Resolution for Color photography

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ABSTRACT

Although it is well known that luminance resolution is most important, the ability to accurately render colored details, color textures, and colored fabrics cannot be overlooked. This includes the ability to accurately render single-pixel color details as well as avoiding color aliasing. All consumer digital cameras on the market today record in color and the scenes people are photographing are usually color. Yet almost all resolution measurements made on color cameras are done using a black and white target. In this paper we present several methods for measuring and quantifying color resolution. The first method, detailed in a previous publication, uses a slanted-edge target of two colored surfaces in place of the standard black and white edge pattern. The second method employs the standard black and white targets recommended in the ISO standard, but records these onto the camera through colored filters thus giving modulation between black and one particular color component; red, green, and blue color separation filters are used in this study. The third method, conducted at Stiftung Warentest, an independent consumer organization of Germany, uses a white-light interferometer to generate fringe pattern targets of varying color and spatial frequency.

Note: the abstract for this paper was originally submitted by one of us (PH), but since that time we decided to combine the work at Foveon with the recent work using interferometry at Stiftung Warentest since both research is on color resolution. Section 3 of this paper reports on research done at Stiftung Warentest which is an independent testing organization that compares everything from hard disk recorders to olive oils. The institute remains autonomous by not working directly with any manufacturers and not accepting any selected samples or prototypes and not publishing any advertisements.

Keywords: color, photography, resolution, MTF, measurement, ISO 12233, Foveon X3, white-light interferometry

1. INTRODUCTION

A previous paper made a comparison of: Spatial Frequency Response of Color Image Sensors: Bayer Color Filters and Foveon X3[1]. In this comparison we used the ISO 12233 standard[2] slanted edge technique in both its normal recommended configuration and then also using a colored slanted edge rather than the standard black and white target. As part of the five-yearly review process of ISO 12233 we have been working on the committee to add some recommendations for making resolution measurements in color in addition to the standard black and white methods. When we reported the slanted edge color target results at EI 2004[1] and at the ISO-TC42 committee in Stockholm in the spring of 2004 there was general agreement that at least some guidelines to measuring resolution of colored scenes should be added as part of the revision process.

At the Stockholm ISO meeting we showed a colored Siemens star target that would allow for easy color resolution measurements with Wueller's method[3] using only slightly modified software. The difficulty we would face in the manufacture of calibrated color resolution targets either in the slanted edge form or the Siemens star target was pointed out at this meeting. To address this concern and to make the implementation of color resolution measurement even easier and more consistent with the current standard, I (PH) proposed (at the Orlando meeting, Jan '05) to instead use colored filters over the camera lens (or the illumination) and keep the existing targets (both the current ISO target and the new Siemens star target) in black and white. This has the advantage that all of the targets and analysis methods in the standard could be repeated to show how well the camera detects modulation of red, green, and blue components of a scene. The use of standard color separation filters (such as Kodak Wratten filters, or the filters described in other photographic standards) was suggested at the meeting. This paper presents a new set of comparisons of the described Siemens Star Color Filter method. The comparison looks at four camera models with two different sensor technologies. The Siemens Star not only shows interesting results between the different color components, but also shows how different color components have variable resolution as a function of angle.

The last section of the paper presents another new method conducted by one of us (MB) that shows some interesting results concerning the dependence of color saturation as a function of spatial frequency. In this method a white-light interferometer is used to produce targets that consists of fringes of a specific mean spatial frequency, but where the exact spatial frequency is dependant on the wavelength of the light. This gives a unique target that can be used to see if the camera under test can faithfully reproduce the wavelength dependent fringes over a range of mean spatial frequencies.

2. COLOR SIEMENS STAR METHOD

After having heard the other proposed changes to the standard and one particular complaint about our color slanted edge target, we set out to find an alternative method of adding color to the resolution standard. The most interesting new method of measuring resolution was presented by Dietmar Wueller in the form of a sine-wave Siemens Star target and accompanying analysis software. [In the current working draft of ISO 12233 this new sine-wave spatial frequency response is referred to as "S-SFR" and the edge-based spatial frequency response is now called "E-SFR".] As I believe will be discussed in his paper in this same session, Wueller's method is less susceptible to demosaicing and sharpening algorithms that concentrate on high contrast edges (at the expense of real resolution that also performs well on textures and other lower contrast scene details). Also, the S-SFR method gives resolution measurements at multiple angles which are particularly important when considering different sensor technologies. By simply making the measurements using the Siemens Star through color separation filters we can obtain color S-SFR measurements for all orientations. This method is easily implemented and controlled and is an easy way to isolate a camera's ability to render modulation of patterns formed by colored objects. By simple specification of the appropriate color separation filters, a method is suggested that avoids the problems and variation involved in fabricating a colored resolution target.

Figure 1 shown the basic set-up for photographing resolution targets as described in ISO 12233. In our color Siemens star method we added colored filters (one at a time) between the camera lens and the target (figure 2) which resulted in resolution measurements for red, green, and blue components independently – as if the target had been made with these color primaries.

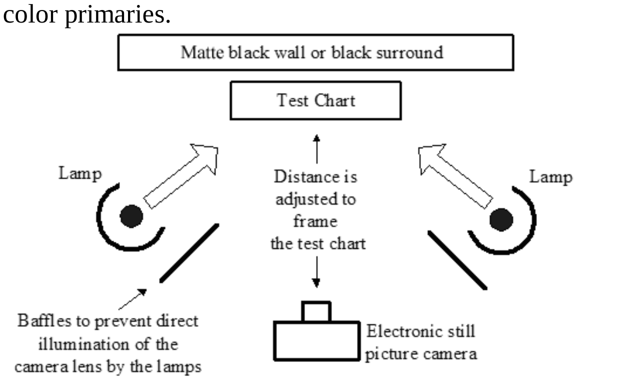

Figure 1: Setup for resolution target measurement as specified in ISO 12233.

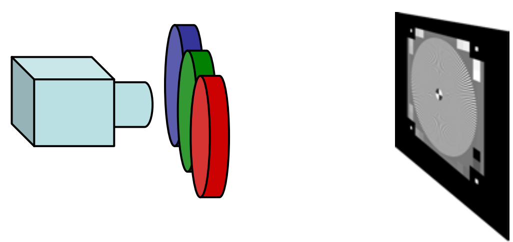

Figure 2: Blue, Green or Red filters are added between the camera lens and the resolution target to achieve color resolution measurements..

2.1 Choice of color filters

One set of color filters proposed is the "Status T" filters specified in the ISO density measurement standard[4]. Kodak Wratten filter sets could also be used for this application such as numbers 29 (red), 61 (green), and 47B (blue) or the less aggressive color separation set numbers 25 (red) , 58 (green), and 47 (blue). Although these filters provide a better analysis of a camera's ability to resolve colored details, other filters could be used either to avoid an overly sensitive interaction with a particular camera's internal filters or as an additional comparison aimed at increasing the range of colors considered. The color filters used in the measurements should be reported with the results. Because these filters are chosen to separate the red, green, and blue components employed in most camera implementations the Nyquist frequencies of the color components can be estimated depending on the results and the particular sensor configuration.

2.2 Camera Settings

In these measurements it is important to make sure that the camera's settings are consistent. We recommend that the camera be adjusted as described in section 4 of ISO 12233 and the illumination used as described in section 4.1.

The focus setting can be adjusted either for each filter or set once without the filter and then not changed as the filters are put into the optical path. In the first case the results will show the differences between sensors being tested and the second case will be more dependent on the optical properties of the imaging lens. Both cases relate to the camera's use since one cannot always determine the spectral content of the subject matter being used to determine the focus of the system. In either case the focus position can be set by either the auto-focusing system or by running a focus sweep and analyzing the image data to determine the optimal focus position.

White balance should be either manually set to the illumination conditions (without the colored filter) or set to the test chart before the filter is added to the optical path (if a pre-shutter release position is used in the camera for this function). In order to obtain sufficient signal-to-noise ratio of the test image, the exposure energy and/or camera ISO speed can be adjusted for each filter so long as the camera's aperture does not change and the shutter speed and ISO speed settings are noted as part of the reporting results.

2.3 Color S-SFR results

To test the method we used two SLR cameras and two point-and-shoot cameras. As with the previous study using the edge-based SFR methods, we tested a camera using Foveon's X3 SLR sensor – the Sigma SD10 (2268 x 1512 x 3 = 10.6M photoelements) which we refer to as X3-SLR and a SLR using a color-filter array sensor from a leading SLR manufacture (3072 x 2048 = 6.3 cfa photoelements) which we refer to as CFA-SLR. Both cameras used the same type of lens (Sigma 50mm f/2.8 macro) although the different lens mounts prevented us from using exactly the same lens. (Since this is a paper about resolution methods and not camera comparisons we chose to omit the CFA camera manufacture's name.) In the first tests we focused each image under each filter separately rather than fix the focus position for the full set of exposures. This was done by taking a focus sweep and choosing the sharpest results.

Figures 3 and 4 shows the green (top), red (middle), and blue (bottom) S-SFR results for the X3-SLR camera (left) and the CFA-SLR camera (right). Each S-SFR plot shows four angles of orientation: horizontal, vertical and two 45 degree diagonals. In both cases, as expected, the green plane shows the best resolution at all angles. In the Sigma camera the red record performed similarly to the green record and the blue channel showed some loss of modulation, probably as a result of noise reduction in the camera's image processing. The performance of the fully populated X3 sensor shows little or no difference between the S-SFR curves for different angles.

Another extremely useful reporting scheme can be generated from the Siemens Star measurements: the s-SFR spider diagram showing the modulation level at one particular spatial frequency at different orientations. Figures 5 and 6 (on the color page) show the modulation levels at 450 LP/PH for the X3-SLR and the CFA-SLR cameras respectively. The colored lines correspond to the colored filters used in the measurement along with the black line that shows the luminance plane of the unfiltered exposure. In figure 5 the fully populated X3 sensor array results in less loss of resolution in the red and blue as well as extremely symmetric curves that corresponds to uniform resolving power in each orientation.

Figures 7 and 8 show similar measurements taken from the Polaroid x530 digital camera (based on the Foveon's F19 X3 image sensor with 1420 x 1060 x 3 = 4.5M photoelements) which we call X3-DSC and a color filter array camera (using a 2272 x 1704 = 4.1M cfa photoelement ccd sensor) which we call CFA-DSC. Here the difference in how the two types of camera sensors resolve color information is even more dramatic. Although the luminance resolution of the CFA-DSC camera in figure 8 is high it is very dependent on orientation and there is a large drop in modulation under the colored filters. This may be partly due to a more aggressive optical low-pass filter (also called a blur-filter or anti-aliasing filter) or could even be due to the camera having less control of the focus position resulting in courser steps in the focus sweep methods.

We repeated the SLR tests but focused each camera on the white-light target and then fixed the focus for the filtered exposures. Although the trends of the results were similar, the difference between the two camera technologies was smaller because of the chromatic effects of the lens coming into play.

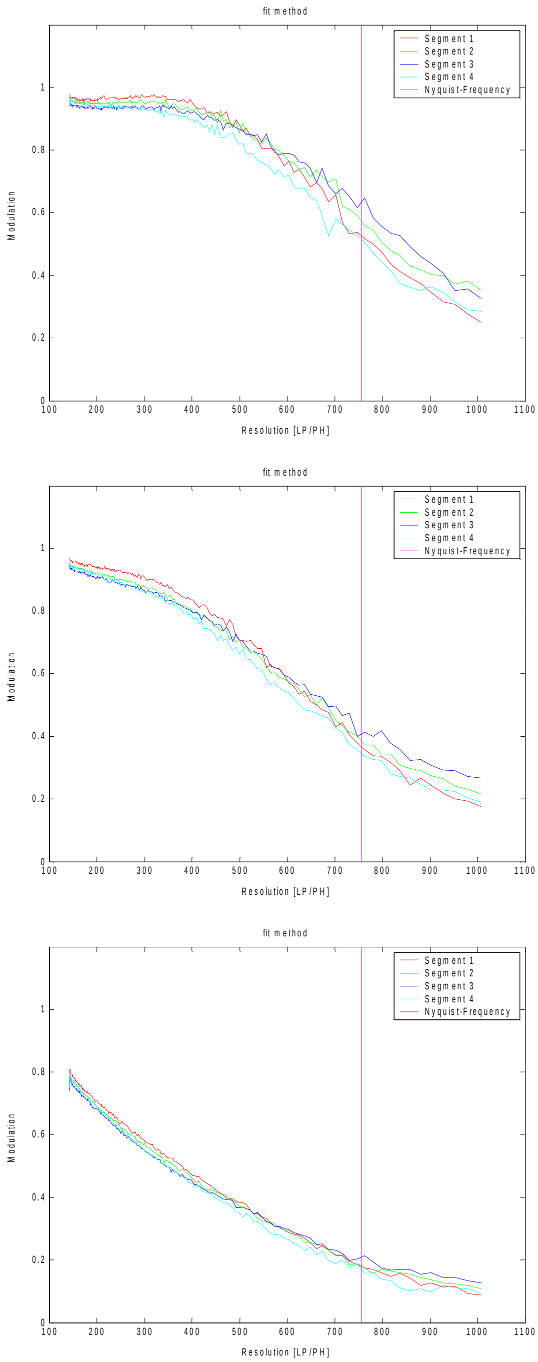

Figure 3: S-SFR curves for Sigma SD10 camera taken through green (top), red (middle) and blue (bottom) colored filters. Curves for four angles of orientation are shown here (horizontal, vertical, and two diagonals).

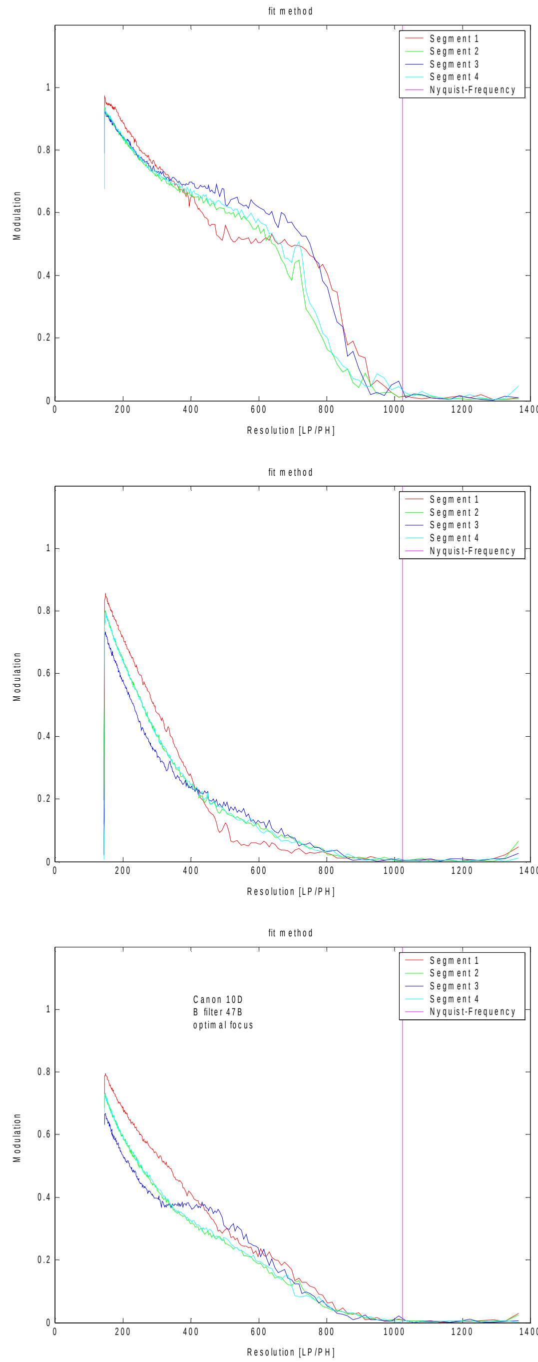

Figure 4: Analogous S-SFR curves for SLR camera using color filter array sensor. The CFA camera does not have as good resolution for red and blue image data and the SFR functions vary considerable for different orientation angles (as expected from the asymmetric Bayer color filter arrangement.

3. INTERFEROMETRY FOR MEASURING COLOR RESOLUTION

In this work, a Michelson interferometer as depicted in figure 9 was used to generate white-light interference patterns of varying spatial frequencies and imaged directly onto the sensor under investigation. Interference patterns have – compared with other fringe structures – the important advantage that their contrast is not determined by the applied imaging system, but depends on coherence of the light source and interferometer parameters[5]. Knowing these parameters, it is possible to determine the properties of the sensor from the images recorded by the camera sensor.

The interferometer consists of the beam splitter, T, and two mirrors, S1 and S2. It is illuminated by a Halogen lamp, Q, through a slit, Sp. The width of the slit determines the extension of the interference area in the vicinity of the sensor under test. The slit width was chosen according to the criterion that even for the smallest generated interference structures the extension of the interference area was in the order of a few hundred microns. The fringe distance, d, is determined by the angle, α, of the two interfering beams and can therefore be adjusted by tilting the interferometer mirrors, S1 or S2. As a result, equidistant parallel fringes appear, gaining colorized boarders going from the centre to periphery of the interferogram area and loosing their contrast at the same time. An example interferogram is shown in figure 10 (color page).

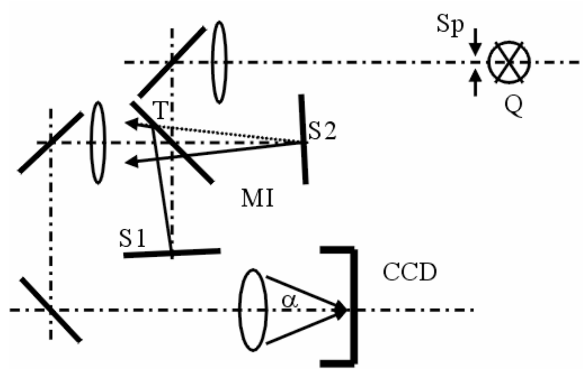

Figure 9 Diagram of the Michelson interferometer

The width of the generated interference fringes depends not only on the tilt angle, α, but also on the centre wavelength λ_0 (centre of gravity of applied spectral band) following the equation:

$$d \sim \lambda_0/\sin\alpha$$

The spectral bandwidth of the light source determines how fast the fringe contrast decreases going from centre to periphery of the interferogram (monochromatic light generates many, white light only a few interference fringes). The three channels of a color camera use different spectral filters and, consequently, have different centre wavelengths, λ_0. The interferograms for the three RGB channels as well as the luminance calculated from these interferograms are shown in the top of figure 11, whereas the bottom of figure 11 presents the corresponding one-dimensional intensity distributions (see color page).

3.1 Color Structure Fidelity

Figure 12 shows images taken of three interferograms at spatial frequencies of 40 LP/PH, 240 LP/PH, and 400 LP/PH using a high-quality color filter array SLR camera. It is evident that color saturation is changing with spatial frequency and that for small structures (at 400 LP/PH) only grey shades remain in the image. The corresponding one-dimensional intensity distributions are displayed under each interferogram image.

From the achieved interferograms, two different parameters were extracted: standard SFR curves analogous to those produced with the E-SFR or S-SFR methods, and something we call "colored structure fidelity". Because the reproduction of the colored structures is strongly dependent on the spatial frequency, we can extract this color metric from interferograms taken at each spatial frequency.

From the intensity plots of the interferograms it can be seen that the fringe distances (the distance between the fringe peaks) for the three color channels converges and finally becomes identical in the 400 LP/H example (thus giving a completely grayscale image). To express this fact quantitatively, the fringe distances d_{red}, d_{green} and d_{blue} for the three color channels were extracted from the pictures and used to calculate the color structure fidelity parameter, δ_{RGB}, according to:

$$\text{color structure fidelity:} \qquad \delta_{RGB} = \frac{d_{red} - d_{blue}}{d_{green}}$$

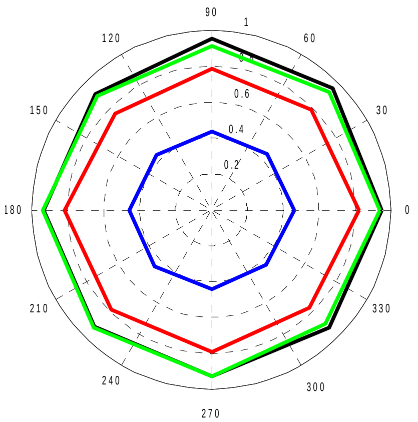

Figure 5: X3-SLR modulation at 450 LP/PH.

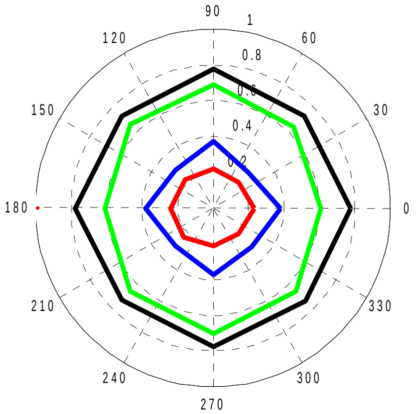

Figure 6: CFA-SLR modulation at 450 LP/PH.

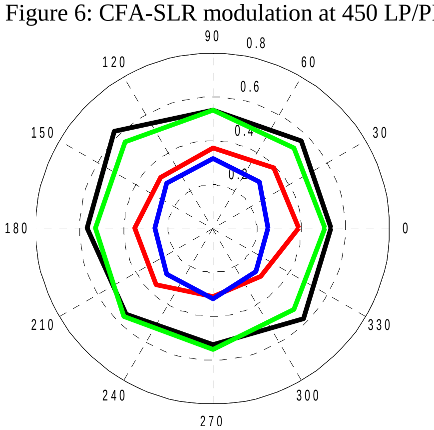

Figure 7: X3-DSC modulation at 450 LP/PH.

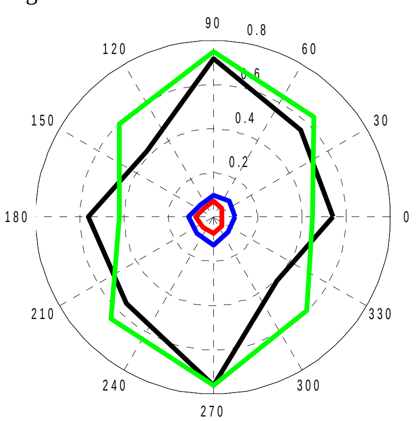

Figure 8: CFA-DSC modulation at 450 LP/PH.


Figure 10: An example white-light interferogram from the Michelson interferometer. The fringe distance varies as a function of wavelength giving a color pattern useful for testing a camera's color resolution.

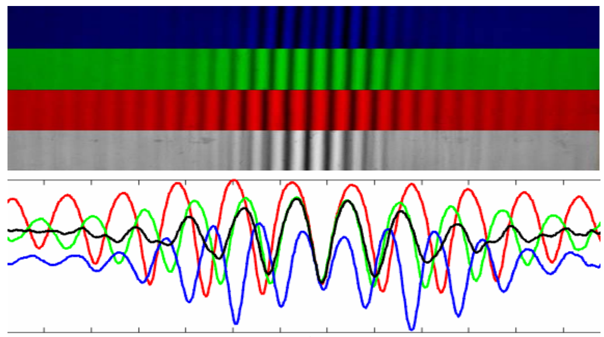
Figure 11: The interferograms for blue, green, and red channels as well as a combined luminance channel. The plot shows how the intensity curves differ.

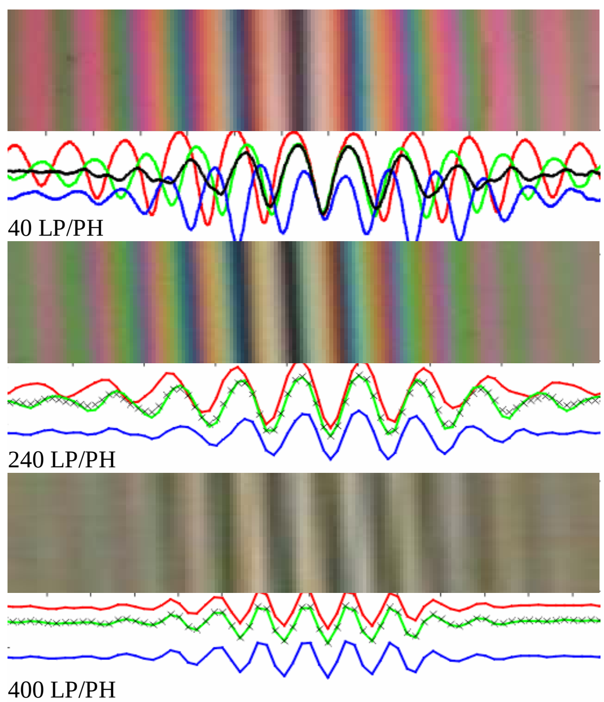

Figure 12: Images of white-light interferograms taken using a color filter array SLR digital camera. As the spatial frequency is increased, the color saturation decreases until all color information is lost. The colored curves that correspond to intensity in the RGB channels become the same.

Assuming centre wavelengths, λ_0, for the color filters of the three channels of λ_{red} = 615 nm, λ_{green} = 550 nm and λ_{blue} = 485 nm, perfect color structure fidelity of the sensors should result in a value of δ_{RGB}= 0.24.
Exemplarily in figure 13 is displayed the dependency of extracted parameter δ_{RGB} on spatial frequency for the CFA-SLR camera body under test that gave the images of figure 12. Most cameras under test showed a similar behavior. The crosses are measured values and the curve is a corresponding fit.

In terms of this color structure fidelity metric, The Sigma SD10 camera differed from other cameras tested in that there was very little drop in the metric as the spatial frequency is increased to above 600 LP/PH (figure 14). Indeed the characteristic desideration of the colored fringes did not occur under the conditions of the test.

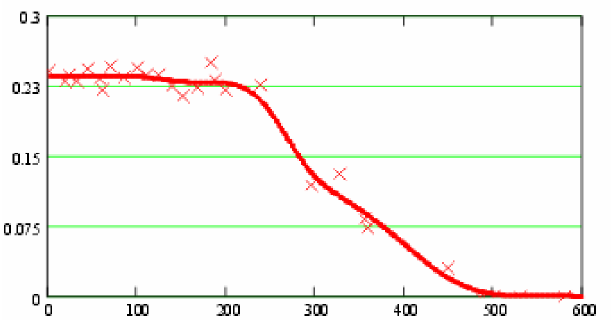

Figure 13: δ_{RGB} as function of spatial frequency (LP/H) for the CFA-SLR. This loss of color at spatial frequencies above 300 LP/PH was typical of all digital cameras tested.

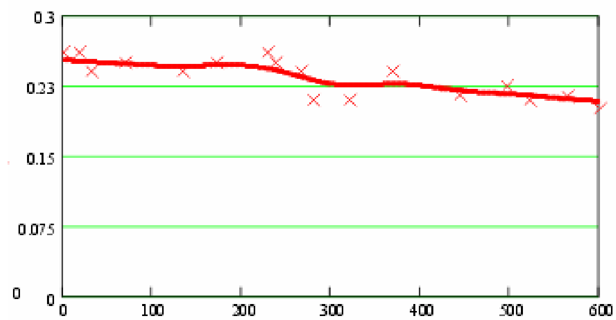

Figure 14: δ_{RGB} as function of spatial frequency (LP/H) for the X3-SLR. The lack fall-off of color saturation with spatial frequency differs from other cameras tested.

4. CONCLUSIONS

In this paper we presented two new methods to measure and report resolution as measured from colored scenes. Since all digital cameras are used to photograph colored scenes and most digital cameras record color information it seems negligent to conduct resolution measurements with only black and white targets. This study shows that fully sampled detector arrays perform better in color resolution tests as compared to color filter array cameras where the incident light is sub-sampled in order to achieve the color records.

The use of color filters in conjunction with the Siemens Star method to measure resolution of a color signal was described and several examples were given. The examples showed the affect the color filter array has on color resolution as well as its impact on SFR measurements taken at different orientations.

An experiment using a white-light interferometer to produce targets of varying spatial frequency was described for measuring resolution in digital cameras. The new metric, *colored structure fidelity*, was introduced that corresponds to contrast between the colored fringe structures in the interferograms (constant with color saturation). The relationship of this metric as a function of spatial frequency showed how most digital cameras tested with this method loose color saturation at frequencies above 250 LP/PH and become completely monochromatic above 500 LP/PH. On the other hand, the Sigma SD10 camera, using a fully populated X3 sensor, showed very little desaturation as the spatial frequency increases. This result is consistent with the Siemens Star color filter measurements that showed far less modulation fall-off in the red and blue components in the fully populated sensor than with those using a color filter mosaic array.

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