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Super-Resolution for Color Imagery

by Isabella Herold and S Susan Young

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Super-Resolution for Color Imagery

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14. ABSTRACT Super-resolution image reconstruction (SRIR) can improve image resolution using a sequence of low-resolution images without upgrading the sensor's hardware. Here, we consider an efficient approach of super-resolving color images. The direct approach is to super-resolve 3 color bands of the input color image sequence separately; however, it requires performing the super-resolution computation 3 times. We transform images in the default red, green, blue (RGB) color space to another color space where SRIR can be used efficiently. Digital color images can be decomposed into 3 grayscale pictures, each representing a different color space coordinate. In common color spaces, one of the coordinates (i.e., grayscale pictures) contains luminance information while the other 2 contain chrominance information. We use only the luminance component in the US Army Research Laboratory's (ARL) SRIR algorithm and upsample the chrominance components based on ARL's alias-free image upsampling using Fourier-based windowing methods. A reverse transformation is performed on these 3 components/pictures to produce a super-resolved color image in the original RGB color space. Five color spaces (CIE 1976 (L*, a*, b*) color space [CIELAB], YIQ, YCbCr, hue-saturation-value [HSV], and hue-saturation-intensity [HSI]) are considered to test the merit of the proposed approach. The results of super-resolving real-world color images are provided.					
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1. Introduction

Certain digital cameras do not produce the quality of photos that are desired. A way to circumvent this problem without replacing the camera is through an image processing algorithm (i.e., super-resolution image reconstruction [SRIR]). The algorithm we are using takes an input image sequence that comprises low-resolution images. A correlation method is used to estimate subpixel shifts between each low-resolution aliased image with respect to a reference image. An error-energy reduction algorithm is derived to reconstruct the high-resolution alias-free output image.¹

Digital images are represented by numerical values that hold information about each pixel. For color images, each pixel is represented by a tuple. This means that the whole image can be visualized as a cube, or an n-by-3 matrix. These numerical values each represent a different coordinate of the image, and these coordinates vary between different color spaces. A color space is a specific way to organize colors. Color spaces can be divided into 3 categories. The first category encapsulates color spaces that describe color by additive color principle, such as the red, green, blue (RGB) and XYZ color spaces. The second category of color spaces comes from conventional television signal standards. Color spaces in this category include YCbCr and YIQ, which was formerly used in National Television Standards Committee (NTSC) broadcasts. The third category revolves around the theory that human eyes often perceive color in 3 dimensions: hue, saturation, and colorfulness. Within this category are the hue-saturation-intensity (HSI) and hue-saturation-value (HSV) color spaces, where the I and V represent intensity and value, respectively.

Digital grayscale images are represented by an n-by-m matrix. This can be visualized as a flat rectangle, where the numerical values represent only the lightness of the images and there is no color information. Our super-resolution algorithm was designed to process grayscale images. However, we would like to be able to super-resolve color images, as well. There are 2 different ways to super-resolve color images. The first way is to take all 3 “bands” of a color image sequence and super-resolve them individually, which can work in any color space. However, this takes lots of time and processing. The proposed approach is to take an image in a color space of the 3 categories discussed, where one band represents luminance or lightness while the other 2 represent chrominance or color, then only super-resolve the luminance band sequence.² The chrominance band sequence need only to be upsampled. These 3 transformed bands can then be combined to produce a final, super-resolved color image.

This report describes the 5 color spaces in which we implemented this approach. We then transformed our digital images in the default standard RGB (sRGB) color space to the desired color space by employing several different color transformation equations. In this report, we detail each of the color spaces we used and the transformations. We then describe the procedure of super-resolution for color imagery in more depth. After that, we present our results and findings.

Our input digital images are in the default color space of sRGB which is a particular RGB color space that is defined by the 3 chromaticities of the red, green, and blue additive primaries, as well as a white point. The sRGB color space is an RGB color space created by HP and Microsoft in 1996 for use on monitors and the Internet. It was standardized by the International Electrotechnical Commission in 1999.

We started by implementing the direct super-resolution approach in the sRGB color space, by super-resolving each band separately. Then, we implemented the proposed approach, in the color spaces the CIE 1976 (L^* , a^* , b^*) color space (CIELAB), YCbCr, YIQ, HSV, and HSI. We chose these color spaces for 2 reasons: ease of transformation to and from sRGB, and having 1 luminance band and 2 chrominance bands.

2. Color Spaces

2.1 CIELAB

The first color space we looked at is CIELAB. The CIELAB color space was designed to approximate human vision and describes mathematically all perceivable colors in the 3 dimensions: L for lightness, and a and b for the color opponents green–red and blue–yellow, respectively. Figure 1 illustrates the transformation equations and processes to transform from sRGB to CIELAB. As shown in Fig. 1, there is no simple transformation from sRGB to CIELAB, so to obtain a digital image in the CIELAB color space, we had to first transform the image in sRGB to the XYZ color space. This simply involves multiplying our sRGB “cube” by a matrix, and then normalizing for a white point.³ The transformation from XYZ to CIELAB is not as simple and involves several different mathematical equations.

Step 1: RGB to XYZ
MAT =
0.4125 0.3576 0.1804
0.2127 0.7152 0.0722
0.0193 0.1192 0.9502
XYZ = MAT * RGB;

Step 2: XYZ to Lab
 $\epsilon = 0.008856$
 $\gamma = 903.3$
 $f_x = \begin{cases} \sqrt[3]{x} & \text{if } x > \epsilon \\ \frac{\gamma x + 16}{116} & \text{otherwise} \end{cases}$
 $f_y = \begin{cases} \sqrt[3]{y} & \text{if } y > \epsilon \\ \frac{\gamma y + 16}{116} & \text{otherwise} \end{cases}$
 $f_z = \begin{cases} \sqrt[3]{z} & \text{if } z > \epsilon \\ \frac{\gamma z + 16}{116} & \text{otherwise} \end{cases}$

Step 3: Get Lab Values
 $L = 116f_y - 16$
 $a = 500(f_x - f_y)$
 $b = 200(f_y - f_z)$

Fig. 1 Transformation from sRGB to CIELAB

2.2 YCbCr

The second color space we used is YCbCr. The Y component represents luminance, the Cb component represents the blue-difference, and the Cr component represents the red-difference. This color space is defined by a mathematical coordinate transformation (Fig. 2) from an associated RGB color space, and thus the transformation is simply matrix multiplication.

Forward Transformation Matrix	Inverse Transformation Matrix
65.4810 128.5530 24.9660	0.0046 0 0.0063
-37.7970 -74.2030 112.0000	0.0046 -0.0015 -0.0032
112.0000 -93.7860 -18.2140	0.0046 0.0079 0

Fig. 2 YCbCr mathematical coordinate transformation

2.3 YIQ

The third color space, YIQ, is similar in that the transformation is matrix multiplication. YIQ is the color space used by the NTSC color TV system. The Y component represents luminance, while the I and Q components represent the

chrominance components.⁴ Figure 3 shows the mathematical coordinate transformation for YIQ.

Forward Transformation Matrix	Inverse Transformation Matrix
1.0000 1.0000 1.0000	1.0000 0.9560 0.6210
0.9560 0.2720 -1.1060	1.0000 -0.2720 -0.6470
0.6210 -0.6470 1.7030	1.0000 -1.1060 1.7030

Fig. 3 YIQ mathematical coordinate transformation

2.4 HSV and HSI

The fourth and fifth color spaces we used, HSV and HSI, are similar. Both of these color spaces are common cylindrical-coordinate representations of points in an RGB color model. Figure 4 shows the visualization of the transformation as a rearrangement of Cartesian (cube) RGB model to a cone model. The transformations from sRGB to these spaces require several different mathematical equations, as opposed to a simple matrix multiplication.

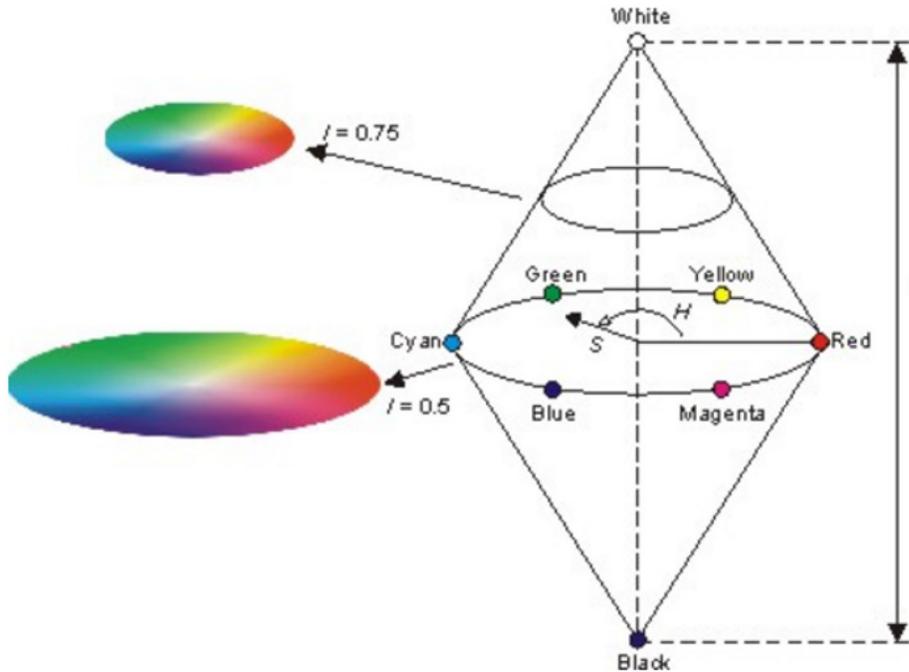


Fig. 4 HSI biconal color model

3. Approaches of Super-Resolution for Color Imagery

3.1 Direct Approach

Figure 5 shows the direct approach of super-resolution for color imagery in which a digital image sequence is split into its 3 separate bands. A digital image is represented as a cube, or an n -by- m -by-3 matrix. When one splits the cube, one then has 3 n -by- m matrices. Each of these displays as a grayscale image, since they all represent only one coordinate of the color space. In our case, we only implemented this approach in the sRGB color space, so the 3 coordinates were red, green, and blue. Then the grayscale image sequences are super-resolved and reassembled into the cube to produce a super-resolved color image.

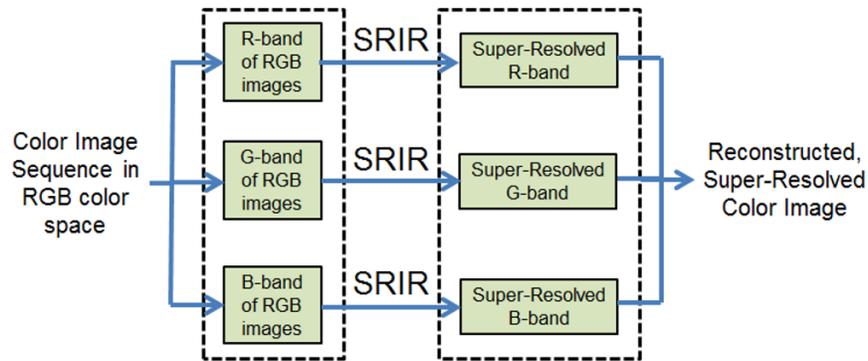


Fig. 5 Direct approach to super-resolution for color imagery

3.2 Proposed Approach

Figure 6 shows the diagram of the proposed approach to super-resolving color images in which only super-resolving one of the grayscale images/coordinates/bands. The first step to doing this is taking our digital image in the sRGB color space and transforming it to 1 of our 5 desired color spaces. From there, we again split up the cube into 3 n -by- m matrices. One of these matrices represents the image's luminance information, while the other 2 represent the chrominance information. The luminance sequence is super-resolved while the first frames of the 2 chrominance sequences are upsampled using the US Army Research Laboratory's (ARL) alias-free image upsampling algorithm.⁵ Because not each of the color transformation matrices are normalized transformations, after these processes, each resultant output image needs to be normalized to the same boundary points that they possessed before the super-resolution or upsampling. This rescaling is to minimize color distortion in our resultant image. After rescaling, the 3 output resultant images are reconstructed into the cube. The cube then has a reverse transformation applied

to it that brings the super-resolved image back into the sRGB color space. We can then view the super-resolved color image.

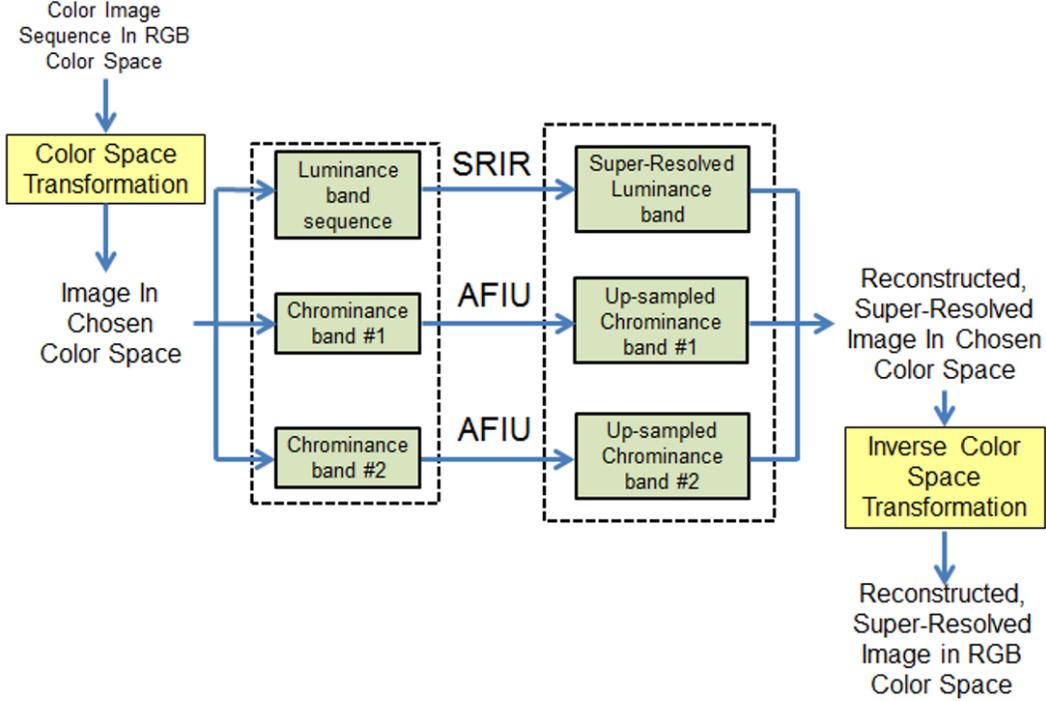


Fig. 6 Proposed approach to super-resolution for color imagery

3.3 Normalization

The super-resolution and upsampling processes could lead to the scale of the individual components being altered. To successfully reconstruct the super-resolved color image while minimizing color distortion, we need to normalize the images so that the scales are the same as what they were before super-resolution/upsampling. We used a simple equation to obtain the scaled image I_s as follows:

$$I_s = \left(\frac{I_o - I_{o,max}}{I_{o,max} - I_{o,min}} \right) * (I_{i,max} - I_{i,min}) + I_{i,min}, \quad (1)$$

where I_o is the super-resolved or upsampled image, I_i is the first frame of the low-resolution luminance/chrominance sequence, and their minimums and maximums are their absolute minimum and maximum values.

4. Results

To examine the merit of super-resolution for color image, we presented our results using 2 separate images, one with a purple background and one with a green

background, shown in Figs. 7 and 8. Between the different color spaces, there were different requirements for normalization, which are detailed within the next section.



Fig. 7 An image with a purple background

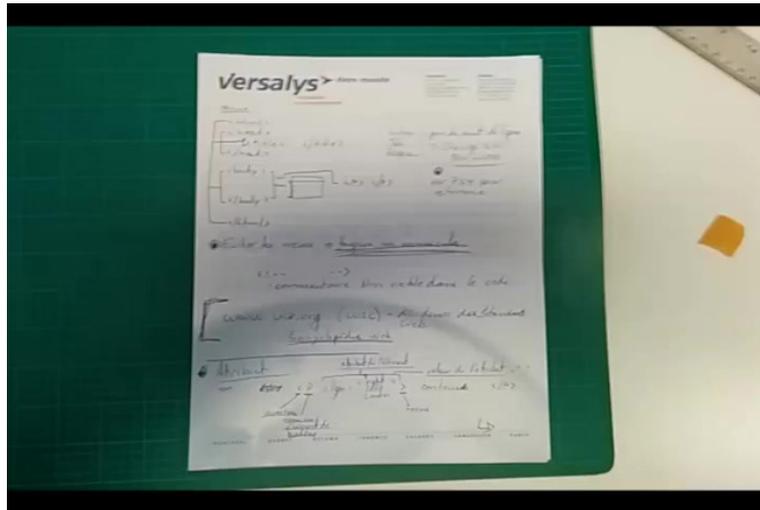


Fig. 8 An image with a green background

4.1. Direct Approach with the Purple Image

Pictured below in Fig. 9 is the result of the direct approach. As one can see, there is extreme color distortion from the original image to the resultant image. Not only is this method inefficient, but it does not produce a good result.

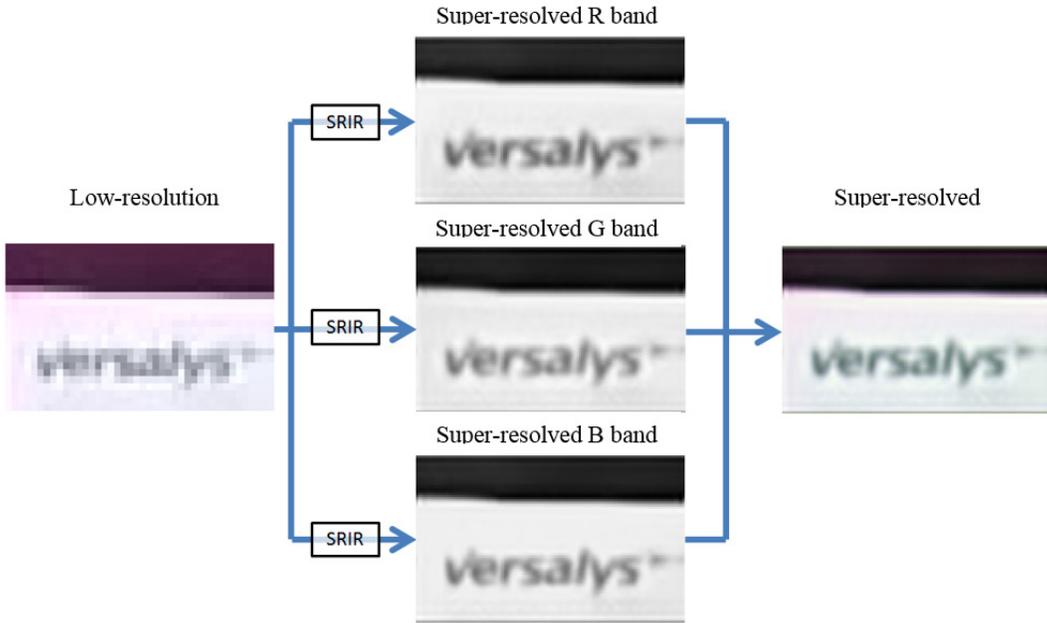


Fig. 9 Direct approach with the purple image

4.2 Image with Purple Background

4.2.1 CIELAB

For the super-resolution of the color image sequence with a purple background in the CIELAB color space, Fig. 10 shows that the resultant image's purple background is a slightly lighter shade of purple. Also, there is some purple coloring on the white paper. Overall, the resultant image is good. After the super-resolution and upsampling processes, only the super-resolved component needed to be normalized before reconstruction.

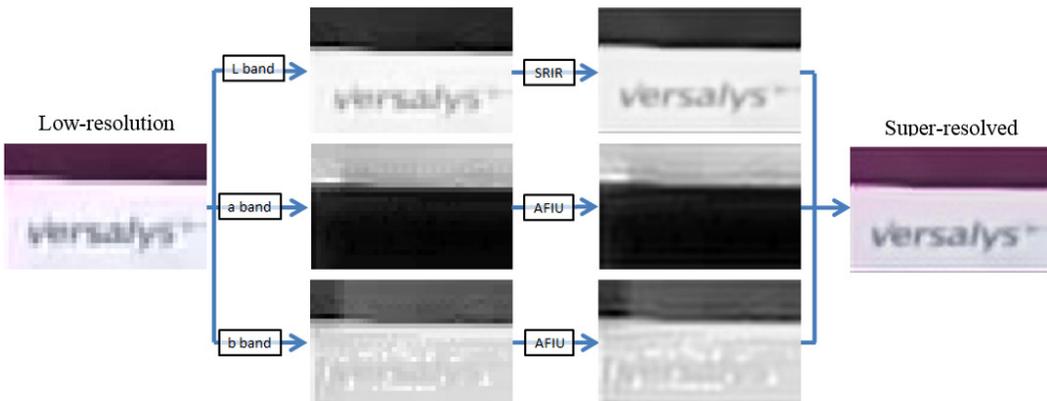


Fig. 10 Super-resolution of the purple-color imagery in CIELAB color space

After the transformation of the sRGB image to the CIELAB image, the numerical values that represent the information that make up the digital image are rescaled based on the transformation function. While the input image scale is 0–255, in Fig. 11, one can see that the L, a, and b components have very different scales.

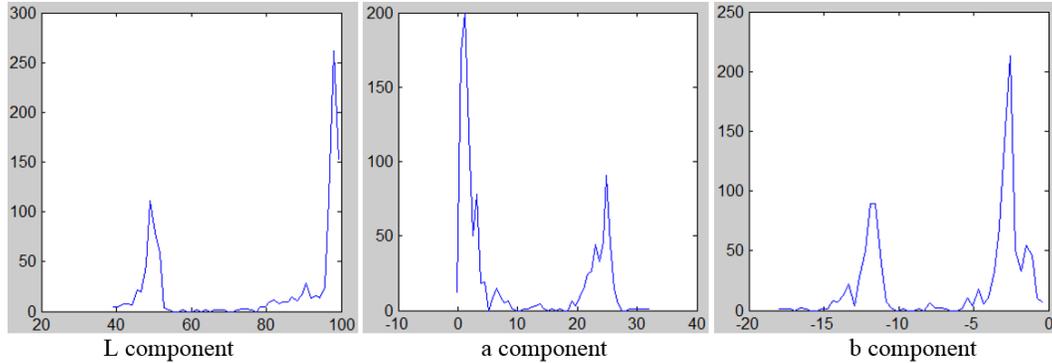


Fig. 11 Histograms of L, a, and b components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

As shown in Figs. 11 and 12, only the scale of the L component changes after the super-resolution process. This means that we have to normalize this component back to its original scale before the super-resolution. After doing this, we are able to successfully reconstruct our super-resolved color image.

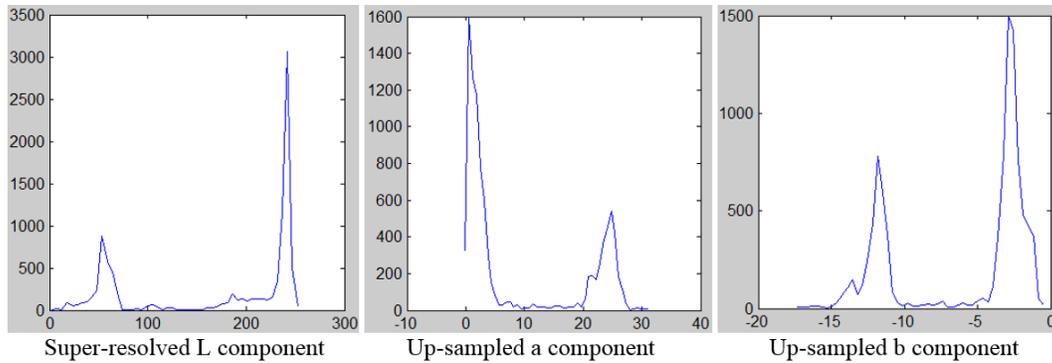


Fig. 12 Histograms of super-resolved L component, upsampled a component, and upsampled b component, respectively

4.2.2 YCbCr

For the super-resolution of the color image with a purple background in the YCbCr color space, Fig. 13 shows that the resultant image’s purple background is again, a slightly lighter shade of purple. Again, there is some purple coloring on the white paper. Overall, the resultant image is good and quite similar to the CIELAB resultant image. After the super-resolution and upsampling processes, all components needed to be normalized before reconstruction.

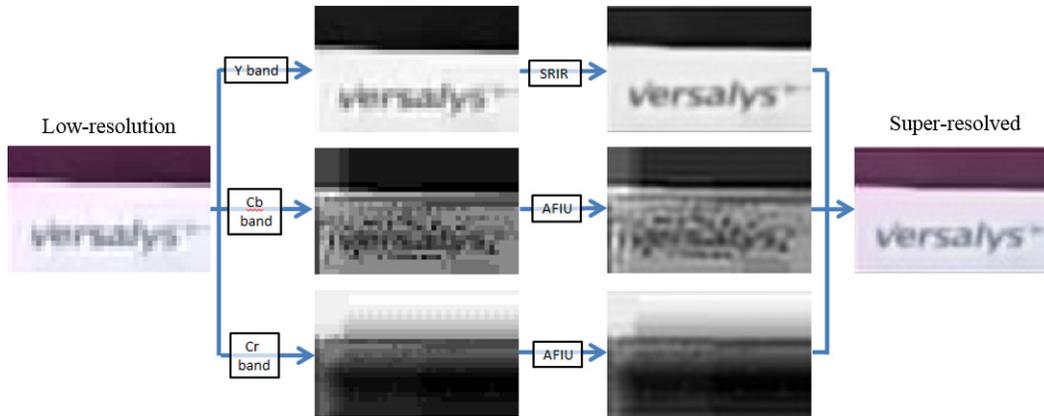


Fig. 13 Super-resolution of the purple-color imagery in YCbCr color space

As shown in Figs. 14 and 15, neither super-resolution nor upsampling affect the scale of the images, so none of them need to be normalized.

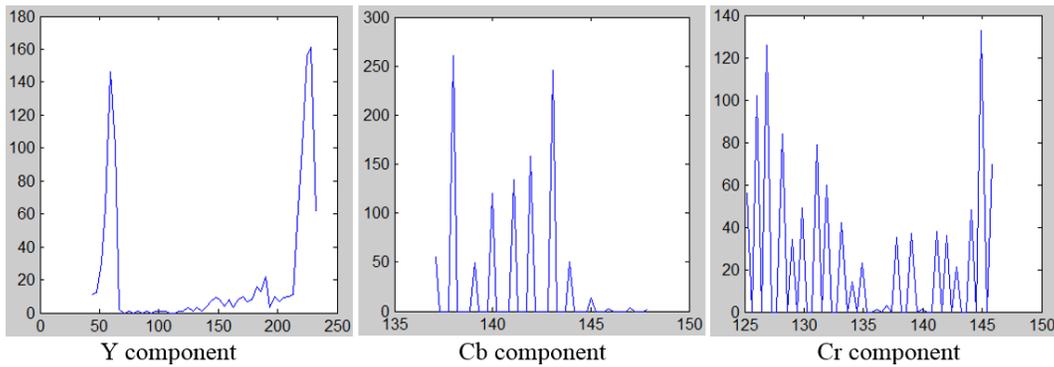


Fig. 14 Histograms of Y, Cb, and Cr components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

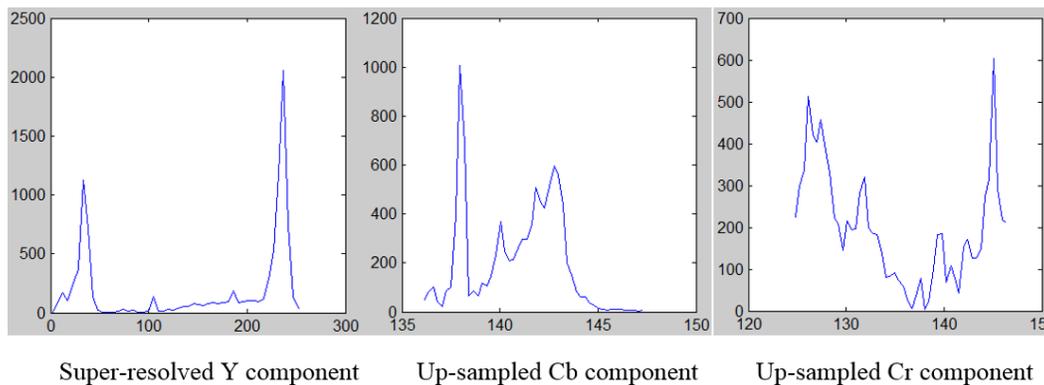


Fig. 15 Histograms of super-resolved Y component, upsampled Cb component, and upsampled Cr component, respectively

4.2.3 YIQ

For the super-resolution of the color image with a purple background in the YIQ color space, Fig. 16 shows that, like with the 2 previous color spaces, the resultant image's purple background is a slightly lighter shade of purple. There is slightly less purple coloring on the white paper than with the other 2 color spaces, and the black font is slightly lighter than it was in the previous 2 color spaces. After the super-resolution and upsampling processes, only the Y component needed to be normalized before reconstruction.

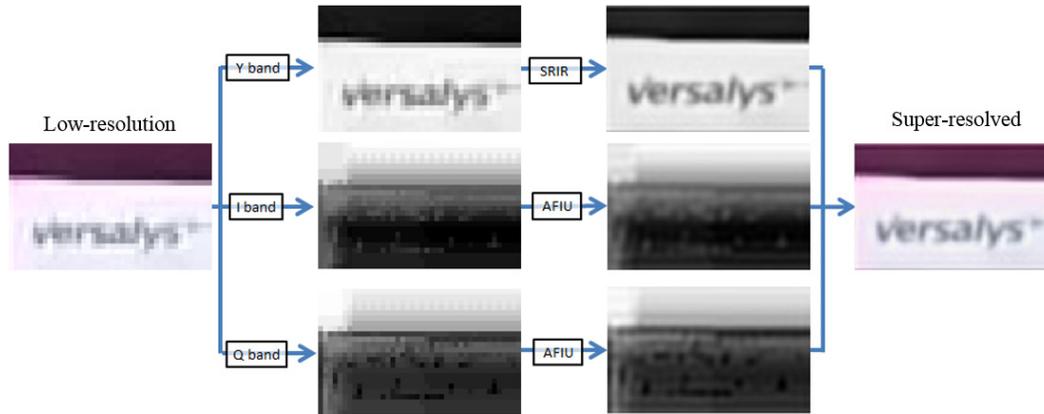


Fig. 16 Super-resolution of the purple-color imagery in YIQ color space

As shown in Figs. 17 and 18, only the Y component needs to be normalized after the super-resolution process.

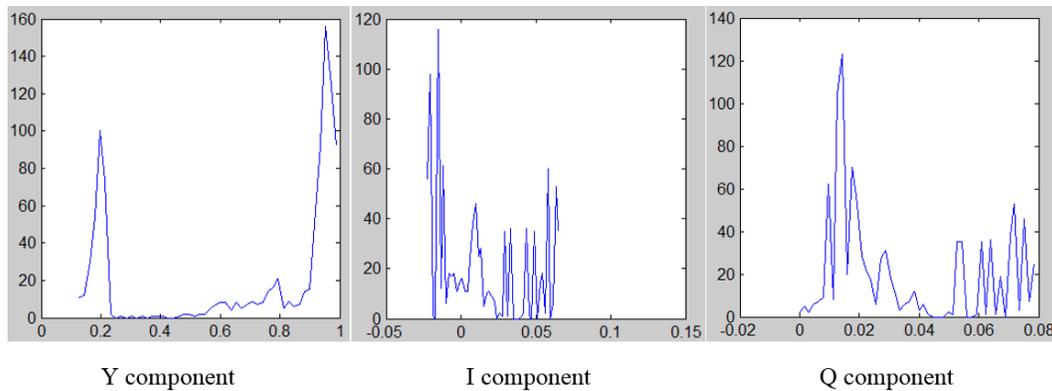


Fig. 17 Histograms of Y, I, and Q components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

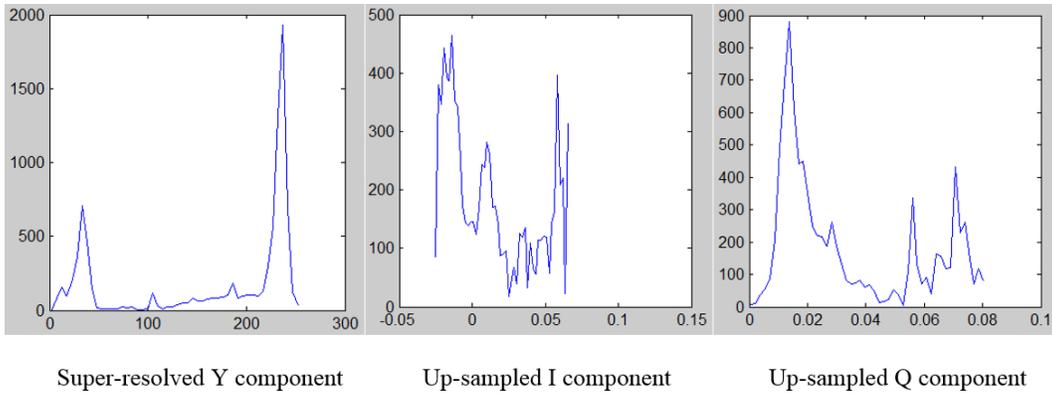


Fig. 18 Histograms of super-resolved Y component, upsampled I component, and upsampled Q component, respectively

4.2.4 HSV

For the super-resolution of the color image with a purple background in the HSV color space, Fig. 19 shows that the purple background is also slightly lighter. This leads up to believe that the super-resolution/upsampling algorithms led to some color distortion. There is even less purple coloring on the white paper in this color space. After the super-resolution and upsampling processes, only the super-resolved component needed to be normalized before reconstruction.

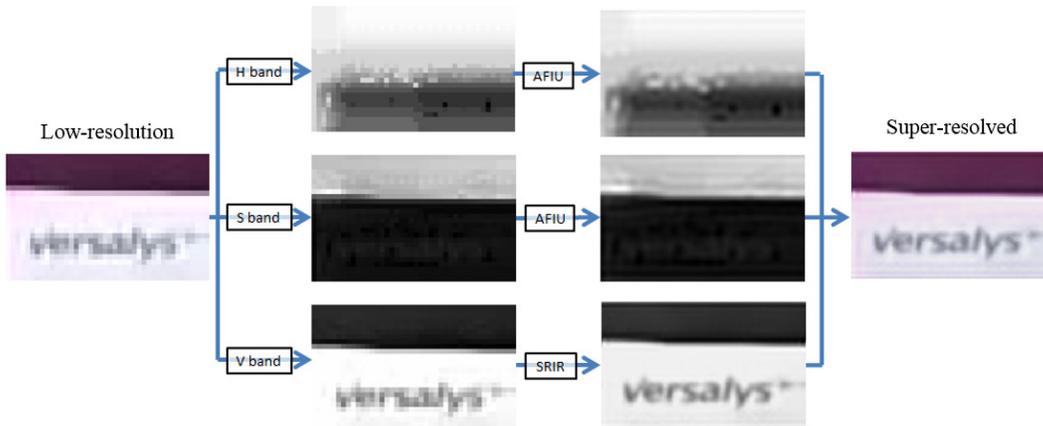


Fig. 19 Super-resolution of the purple-color imagery in HSV color space

As shown in Figs. 20 and 21, only the V component needed to be rescaled after super-resolution.

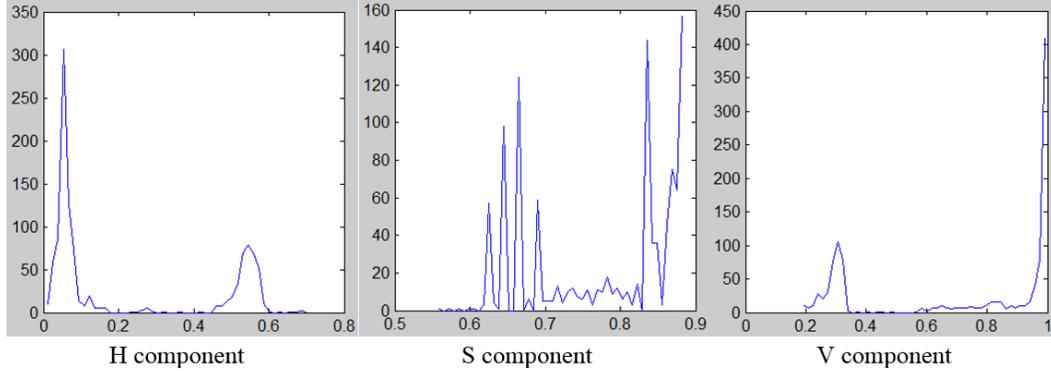


Fig. 20 Histograms of H, S, and V components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

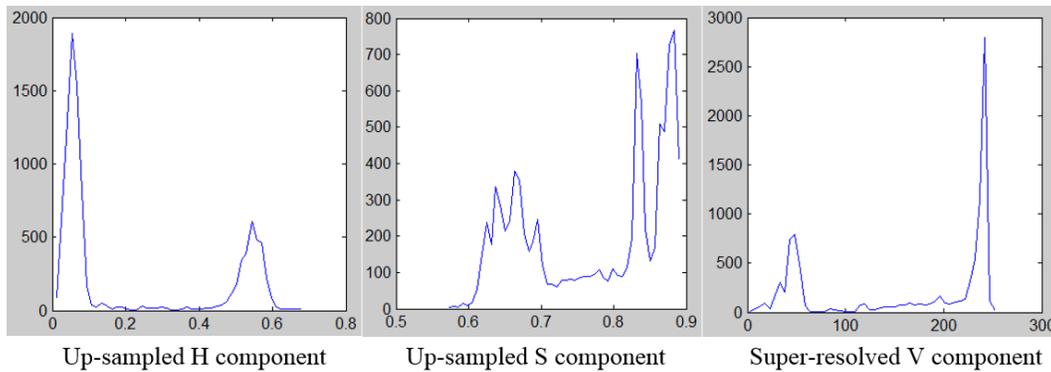


Fig. 21 Histograms of upsampled H component, upsampled S component, and super-resolved V component, respectively

4.2.5 HSI

For the super-resolution of the color image with a purple background in the HSI color space, Fig. 22 shows that the resultant image's purple background is a slightly lighter shade of purple than the resultant image in the HSV color space. However, the color of the white paper is better preserved throughout the super-resolution and upsampling processes. After the super-resolution and upsampling processes, only the super-resolved component needed to be normalized before reconstruction.

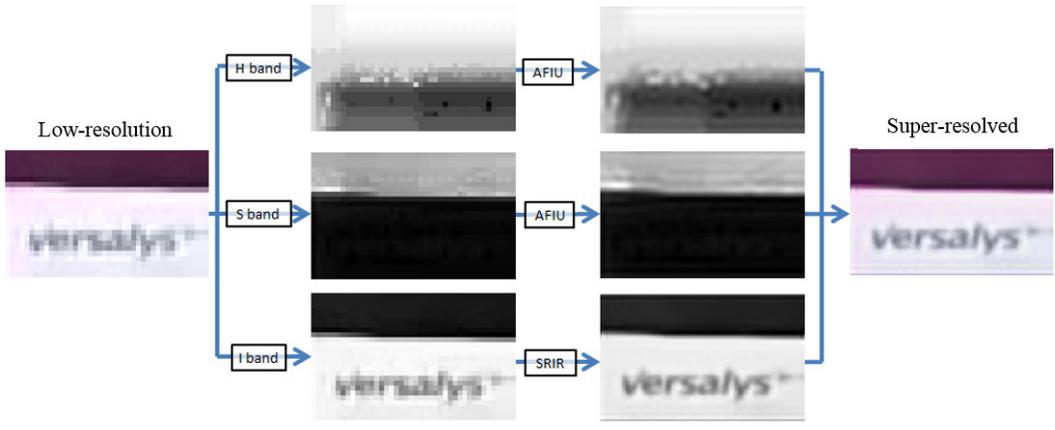


Fig. 22 Super-resolution of the purple-color imagery in HSI color space

As shown in Figs. 23 and 24, only the I component needed to be rescaled after super-resolution.

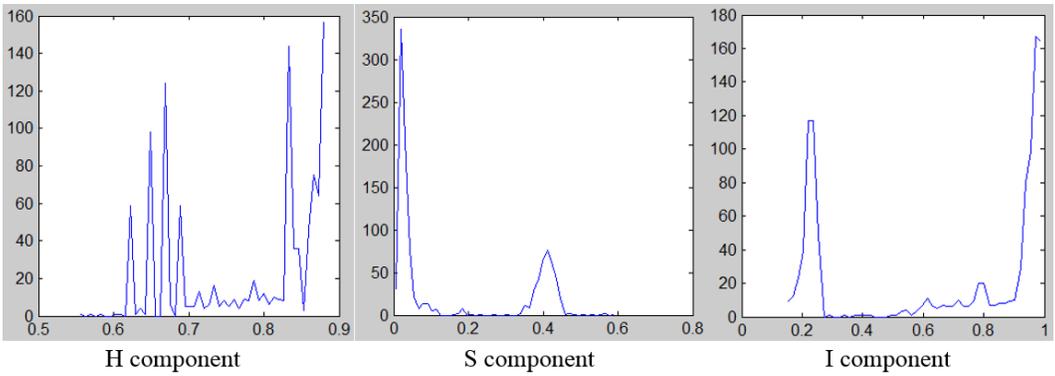


Fig. 23 Histograms of H, S, and I components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

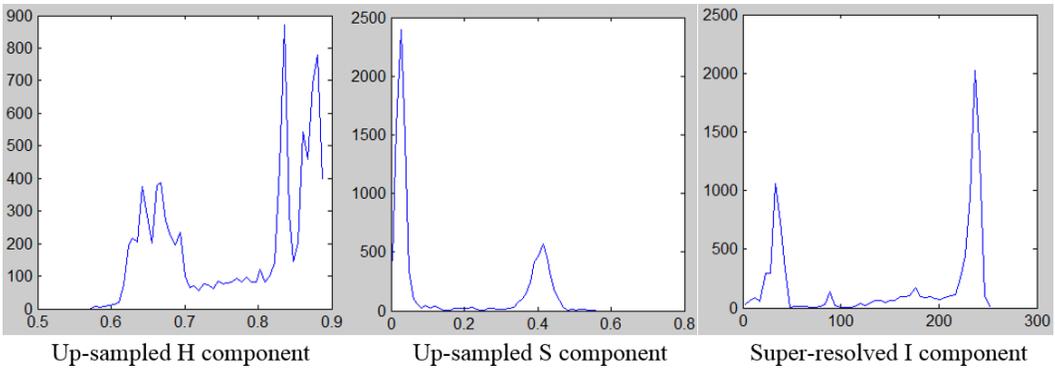


Fig. 24 Histograms of upsampled H component, upsampled S component, and super-resolved I component, respectively

4.3 Image with Green Background

4.3.1 CIELAB

For the super-resolution of the color image with a green background in the CIELAB color space, Fig. 25 shows that the resultant image's green background is a slightly lighter shade of green. In this different image, we can conclude that there must be some color distortion that occurs during the super-resolution and/or upsampling processes. In contrast, the "white" paper has acquired a gray tint. In this image, the super-resolution is not needed to enhance the image quality as much as in the previous image. However, we included it to present the merit of super-resolution of a variety of color imagery. After the super-resolution and upsampling processes, only the super-resolved component needed to be normalized before reconstruction.

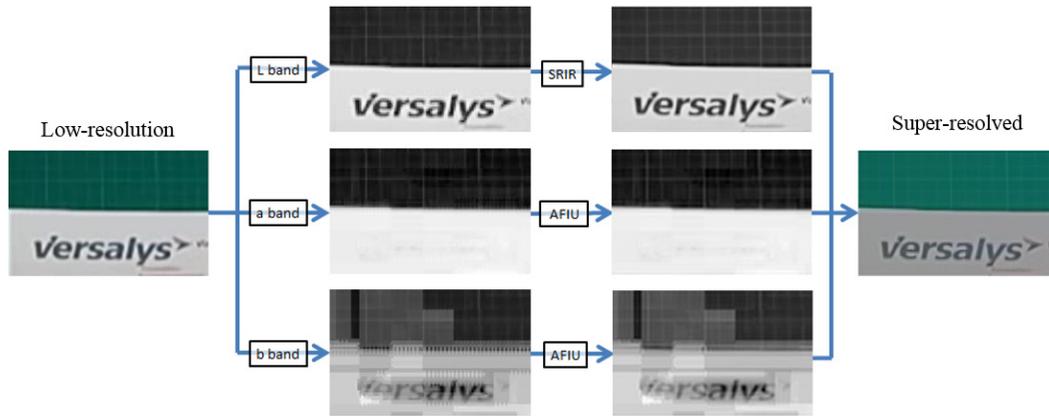


Fig. 25 Super-resolution of the green-color imagery in Lab color space

As shown in Figs. 26 and 27, only the L component needed to be rescaled after super-resolution.

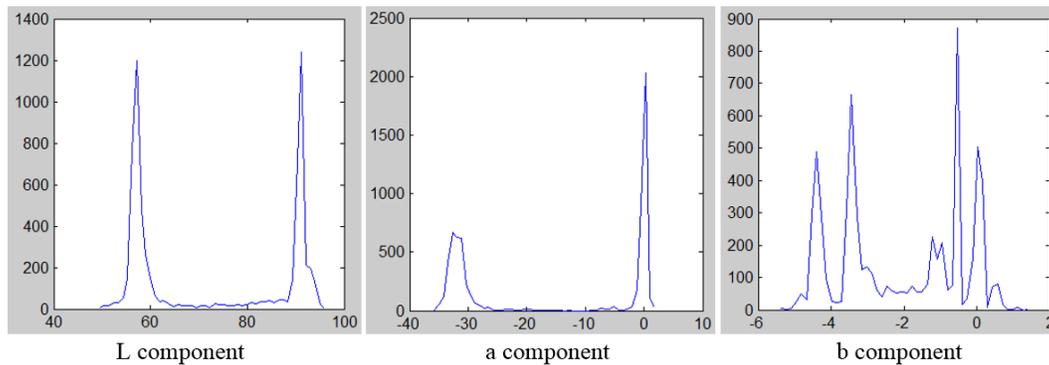


Fig. 26 Histograms of L, a, and b components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

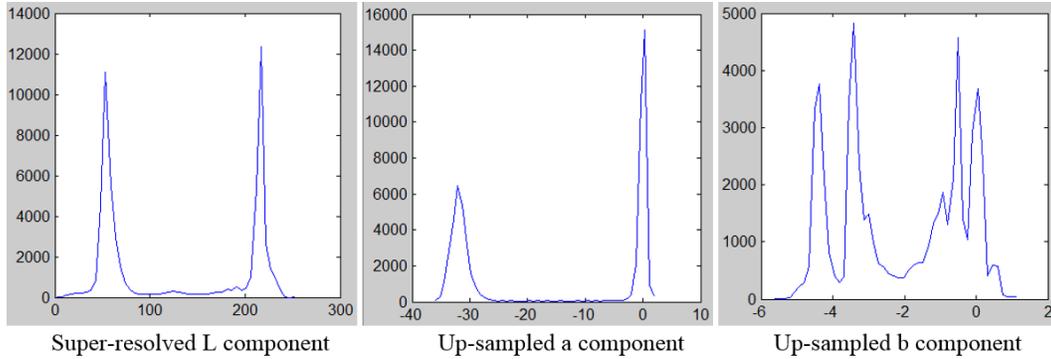


Fig. 27 Histograms of super-resolved L component, upsampled a component, and upsampled b component, respectively

4.3.2 YCbCr

For the super-resolution of the color image with a green background in the YCbCr color space, Fig. 28 shows that the resultant image comes out pretty close to the original image, compared to the CIELAB color space's resultant image. There is less color distortion. After the super-resolution and upsampling processes, only the super-resolved component needed to be normalized before reconstruction.

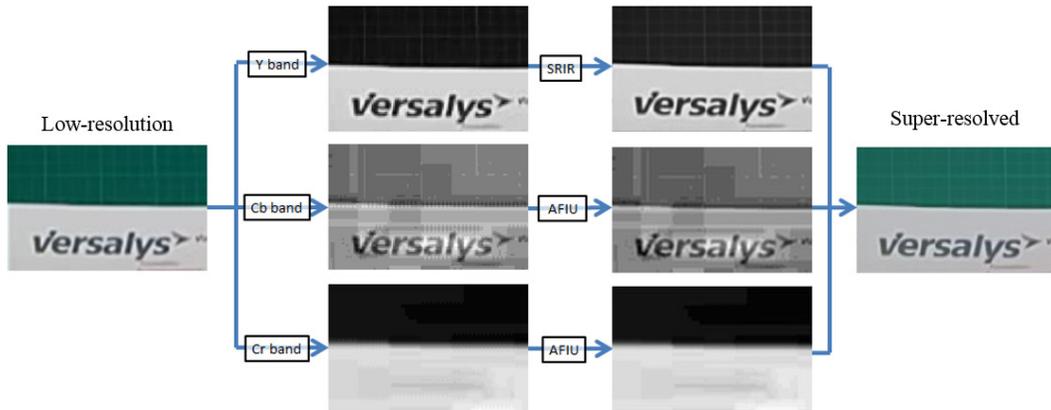


Fig. 28 Super-resolution of green color imagery in YCbCr color space

As shown in Figs. 29 and 30, only the Y component needed to be rescaled after super-resolution.

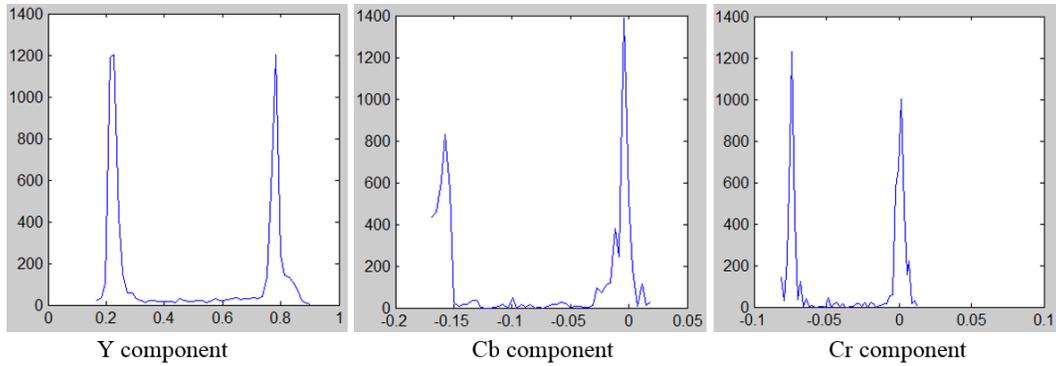


Fig. 29 Histograms of Y, Cb, and Cr components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

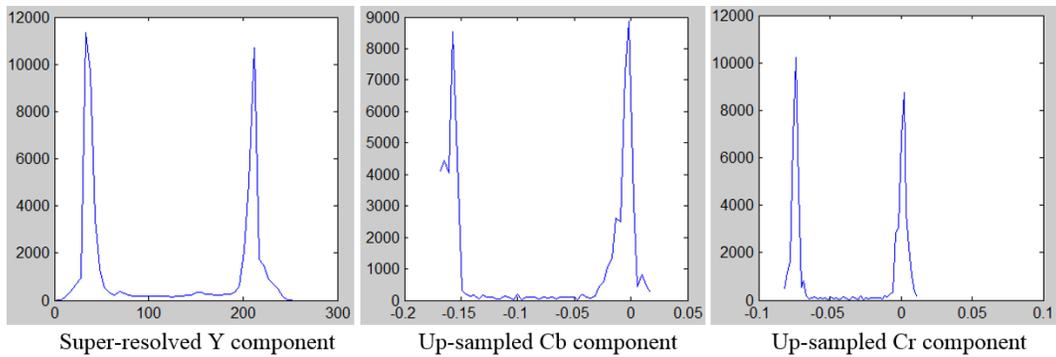


Fig. 30 Histograms of super-resolved Y component, up-sampled Cb component, and up-sampled Cr component, respectively

4.3.3 YIQ

For the super-resolution of the color image with a green background in the YIQ color space, Fig. 31 shows that this resultant image also comes out pretty close to the original image with minimal color distortion. After the super-resolution and upsampling processes, only the super-resolved component needed to be normalized before reconstruction.

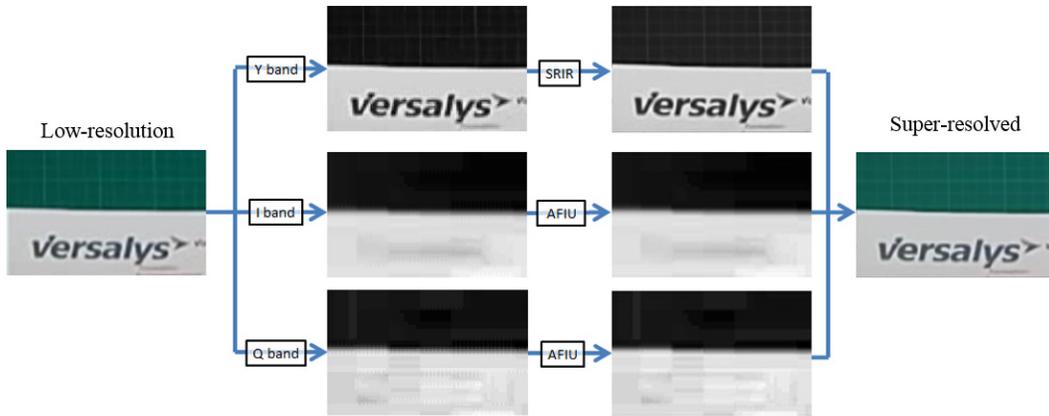


Fig. 31 Super-resolution of the green-color imagery in YIQ color space

Figures 32 and 33 show that only the Y component needed to be rescaled after super-resolution.

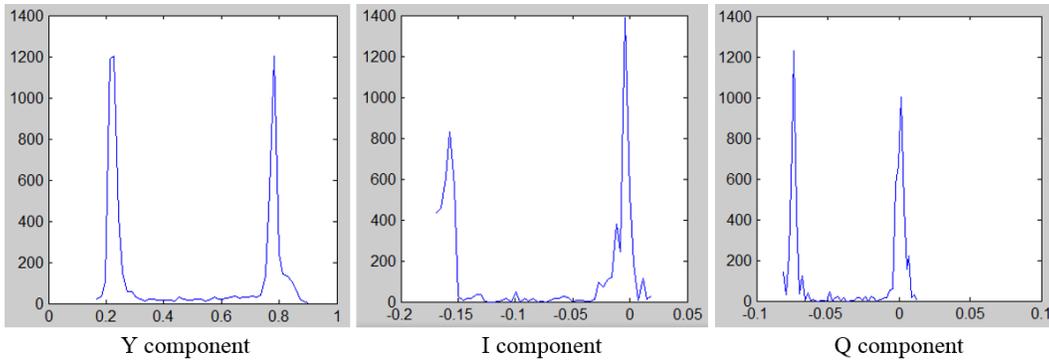


Fig. 32 Histograms of Y, I, and Q components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

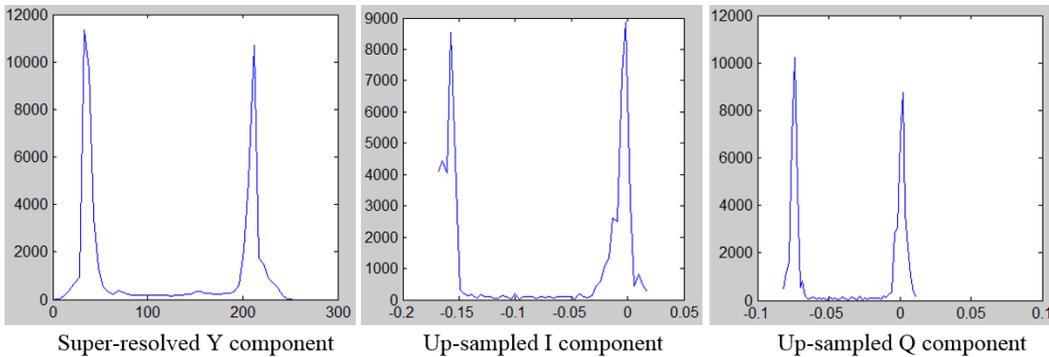


Fig. 33 Histograms of super-resolved Y component, up-sampled I component, and up-sampled Q component, respectively

4.3.4 HSV

In contrast to all of the previous examples, this reconstruction in the HSV color space produces not a lighter background, but a background with a seemingly blue tint over the green background. This can be seen in Fig. 34. After the super-resolution and upsampling processes, all components needed to be normalized before reconstruction.

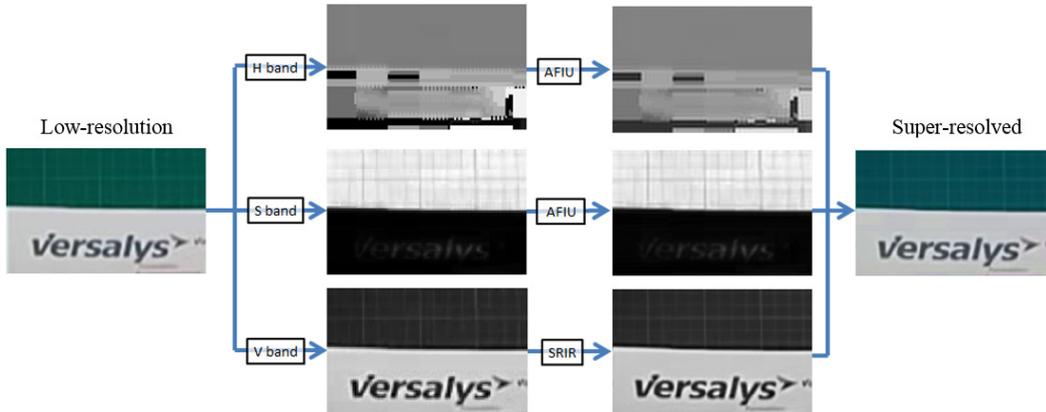


Fig. 34 Super-resolution of the green-color imagery in HSV color space

Figures 35 and 36 show that all 3 components needed to be rescaled after super-resolution and upsampling.

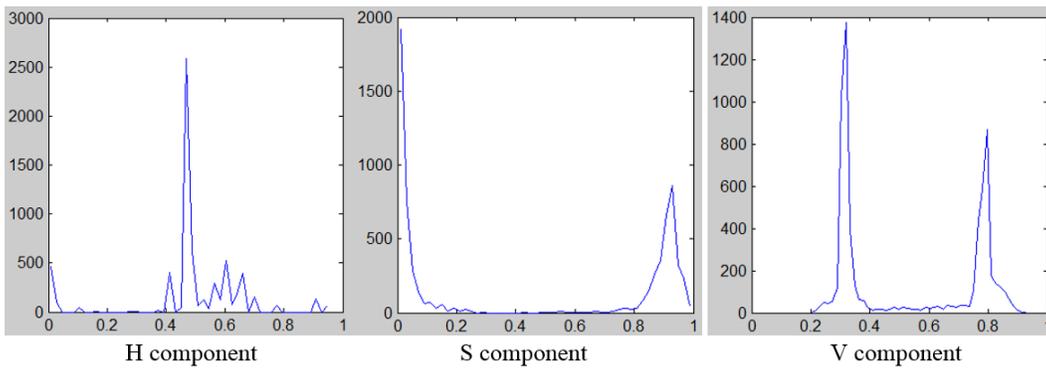


Fig. 35 Histograms of H, S, and V components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

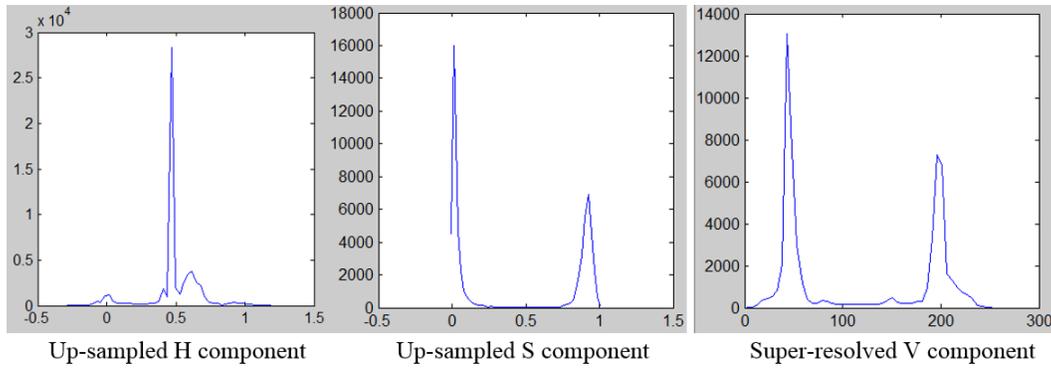


Fig. 36 Histograms of upsampled H component, upsampled S component, and super-resolved V component, respectively

4.3.5 HSI

Similarly to the resultant HSV reconstructed image with a green background, the resultant image from using the HSI color space produces some color distortion over the green background, with a more concentrated blue tint seen in Fig. 37. After the super-resolution and upscaling processes, all components needed to be normalized before reconstruction.

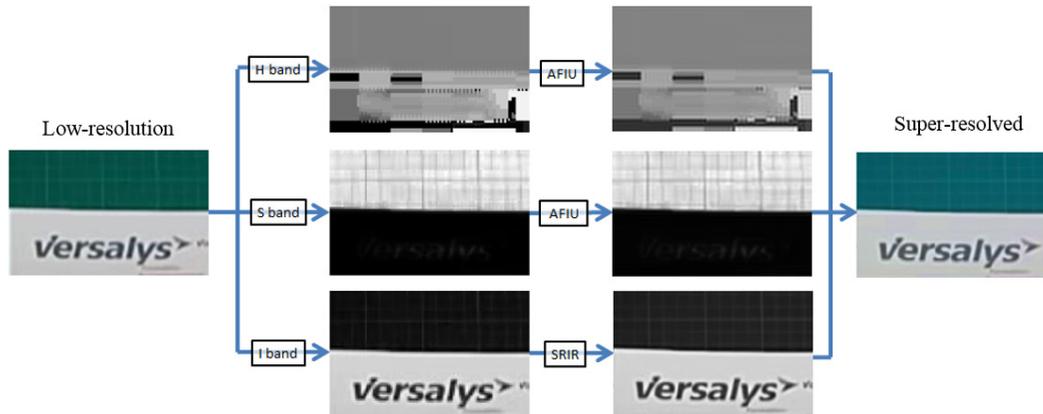


Fig. 37 Super-resolution of the green-color imagery in HSI color space

Figures 38 and 39 show that all 3 components needed to be rescaled after super-resolution and upsampling.

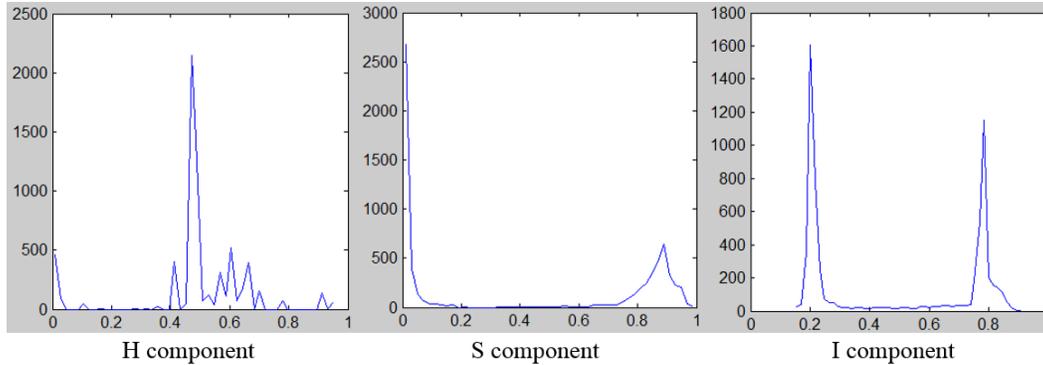


Fig. 38 Histograms of H, S, and I components, respectively, of the first frame of the low-resolution input sequence before the super-resolution and upsampling processes

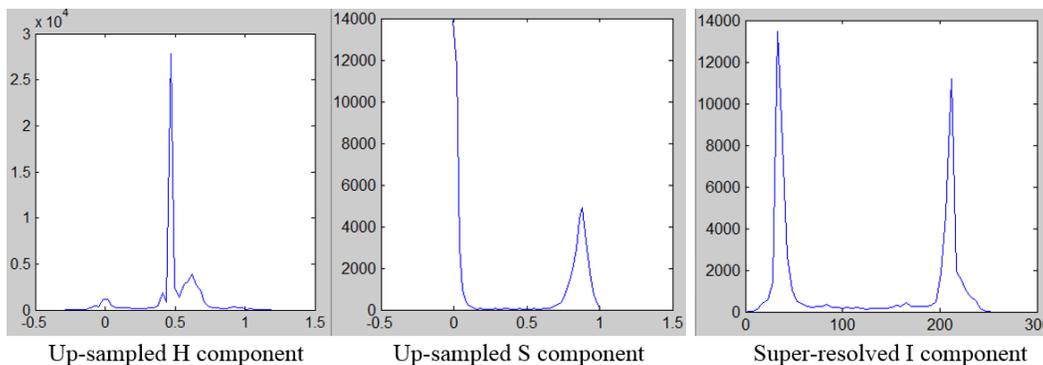


Fig. 39 Histograms of upsampled H component, upsampled S component and super-resolved I component, respectively

5. Discussion and Conclusion

Looking at the histogram results, the super-resolved images all are scaled to be 0–255. This explains why most of the color space inverse transformations require the super-resolved images to be scaled. The ones that don't require this have transformations that require the range to be 0–255. The upsampling process does not change the scale for the most of the examples. However, it changes the scales of HSI and HSV for green images. Some further research needs to be done to explain this.

6. Recommendations

Going forward, there are a few things that can be done to elaborate the results. Also, there are several more color spaces in which the proposed approach could be implemented.

7. References

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List of Symbols, Abbreviations, and Acronyms

ARL	US Army Research Laboratory
CIELab	CIE 1976 (L*, a*, b*) color space
HSI	hue-saturation-intensity
HSV	hue-saturation-value
I	intensity
NTSC	National Television System Committee
RGB	red, green, and blue
sRGB	standard red, green, and blue
SRIR	super-resolution image reconstruction
V	value

Glossary

CIELAB	Color space was designed to approximate human vision, and describes mathematically all perceivable colors in the 3 dimensions: L for lightness, and a and b for the color opponents green–red and blue–yellow, respectively.
YCbCr	Y component represents luminance, the Cb component represents the blue-difference, and the Cr component represents the red-difference.
YIQ	Y component represents luminance, while the I and Q components represent the chrominance components.

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