What are the ideal wavelengths for full color holography?

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Abstract. One of the holy grails in display holography is the production of natural color holographic images. Various sets of wavelengths for recording have been suggested, some favoring three wavelengths, some four, and even more. I will argue that the choice of recording wavelengths is completely independent of the holographic process; it was in fact was solved once and for all by scientists working in general lighting in the 1970s. I will suggest an ideal set of wavelengths which will produce color rendition equal to better than conventional photographic processes.

1. Introduction
Color science is an extremely complex subject. It is a subtle combination of many disciplines, including physics, chemistry, physiology and psychology. Under normal circumstances, our perception of colors derives from the spectral power distribution of the illuminating source (normally continuous, e.g. the sun), the spectral reflectivity of the object being viewed, and finally our eye/brain combination. The fundamental problem in color holography is that the illuminating source (2 or more laser sources) is not continuous, but discrete. Hence the only information we have on the spectral reflectivity is at those discrete wavelengths. The problem, then, is which wavelengths we choose to get the best color rendition of the object.

In this paper I shall follow the following reasoning:

• When the loci of the recording wavelengths are plotted in the CIE Color Chromaticity Chart, it is a widely held view that the geometric recording wavelengths must cover as large an area of the diagram as possible; this assumption is incorrect;
• There are good reasons for not covering the largest area referred to above;
• The choice of recording wavelengths has little if anything to do with holography, and has been addressed and solved by researchers working in the area of color and illumination.

(Most of the content contained herein was first published in 1989 by Bazargan [1].)

2. the CIE Color Chromaticity Chart
Many systems have been developed to represent systematically all the colors we perceive. All the systems are three-dimensional, i.e. need three variables in order to define all visible colors. Examples of these variables are RGB, HSB, LUV, etc – see figure 1.
But a three-dimensional model is hard to work with, as it cannot be easily represented on paper. In order to have a convenient 2D model, one of the axes needs to be ignored. The CIE color model does this by ignoring the Lightness scale. The 1931 CIE Color Chromaticity Chart (figure 2) is still the most popular chart for plotting colors, but the 1976 chart (figure 3), which is a geometric transformation of the original chart, and which has a more realistic distribution of colors, is recommended and should be used instead. The saturated colors are represented by points near the periphery of the shape, with the pure spectral colors being represented by the curve on the left and top of the shape. Approximate positions for three wavelengths are shown in figures 2 and 3.

A useful property of the CIE color chart is that it allows the prediction of which colors can be matched by the additive mixture of several other colors. Let us consider the black triangle
in figure 3. The vertices of the triangle represent three pure spectral colors, as for instance generated by a laser. According to the geometric principle of the chart, all colors within the triangle can be perfectly matched by mixing the three spectral colors in the correct proportions.

If we look at publications on color holography since the early days, it is almost always assumed that the choice of laser colors has to be such that the greatest area of the CIE chart is covered, in order that any conceivable color can be reproduced in the hologram. But this is a misconception, as I will show below.

3. Why we don’t need the biggest triangle
The key point that holographers have been missing is that the CIE chart represents all colors that the eye can perceive, not all colors occurring in everyday objects. Let us plot some real object colors onto the chart to get an idea of the area that we need to cover. In figure 4 we have plotted some common everyday colors and a few saturated colors from the Macbeth Color Checker Chart (B, G, Y, R). We can see that they are all clustered in an area away from the periphery of the chart. The irregular triangular shape enclosing these colors is the gamut of all natural and man-made object colors that could be found by Wintringham [2] in 1951. In 1980, Pointer [3] extended the gamut slightly, mainly to include more recent artificial materials. But we are unlikely to come across any colors in everyday life that lie outside Wintringham’s original gamut, and most triangles formed by RGB laser primaries will cover almost the entire gamut of everyday colors.

Figure 4. The 1976 CIE Color Chromaticity Chart gives a better distribution of colors and should be used in place of the original 1931 chart.

4. Reason for not choosing a large triangle
Notwithstanding the above argument, one might be tempted to use a larger polygon or triangle of colors, on the basis that there is no disadvantage. But in fact there are good reasons not to choose wavelengths at the extremes of the spectrum. Figure 5 depicts the Luminous efficiency curve, which shows the sensitivity of the eye to the visible spectrum. It can be seen that for the same power of a laser beam, colors near the centre of the spectrum seem brighter than those
Figure 5. The luminous efficiency curve, showing that the eye is most sensitive to the centre of the visible spectrum, i.e. around 540 nm, and falls off to zero around 400 and 700 nm. So the same power emitted by the laser beam will look less bright towards the extremes of the visible spectrum.

Figure 6. The luminous efficiency curve plotted on the locus of spectral colors of the CIE chart. Colors below ~350 nm and above ~750 nm will be completely invisible to the eye.

Let us now plot this curve onto the periphery of the CIE curve (figure 6). We can see that as the blue and red wavelengths approach the extremes of the visible spectrum. In the limit of trying to obtain the largest polygon or triangle, the red and blue wavelengths will be invisible, or appear to be of very low brightness.

So all else being equal, this is a good reason not to try and cover the entire CIE chart with the recording wavelengths.

5. So which wavelengths should we use?
The conclusion from the above arguments must be that the CIE chart is of little use for choosing wavelengths for color holography.

Let us now look at how we perceive colors in everyday life. Figure 7 shows a simplistic diagram of an observer viewing an object. The colors that we perceive depend essentially on two parameters:
Figure 7. How we see objects depends on the properties of the object, and those of the illuminating source.

- Spectral reflectivity of the object;
- Spectral power distribution (SPD) of the illuminating source.

Figure 8 is a schematic diagram to show how we perceive colors under normal conditions. The light has a spectral power distribution (which, for example, determines whether it is a warm or cool light, etc). Each object has a spectral reflectivity curve which determines how much of each wavelength it reflects. The combination of these two spectral functions create a composite spectral distribution which determines the color the eye perceives. The essential point here is that the SPD of the light is in general continuous, so the object is ‘tested’ at all visible wavelengths.

When recording a color hologram, we are only using a small set of wavelengths (let us say three). For the purposes of discussion we can in fact forget the fact that we are making a hologram. The problem is one of the illumination source. So effectively the SPD of the source is three discrete lines in the spectrum, as illustrated in figure 9. So in contrast with normal conditions whereby the eye receives information about the reflectivity of the object throughout the spectrum, now only three discrete values are received.

So here is the question. Is it possible to choose an illuminating source comprising three wavelengths, such that everyday objects look to the eye the same color as they would under broadband illumination? It would seem an impossible task as the data received by the eye is so small. But there is a key publication which can shed light on the problem. In 1971 William Thornton [4] published his results on a comprehensive examination of the Color Rendering Index (CRI) of white light. He found that there are three areas in the spectrum (around 450, 540, and 610 nm) which seem to have a disproportionate ‘pull’ in the CRI. In fact, his conclusion was that a light comprising solely of these three narrow wavelengths had a higher CRI than any other combination of wavelengths, whether discrete or continuous.

Thornton named these the Prime-color wavelengths. How these wavelengths relate to the absorption dyes in the eye is still debated today, but as far as color holography is concerned, I believe that these ‘magic’ wavelengths are the ideal for holography, and will deliver color rendering as good as any photographic process.

6. Conclusions
The CIE chart is of little use in determining the wavelengths to use in full color holography. The choice of wavelengths is not related to holography at all, but to color science. Thornton’s prime-color wavelengths (around 450, 540, and 610 nm) are the ideal set for holography.
**Figure 8.** Viewing a scene under normal conditions. The spectral power distribution of the illuminating source is continuous, so the reflectivity of the object is tested throughout the entire spectrum.

**Figure 9.** Viewing a scene using discrete light sources, e.g. three laser wavelengths. They eye receives a tiny proportion of the information regarding the reflectivity of the object. Is it possible to find three wavelengths that can emulate a continuous source?

**Figure 10.** Thornton’s ‘prime-color wavelengths’ plotted on the CIE diagram.
[1] Bazargan K 1989 Second International Conference on Holographic Systems, Components and Applications Proc. IEE (Bath, 1989) 49–50
[2] Wintringham W 1951 Proceedings of the IRE 39 1135–1172
[3] Pointer M R 1980 Color Research and Application 5 145–155
[4] Thornton W A 1971 JOSA 61 1155–1163