acknowledge helpful exchanges with the fellow members of Cell Phone Image Quality (CPIQ) initiative organized Jim Peyton (I3A), and chaired by Ming Gao (HP).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