# Analysis of Irregular Sampling for Color Interpolation

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## Abstract

*Selection of a subset of possible color values is a common step in color imaging. Color look-up tables or profiles are often constructed using uniform or regular sampling schemes for a given color space. Color order systems are often constructed based on systematic geometric schemes, such as the radial configuration of the Munsell Book of Color[1] or the cubo-octahedral configuration of the Optical Society of America's Uniform Color Scales[2]. This paper explores the use of an irregular sampling scheme for the creation of a custom color chart and analyzes the performance of the chart when applied to a mobile color sensing application. Because it allows the set of colors to be expanded in increments of one color, this scalable sampling scheme has a wide range of applications, including device calibration, and for computing unique color fan decks and spot color charts.*

## Introduction

Many applications in color imaging make use of a particular sampling scheme. These sampling schemes attempt to subsample or reduce the total number of colors to be processed, measured or visualized. For example, color sampling is central to color interpolation, selection of nodes for color order systems, and the design of color charts and targets. This paper focuses on the application of an efficient and scalable irregular sampling scheme for all of the above applications.

Device calibration and characterization often rely on color sampling schemes that are either printed (in the case of printers), displayed (in the case of displays) or captured (in the case of scanners or digital cameras) in order to compute look-up tables or profiles used in managing color. Common printer CMYK targets include the 928 patch extended IT8.7/3 target[2], the 1485 patch ECI2002 target[3], and the 1617 patch IT8.7/4 target[4]. All of these targets sample the colorant space somewhat uniformly. Monitor profiling charts typically include a regular sampling in RGB space along with additional patches along the primary and neutral axes. For digital camera calibration, the targets of choice include the 24 patch X-Rite (formerly GretagMacbeth) ColorChecker Classic chart, and the no longer available but still widely used 237 patch, 177 color GretagMacbeth ColorChecker DC chart.

The common theme among all of these color targets is that they are either painstakingly manually selected, or they rely on regular samplings in device space. This presents the problem that if the size of the color target has to be altered in order to accommodate a special need or application format, the entire color sampling has to be entirely regenerated manually, or the size of the color sampling has to increase or decrease by some factor corresponding to the size and dimensionality of the sampling scheme. In other words, the task of adding or removing one color to an existing set is non-trivial.

Random sampling is occasionally referred to or used, such as in the case of selecting test colors during model validation. However a random or pseudo-random selection of colors will by definition tend to provide a sampling with densities that are higher or lower in different regions. The apparent clusters are a function of the algorithms and their parameters.

## Void-Filling Algorithm

To overcome this limitation, a void-filling irregular sampling scheme is employed that iteratively adds colors to a set based on a larger set of candidate colors. The process starts with an optional set of starting colors, then adds new points one at a time that have the largest color difference (furthest away in CIELAB space) from its closest color already in the set. As new points are added to the set, they tend to fill the largest void in the color gamut; hence we call this algorithm "void-filling."

The general idea of using a greedy algorithm for selecting maximally different colors is not new. In 1965, physicist Kenneth Kelly described a color coding system consisting of 22 colors which provide maximum contrast for those with color deficient vision[5]. More recently, Cheung and Westland employed a similar algorithm, which they called MAXMINC, in the selection of color samples used for global camera characterization[6]. This paper differs from prior research in that it focuses on dynamic tetrahedral interpolation for a region of interest using a printed color chart and a mobile camera phone or tablet. In addition, our results consider the performance over a wider scale of sampling points ranging from dozens to thousands. We have prototyped our solution for the creation of printed general purpose charts, spot color charts, and custom fan decks.

Figure one shows a graphical comparison of two regular sampling schemes, uniform grid and radial, and two irregular sampling schemes, random and void-filling, for two different sampling densities. The figure shows selected color as white nodes with neighbors connected via black edges. Each sub-region shows a two-dimensional slice through a given color spaces but the sampling is applied here in three dimensions. Note that for the regular sampling schemes, to increase sampling rates while still keeping the previous utilized nodes requires that the sampling rate be increased multiplicatively. Likewise for the random sampling scheme there is no systematic manner to decrease or increase sampling rates locally. In comparison, the void filling sampling scheme can include all previously selected color samples even if the new number of points is not divisible by the previous number of points. Furthermore, to fully occupy the void-filling sampling the colors were initialized with the minimum and maximum values at the corners and three additional interior points. The void filling algorithm starts with these optional initial values and then adds sampling points to the largest void in the current sampling until the desired number of points is reached.

 

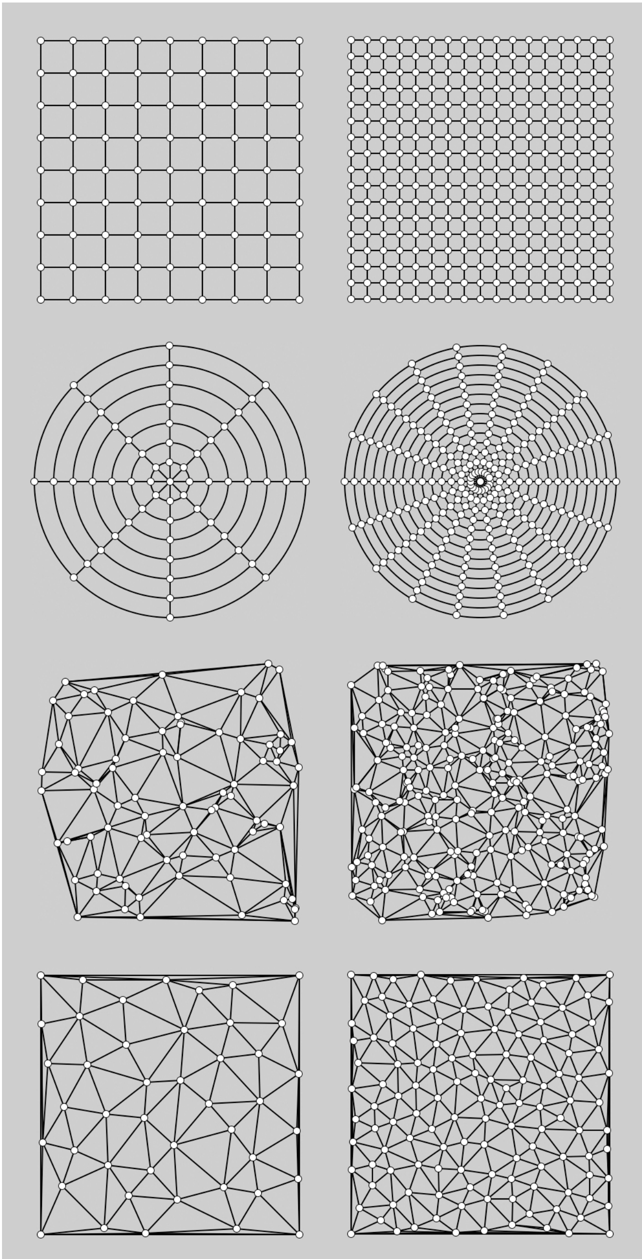

***Figure 1.*** *Visualization of four different sampling schemes. From top to bottom: regular grid sampling, regular radial sampling, random sampling and void-filling irregular sampling. Right column depicts a higher sampling rate than the left column.*

## Experimental Setup

The performance of irregular sampling was tested in the context of a mobile color sensing application. A printed color chart with known colorimetric data is inserted into the scene and is used to color correct a particular region of interest. The scene is captured using a digital camera, and a dynamic tetrahedral tessellation in RGB space is performed on the color patches in the printed target. Next, the captured post-rendered RGB value of the region of interest is compared with the tessellation and the enclosing tetrahedron is found. Finally, a tetrahedral interpolation is performed in order to transform the RGB value into device-independent CIELAB space. Note that we are not using the corresponding color values for a pseudo-inverse color correction or other conventional camera color calibration process.

As a test set, we used the GretagMacbeth ColorChecker DC chart. Color charts were printed on an HP Designjet Z3200 12-ink printer using HP Super Heavyweight Plus Matte paper. A typical mobile phone with a 5-megapixel sensor was used to capture the scene under tungsten as well as cool white fluorescent illumination. The void-filling algorithm described above was used to generate a test chart containing 360 color patches from a set of 21-cubed (9261) candidate colors. This irregularly sampled chart was tested along with charts made up of regular RGB samplings of 2- through 7-cubed, producing 8, 27, 64, 125, 216 and 343 patches respectively. Corrected LAB D65 values of the colors in the test set were compared to measurements taken with an X-Rite i1 Pro and differences were computed in terms of $\Delta E_{00}$. As a baseline, the uncorrected captured RGB value of each color in the test set is converted to LAB D65 using the standard conversion from sRGB space.

## Results

As digital cameras tend to produce more accurate colors under natural daylight than under artificial illumination, we chose to focus our tests on more challenging lighting conditions, including tungsten and cool white fluorescent. Figure 2 shows the results under tungsten illumination as a function of number of patches in the target color chart. In this case, the uncorrected colors suffer from the warm cast of the light source, resulting in a median $\Delta E_{00}$ of 17.1. The irregular sampling scheme tracks the regular cube sampling pretty well, driving down the color difference to below 4 at around 64 points. In this case there are two noteworthy results. The first is that for the same number of sample points, there is largely no significant difference between regular and irregular sampling. The second is that unlike the regular grid sampling (red squares), the void filling sampling (solid blue line) allows sampling rates in increments of one color point.

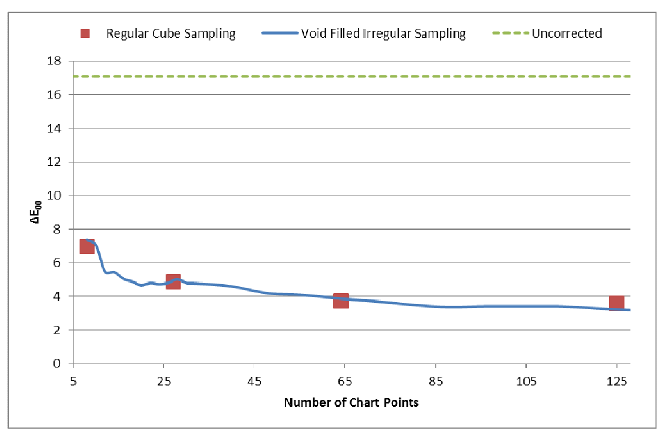


***Figure 2****. Median color accuracy ($\Delta E_{00}$) of test sample using regular RGB cube sampling (red squares), void filled irregular sampling (solid blue line), and uncorrected (dashed green line) under tungsten illumination.*

Figure 3 shows the results under cool white fluorescent illumination, which is another difficult condition for the automatic white balancing algorithms to handle. Here, the uncorrected route gives a median of $\Delta E_{00}$ 21.3. Even with as few as 8 points, both the RGB-cubed and irregularly sampled charts are able to reduce the median color difference to below 11, while increasing the number of points to 64 further reduces it to around 4. For this lighting condition, the void-filling irregular sampling result consistently out-performs the corresponding regular cube sampling at 10 sample points and above. Once again, the regular cube sampling can only achieve a relatively small and discrete number of samples, shown as red cubes, while the void-filling sampling is shown as a blue line.

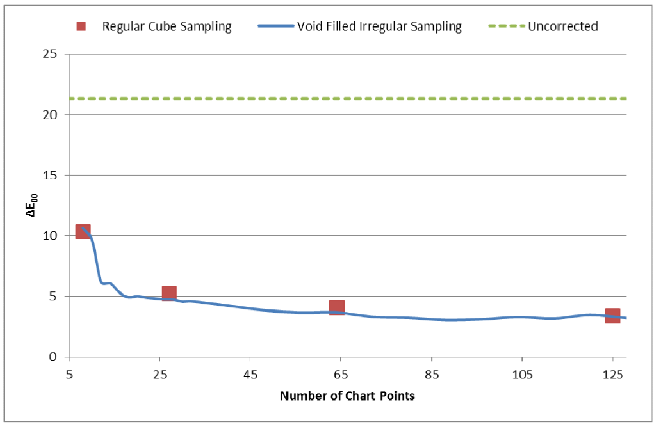


***Figure 3.*** *Median color accuracy ($\Delta E_{00}$) of test sample using regular RGB cube sampling (red squares), void filled irregular sampling (solid blue line), and uncorrected (dashed green line) under cool white fluorescent illumination.*

Tables 1 and 2 show the median, $95^{th}$ percentile and maximum $\Delta E_{00}$ accuracy scores for the same tests. As a reference, the tungsten illuminated uncorrected color samples scored a $95^{th}$ percentile of 23.6 $\Delta E_{00}$ and a maximum of 29.53 $\Delta E_{00}$ while the cool white fluorescent illuminated uncorrected samples scored 29.4 $\Delta E_{00}$ and 34.0 $\Delta E_{00}$ respectively. Testing with four additional mobile devices yields results that are consistent with the above. Void-filling irregular sampling is as good as or in some cases better than regular sampling and provides a sampling scheme that can achieve a user specified number of color patches with a significant improvement, especially for the coarsest sampling rates.

## Scalability

Since the void-filling algorithm allows the set of colors to be expanded in increments of one color, it provides a scalable solution for selecting colors for a wide range of applications. As an experimental case study, a large set of 8961 candidate colors was printed on an HP Indigo 7000 digital press using 7 inks: CMYK plus orange, violet and green (Figure 4). An initial base set of colors was selected consisting of solid primaries, secondaries and several neutral axis points. The void-filling sampling scheme was then applied to generate several different color samplings.

A printed general purpose color chart consisting of 153 targets was produced for use with the mobile color correction system described above (Figure 5). Using a higher throughput device such as the HP Indigo digital press allowed for the production of a longer run of charts. By limiting the set of candidate colors to a subsection of the CIELAB color space, the algorithm was also able to generate a spot color chart containing a higher density of points surrounding a particular target color, with the goal of achieving even high color accuracy because of the denser sampling (Figure 6). As another application, graphic designers often use hardcopy fan decks when selecting colors for their designs. By increasing the sampling size to 1001, the algorithm calculated a dispersed sampling of distinct colors that evenly samples the large Indigo 7-color CMYKOVG gamut. With a little bit of formatting, this sampling of 1001 colors produced the custom fan deck[8] depicted in Figure 7.

**Table 1: Accuracy of color corrected test samples using irregularly sampled chart (left) and regular RGB sampling (right) under natural tungsten illumination, expressed in terms of median, $95^{th}$ percentile and maximum $\Delta E_{00}$.**

| | Void-Filling Irregular Sampling | | | Regular RGB Cube Sampling | | |
|---|---|---|---|---|---|---|
| Samples | Median | 95% | Max | Median | 95% | Max |
| 8 | 7.4 | 30.8 | 38.8 | 7.0 | 27.9 | 35.4 |
| 27 | 4.9 | 13.5 | 25.2 | 4.9 | 13.1 | 17.9 |
| 64 | 3.9 | 9.7 | 13.8 | 3.7 | 11.0 | 16.9 |
| 125 | 3.2 | 9.1 | 14.2 | 3.6 | 9.4 | 14.7 |
| 216 | 3.2 | 9.1 | 16.5 | 2.6 | 9.3 | 16.7 |
| 343 | 2.8 | 8.3 | 12.4 | 2.7 | 8.8 | 14.2 |

**Table 2: Accuracy of color corrected test samples using irregularly sampled chart (left) and regular RGB sampling (right) under cool white fluorescent illumination, expressed in terms of median, $95^{th}$ percentile and maximum $\Delta E_{00}$.**

| | Void-Filling Irregular Sampling | | | Regular RGB Cube Sampling | | |
|---|---|---|---|---|---|---|
| Samples | Median | 95% | Max | Median | 95% | Max |
| 8 | 10.7 | 23.7 | 30.6 | 10.4 | 23.1 | 30.3 |
| 27 | 4.8 | 12.7 | 18.1 | 5.2 | 15.5 | 25.0 |
| 64 | 3.7 | 10.4 | 17.1 | 4.1 | 11.9 | 24.2 |
| 125 | 3.3 | 9.8 | 18.7 | 3.4 | 11.0 | 27.5 |
| 216 | 3.2 | 9.7 | 18.7 | 3.3 | 11.4 | 26.3 |
| 343 | 3.4 | 9.7 | 18.3 | 3.4 | 10.0 | 16.8 |

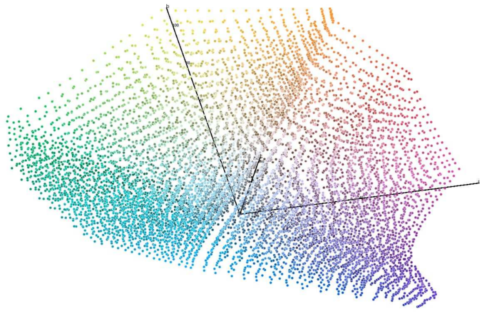

***Figure 4**. Gamut plot of 8961 candidate colors printed on the HP Indigo 7000 digital press using 7-inks: cyan, magenta, yellow, black, orange, violet, green.*

The void-filling irregular sampling provides a single systematic means to select a general color chart that can also be a complete subset of a much larger color sampling for a fan deck. This same scheme can also provide even finer spot color sampling schemes that are also a partial sub-set of the general chart and the fan deck. This complete and partial nesting is possible because each color is added as part of a local optimization and is not constrained by an inflexible global sampling geometry. This flexibility of scale, both in number of samples and in range of sampling, is a significant advantage. Furthermore, the performance of the void-filling sampling in combination with the dynamic tetrahedral interpolation can be contrasted with other published sampling and interpolation results[9-11].

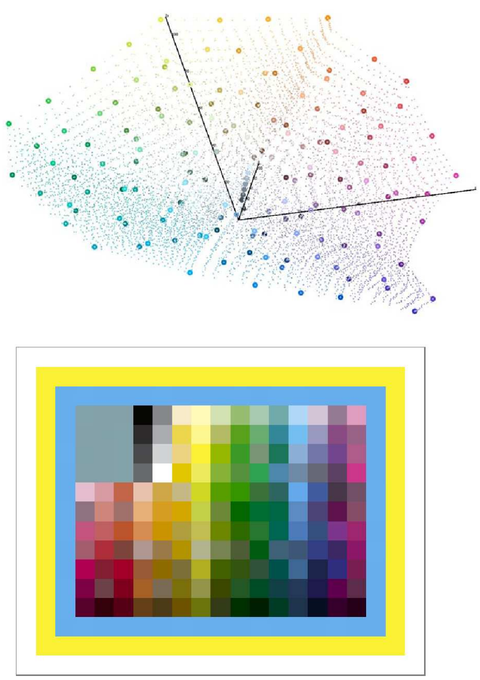

***Figure 5**. Gamut plot showing the selection of 153 irregularly-sampled colors from a set of 8961 candidate colors (above) and the resulting general purpose color chart (below) .*

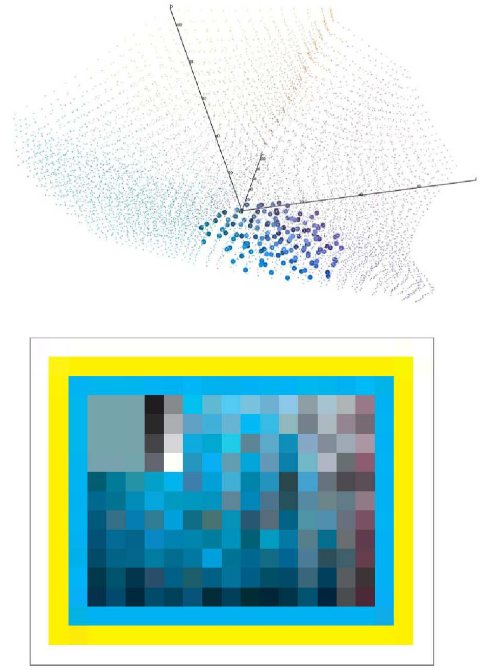

***Figure 6**. Gamut plot showing the selection of 153 irregularly-sampled colors from a subset of 8961 candidate colors (above) and the resulting spot color chart (below).*

***Figure 7**. Gamut plot showing the selection of 1001 irregularly-sampled colors from a set of 8961 candidate colors (above) and the resulting color fan deck (below).*

## Conclusion

In comparison to regular sampling schemes, irregular sampling schemes, such as the void-filling scheme, can be applied in increments of one color sample, allowing for the creation color sampling of any arbitrary size. Experiments using printed color charts for dynamic tetrahedral interpolation show comparable results for the two sampling schemes for equal number of samples. Both schemes were able to reduce the color error in a common mobile camera phone under daylight and halogen illumination. Due to its scalable nature, the irregular sampling scheme has a wide range of applications, including printed general color charts, spot color charts and custom fan decks. With a little creativity, many other applications can be realized.

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## Author Biography

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*Melanie Gottwals joined HP Labs in 1989 after receiving her B.S. in Electrical Engineering from the University of California at Davis. She started her career in storage technologies working on advanced read/write channels, media and heads to increase performance of disk and tape drives. In 2003, her research shifted to networked storage performance and evaluation of the roles of storage caching in SAN environments. In 2005, she joined the Digital Printing and Imaging Lab and began working on color technology. Here she has worked on a low cost colorimeter and height sensor and color correction via mobile phone applications.*