Comparison of Three Full-Reference Color Image Quality Measures

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ABSTRACT

Image quality assessment plays a major role in many image processing applications. Although much effort has been made in recent years towards the development of quantitative measures, the relevant literature does not include many papers that have produced accomplished results. Ideally, a useful measure should be easy to compute, independent of viewing distance, and able to quantify all types of image distortions. In this paper, we will compare three full-reference full-color image quality measures (M-DFT, M-DWT, and M-DCT). Assume the size of a given image is nxn. The transform (DFT, DWT, or DCT) is applied to the luminance layer of the original and degraded images. The transform coefficients are then divided into four bands, and the following operations are performed for each band: (a) obtain the magnitudes M_{oi}, i=1,…, (nxn/4) of original transform coefficients, (b) obtain the magnitudes M_{di}, i=1,…, (nxn/4) of degraded transform coefficients, (c) compute the absolute value of the differences: $|M_{oi}-M_{di}|$, i=1,…, (nxn/4), and (d) compute the standard deviation of the differences. Finally, the mean of the four standard deviations is obtained to produce a single value representing the overall quality of the degraded image. In our experiments, we have used five degradation types, and five degradation levels. The three proposed full-reference measures outperform the Peak-Signal-to-Noise Ratio (PSNR), and two state-of-the-art metrics Q and MSSIM.

Keywords: image quality, quantitative measures, subjective evaluation, PSNR, Q, MSSIM, DFT, DWT, and DCT.

1. INTRODUCTION

An important criterion used in the classification of image quality measures is the type of information needed to evaluate the distortion in degraded images. Measures that require both the original image and the distorted image are called "full-reference" or "non-blind" methods, measures that do not require the original image are called "no-reference" or "blind" methods, and measures that require both the distorted image and partial information about the original image are called "reduced-reference" methods.

Although no-reference measures are needed in some applications in which the original image is not available, they can be used to predict only a small number of distortion types. In the current literature, a few papers attempt to predict JPEG compression artifacts [1,2,3,4], and others blurring and JPEG 2000 artifacts [5,6]. Reduced-reference measures are between full-reference and no-reference measures; [7] evaluates the quality of JPEG and JPEG2000 coded images whereas [8] provides assessment for JPEG and JPEG2000 compressed images, images distorted by white Gaussian noise, Gaussian blur, and the transmission errors in JPEG2000 bit streams.

The applicability of full-reference measures is much wider. They can be used to estimate a spectrum of distortions that range from blurriness and blockiness to several types of noise. Recent examples of such measures are given in Table 1.

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Table 1. Full-reference image quality measures

Publication	Domain type	Type of distortion predicted
Wang and Bovik [11]	Pixel	Impulsive salt-pepper noise, additive Gaussian noise, multiplicative speckle noise, mean shift, contrast stretching, blurring, and JPEG compression
Wang, Bovik, Sheikh and Simoncelli [12]	Pixel	JPEG compression, JPEG 2000 compression
Van der Weken, Nachtegael and Kerre [9]	Pixel	Salt and pepper noise, enlightening, and darkening
Beghdadi and Pesquet-Popescu [10]	Discrete Wavelet Transform (DWT)	Gaussian noise, grid pattern, JPEG compression

A full-reference paper [11] presents a new numerical measure for gray scale images, called the Universal Image Quality Index, Q, which is defined as

$$\mathrm{Q} = \frac{4\sigma_{xy}\mu_x\mu_y}{(\sigma_x^2 + \sigma_y^2)(\mu_x^2 + \mu_y^2)]},$$

where $x_i, y_i, i = 1,...n$, represent the original and distorted signals, respectively, $\mu_x = \frac{1}{n}\sum_{i=1}^{n} x_i$, $\mu_y = \frac{1}{n}\sum_{i=1}^{n} y_i$, $\sigma_x^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu_x)^2$, $\sigma_y^2 = \frac{1}{n-1}\sum_{i=1}^{n}(y_i - \mu_y)^2$, and $\sigma_{xy} = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu_x)(y_i - \mu_y)$.

The dynamic range of Q is [-1,1], with the best value achieved when $y_i = x_i$, $i = 1,2,\ldots,n$. This index models any distortion as a combination of three different factors - loss of correlation, mean distortion, and variance distortion:

$$\frac{\sigma_{xy}}{\sigma_x\sigma_y}, \quad \frac{2\mu_x\mu_y}{(\mu_x)^2 + (\mu_y)^2}, \text{ and } \frac{2\sigma_x\sigma_y}{\sigma_x^2 + \sigma_y^2}.$$

It is applied to 512x512, 8 bits/pixel Lena using a sliding window approach with a window size of 8x8. The index is computed for each window, leading to a quality map of the image. The overall quality index is the average of all the Q values in the quality map:

$$\mathrm{Q} = \frac{1}{M}\sum_{j=1}^{M}\mathrm{Q}_j, \; M = \text{total number of windows.}$$

Q produces unstable results when either $(\mu_x^2 + \mu_y^2)$ or $(\sigma_x^2 + \sigma_y^2)$ is very close to zero. To avoid this problem, the measure has been generalized to the Structural Similarity Index (SSIM) [12]:

$$\mathrm{SSIM} = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)}$$

Q is a special case of SSIM that can be derived by setting C_1 and C_2 to 0. The performance of SSIM has been tested using a database of JPEG and JPEG 2000 compressed color images. In the experiments, only the luminance component of each compressed image is used. The authors argue that the use of color components does not significantly change the performance of the model, even though they acknowledge the fact that this may not be generally true for color image quality assessment. As in the case of Q, the overall image quality MSSIM is obtained by computing the average of SSIM values over all windows:

$$\text{MSSIM} = \frac{1}{M}\sum_{j=1}^{M} \text{SSIM}_j$$

In this paper, we will compare three full-reference full color image quality measures:

- M-DFT: A Full-Reference Color Image Quality Measure in the DFT Domain [13]
- M-DWT: A Full-Reference Color Image Quality Measure in the DWT Domain [14]
- M-DCT: A Full-Reference Color Image Quality Measure in the DCT Domain [15]

YUV and RGB are two of the commonly used color models for images and video. The model YUV is a linear transformation between the gamma-corrected RGB components to produce a luminance signal and a pair of chrominance signals. The luminance signal conveys color brightness levels, and each chrominance signal gives the difference between a color and a reference white at the same luminance. A common approach employed in developing a quality measure for color images is to use only the luminance signal.

Assume the size of a given image is nxn. Each proposed algorithm is as follows:

2. Apply the transform (DFT, DWT, or DCT) to the luminance layer of the original image.
3. Apply the transform to the luminance layer of the degraded image.
4. Divide the transform coefficients into four bands.
5. For each band, perform the following operations:
    a. Obtain the magnitudes M_{oi}, i=1,…, (nxn/4) of original transform coefficients.
    b. Obtain the magnitudes M_{di}, i=1,…, (nxn/4) of degraded transform coefficients.
    c. Compute the absolute value of the differences: $|M_{oi}-M_{di}|$, i=1,…, (nxn/4).
    d. Compute the standard deviation of the differences.
6. Obtain the mean of four standard deviations.

2. EXPERIMENTS

The three measures were applied to four 512x512 full color images (Lena, Goldhill, Peppers, and Airplane). The images, shown in Figure 1, have different frequencies, ranging from low frequency content (e.g., clouds in the Airplane image) to high frequency content (e.g., feathers in the Lena image) .

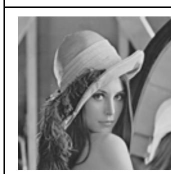
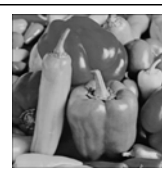
Lena	Goldhill	Peppers	Airplane
			

Figure 1. Test images

Table 2 shows the tools and parameters for five degradation types, and five degradation levels. Note that all of these degradations are performed in the pixel domain. The 25 distorted images for each test image are shown in Figures 3-6.

For each test image, high quality printouts of 25 distorted images were subjectively evaluated by approximately 15 observers. The printer was a Hewlett-Packard printer with model number “HP Color Laserjet 4600dn.” The 8”x8” images were printed on 8-1/2”x11” white paper with the basis weight 20lb and brightness 84.

Table 2. Distortion types and distortion levels

Type \ Level	Level 1	Level 2	Level 3	Level 4	Level 5
JPEG (XnView)	20:1	40:1	60:1	80:1	100:1
JPEG2000 (XnView)	20:1	40:1	60:1	80:1	100:1
Gaussian blur (Photoshop)	1	2	3	4	5
Gaussian noise (Photoshop)	3	6	9	12	15
Sharpening (XnView)	10	20	30	40	50

The observers were chosen among the graduate students and instructors from the Department of Computer and Information Science at Brooklyn College. About half of the observers were familiar with image processing, and the others had a general computer science background. They were asked to rank the images using a 50-point scale in two ways: within a given distortion type (i.e., rating of the 5 distorted images), and across five distortion types (i.e., rating of the 5 distorted images for each distortion level).

As the proposed measure is not HVS-based, no viewing distance was imposed on the observers in the experiment. In subjective evaluation [16], the widest scale is [0,10]. In order to give the observers a wider scale, grade 1 was assigned to the best image, and grade 50 was assigned to the worst image.

We will show the overall performance of the measures using two criteria: Correlation Coefficient (CC) and Root Mean Squared Error (RMSE) between Mean Opinion Score (MOS) and objective prediction. The real success of objective quality assessment can be determined by predicting the quality not only within a given distortion type but also across different distortion types.

We will also compute two additional sets of data in comparing the performance of the measures:

- CC and RMSE within each of the 5 distortion types, and
- CC and RMSE across each of the 5 distortion levels.

Finally, we will compare the performance of the three measures with PSNR, and two state-of-the-art metrics, Q and MSSIM.

The main purpose of the Video Quality Experts Group (VQEG) is to provide input to the relevant standardization bodies responsible for producing international Recommendations regarding the definition of an objective Video Quality Metric (VQM) in the digital domain.

In the FR-TV Phase I testing and validation, a nonlinear mapping between the objective model outputs and subjective quality ratings was used [17]. The performance of the 9 proponent models was evaluated after compensating for the nonlinearity. In our experiments, we followed the same procedure by fitting a logistic curve to establish a nonlinear mapping. The logistic function has the form

$$\text{logistic}(\tau, x) = \frac{1}{2} - \frac{1}{1+\exp(\tau x)},$$

where τ is a constant parameter.

Level/Distortion type	Gaussian blur	JPEG	JPEG 2000	Gaussian noise	Sharpening
1					
2					
3					
4					
5					

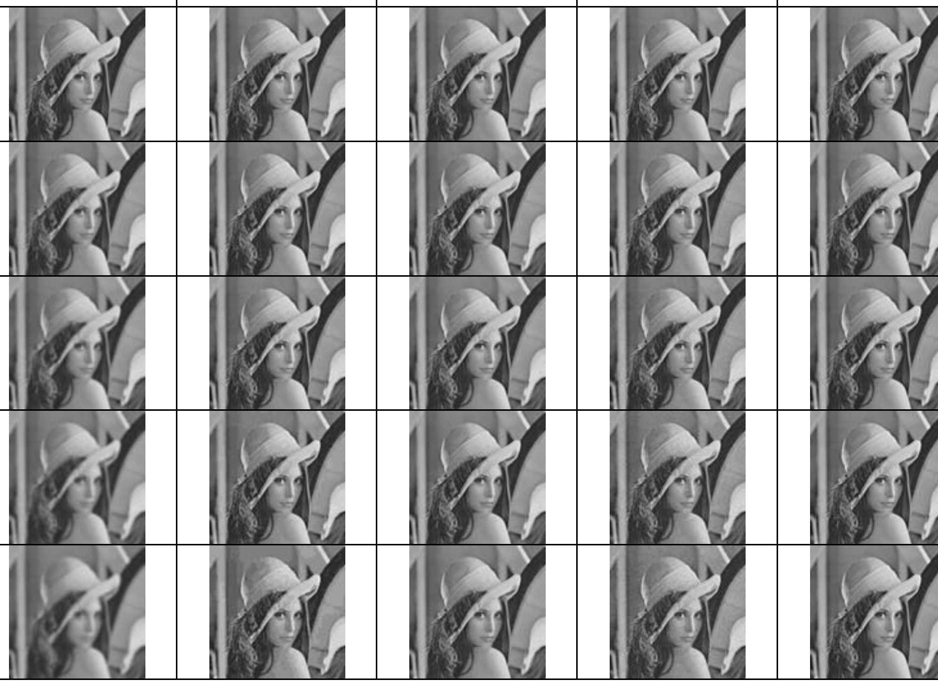


Figure 3. Lena

Level/Distortion type	Gaussian blur	JPEG	JPEG 2000	Gaussian noise	Sharpening
1					
2					
3					
4					
5					

Figure 4. Goldhill

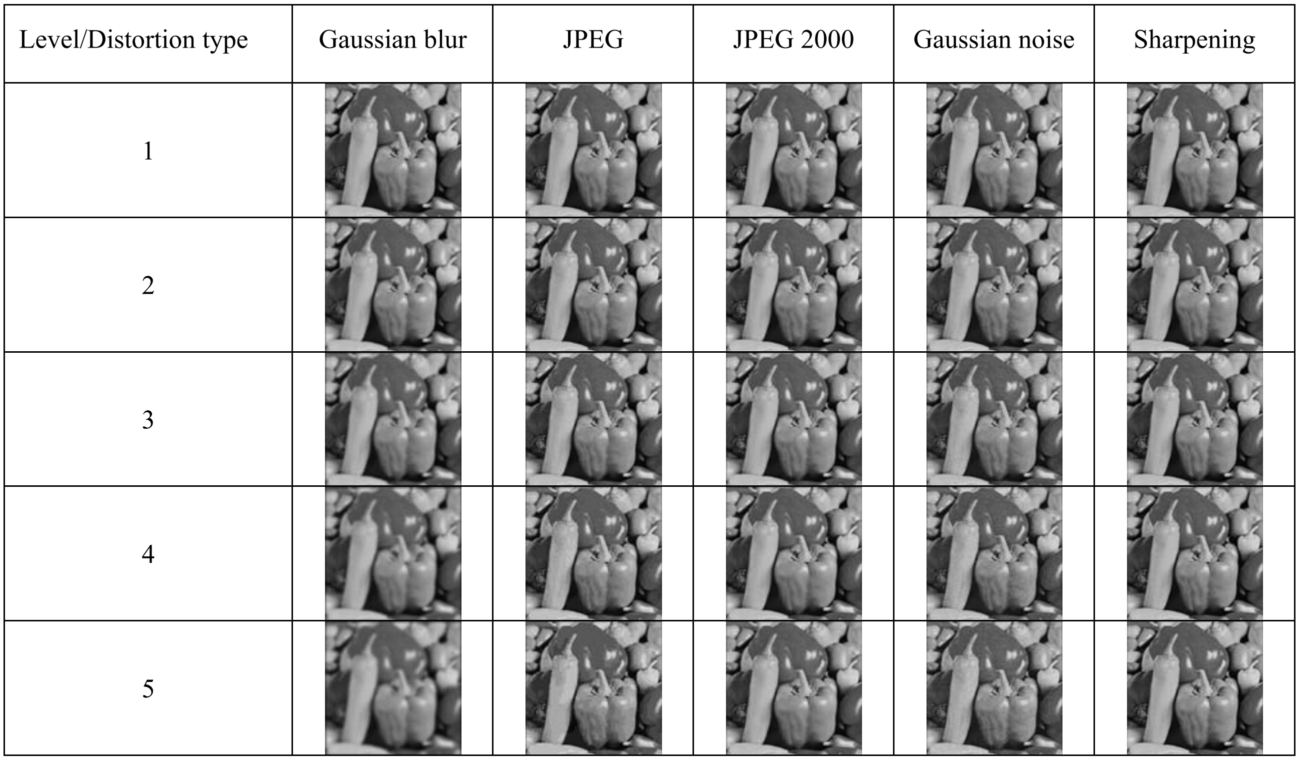


Figure 5. Peppers

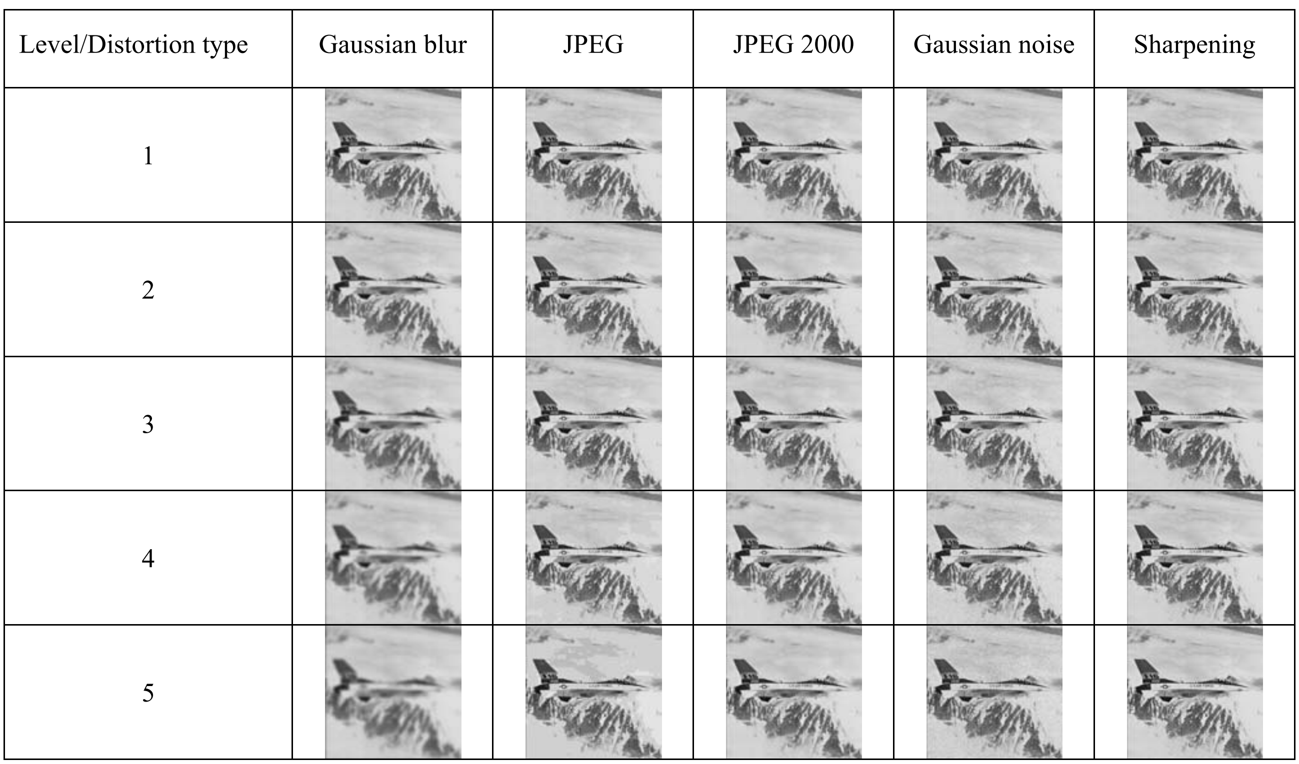


Figure 6. Airplane

2.1 M-DFT: A Full-Reference Color Image Quality Measure in the DFT Domain

Figure 7 shows the curves fitted for all the four measures (PSNR, Q, MSSIM, and M-DFT) compared.

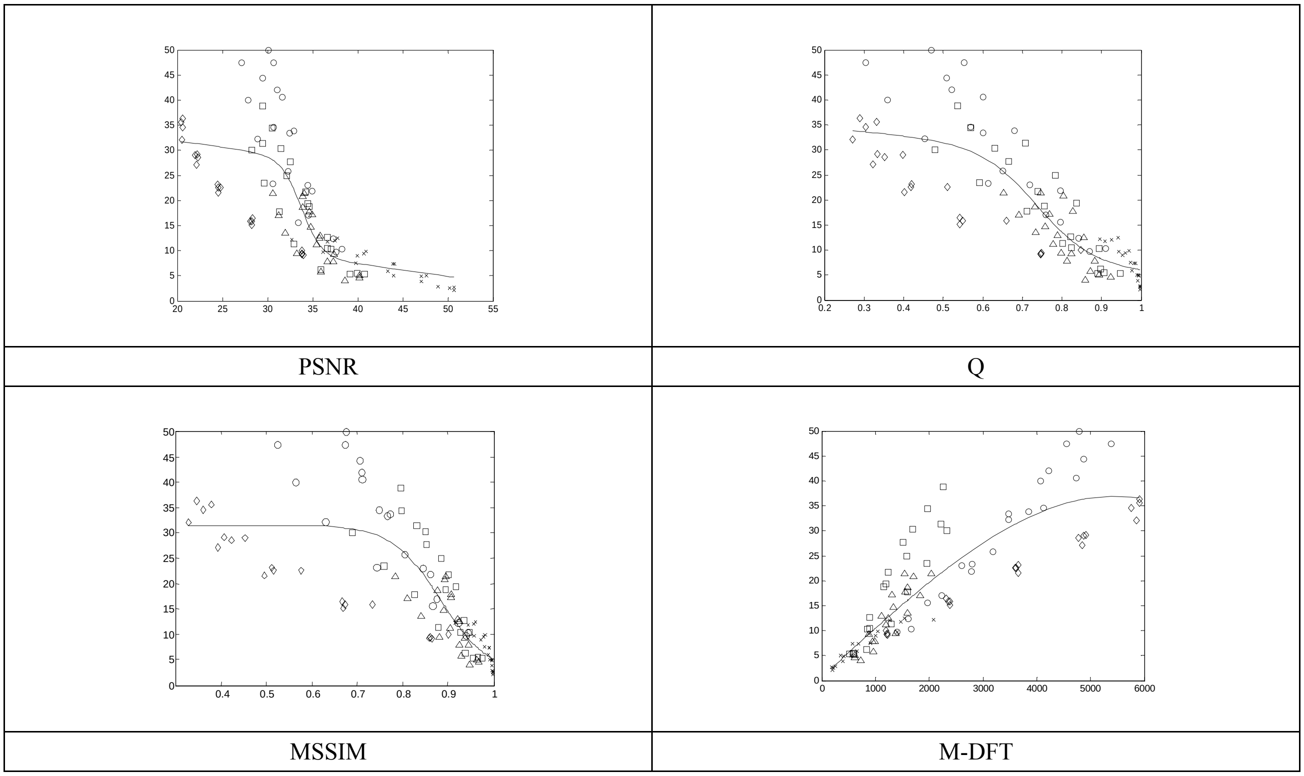


Figure 7. Comparison of the scatter plots for PSNR, Q, MSSIM, and M-DFT. In each plot, the y-axis represents the Mean Opinion Score (MOS), the x-axis represents the quantitative measure, and each mark represents one distorted image. The mapping between the distortion types and the marks is as follows: JPEG (□), JPEG 2000 (Δ), Gaussian blur (o), Gaussian noise (◊), Sharpening (x).

Table 3 displays the overall performance of the measures using two criteria: Correlation Coefficient (CC) and Root Mean Squared Error (RMSE) between MOS and objective prediction.

Table 3. Comparison of four measures

Criteria/Measure	PSNR	Q	MSSIM	M-DFT
CC	0.8038	0.8482	0.8282	0.8800
RMSE	7.0857	6.3096	6.6749	5.6579

The performance of the measures within each distortion type and across different distortion types are given in Tables 4 and 5, respectively. We observe that M-DFT outperforms all the other measures not only in overall performance but also within each distortion type and across each distortion level.

Table 4. (a) CC-based performance within each distortion type

Distortion type/Measure	PSNR	Q	MSSIM	M-DFT
JPEG	0.8877	0.9136	0.8768	0.9314
JPEG2000	0.7799	0.7810	0.8354	0.9042
Gaussian blur	0.8773	0.9124	0.9248	0.9804
Gaussian noise	0.9947	0.9585	0.9766	0.9950
Sharpening	0.9513	0.9662	0.9627	0.9739

(b) RMSE-based performance within each distortion type

Distortion type/Measure	PSNR	Q	MSSIM	M-DFT
JPEG	4.7647	4.2082	4.9762	3.7709
JPEG2000	3.5505	3.5387	3.1151	2.4208
Gaussian blur	6.1557	5.2497	4.8780	2.5280
Gaussian noise	0.9181	2.5556	1.9291	0.8941
Sharpening	1.0498	0.8783	0.9215	0.7723

Table 5. (a) CC-based performance across each distortion level

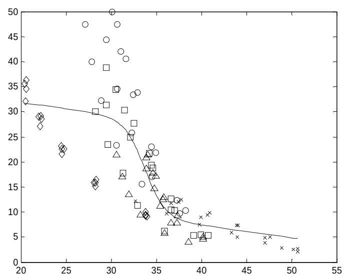
Distortion level/Measure	PSNR	Q	MSSIM	M-DFT
1	0.8024	0.7783	0.8436	0.9726
2	0.8246	0.8405	0.8542	0.9426
3	0.8361	0.8408	0.8402	0.8710
4	0.8422	0.8601	0.8549	0.8969
5	0.8358	0.8818	0.8755	0.9057

(b) RMSE-based performance across each distortion level

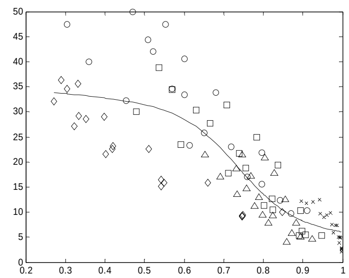
Distortion level/Measure	PSNR	Q	MSSIM	M-DFT
1	2.1151	2.2253	1.9028	0.8239
2	3.3381	3.1974	3.0679	1.9707
3	4.6552	4.5944	4.6026	4.1711
4	5.6156	5.3127	5.4026	4.6057
5	6.7775	5.8218	5.9646	5.2368

2.2 M-DWT: A Full-Reference Color Image Quality Measure in the DWT Domain

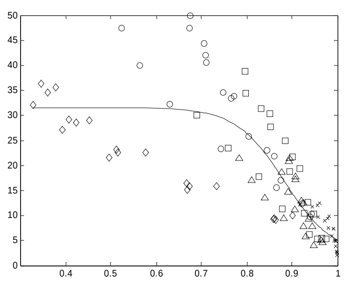
Figure 8 shows the curves fitted for all the four measures (PSNR, Q, MSSIM, and M-DWT) compared.



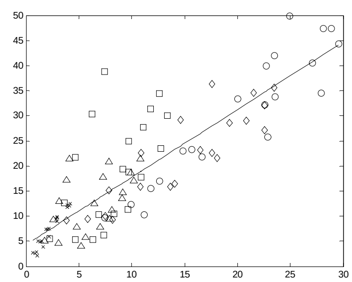
PSNR



Q



MSSIM



M-DWT

Figure 8. Comparison of the scatter plots for PSNR, Q, MSSIM, and M-DWT. In each plot, the y-axis represents the Mean Opinion Score (MOS), the x-axis represents the quantitative measure, and each mark represents one distorted image. The mapping between the distortion types and the marks is as follows: JPEG (□), JPEG 2000 (Δ), Gaussian blur (o), Gaussian noise (◊), Sharpening (x).

Table 6 displays the overall performance of the measures using two criteria: Correlation Coefficient (CC) and Root Mean Squared Error (RMSE) between MOS and objective prediction.

Table 6. Comparison of four measures

Criteria\Measure	PSNR	Q	MSSIM	M-DWT
CC	0.8038	0.8482	0.8282	0.8724
RMSE	7.0857	6.3096	6.6749	5.8214

The performance of the measures within each distortion type and across different distortion types are given in Tables 7 and 8, respectively.

We observe that the overall performance of M-DWT is better than the other three measures. The performance is not as good as the performance of PSNR, Q, and MSSIM for three types of distortion. However, the performance of M-DWT is considerably more consistent across distortion levels, a problem which is very difficult to solve.

Table 7. (a) CC-based performance within each distortion type

Distortion type\Measure	PSNR	Q	MSSIM	M-DWT
JPEG	0.8877	0.9136	0.8768	0.6123
JPEG2000	0.7799	0.7810	0.8354	0.5559
Gaussian blur	0.8773	0.9124	0.9248	0.9336
Gaussian noise	0.9947	0.9585	0.9766	0.8834
Sharpening	0.9513	0.9662	0.9627	0.9777

(b) RMSE-based performance within each distortion type

Distortion type\Measure	PSNR	Q	MSSIM	M-DWT
JPEG	4.7647	4.2082	4.9762	8.1811
JPEG2000	3.5505	3.5387	3.1151	4.7102
Gaussian blur	6.1557	5.2497	4.8780	4.5941
Gaussian noise	0.9181	2.5556	1.9291	4.2007
Sharpening	1.0498	0.8783	0.9215	0.7150

Table 8. (a) CC-based performance across each distortion level

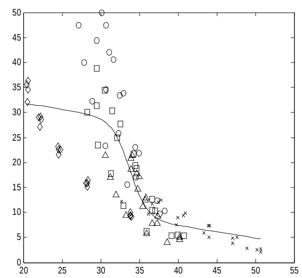
Distortion level\Measure	PSNR	Q	MSSIM	M-DWT
1	0.8024	0.7783	0.8436	0.8788
2	0.8246	0.8405	0.8542	0.9417
3	0.8361	0.8408	0.8402	0.9010
4	0.8422	0.8601	0.8549	0.8979
5	0.8358	0.8818	0.8755	0.8963

(b) RMSE-based performance across each distortion level

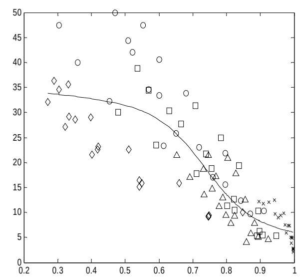
Distortion level\Measure	PSNR	Q	MSSIM	M-DWT
1	2.1151	2.2253	1.9028	1.6911
2	3.3381	3.1974	3.0679	1.9851
3	4.6552	4.5944	4.6026	3.6815
4	5.6156	5.3127	5.4026	4.5840
5	6.7775	5.8218	5.9646	5.4741

2.3 M-DCT: A Full-Reference Color Image Quality Measure in the DCT Domain

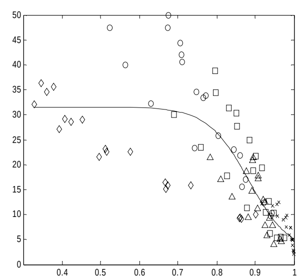
Figure 9 shows the curves fitted for all the four measures (PSNR, Q, MSSIM, and M-DCT) compared.



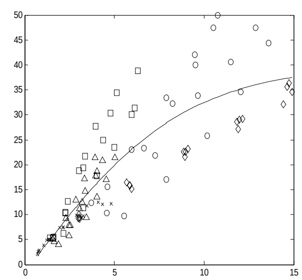
PSNR



Q



MSSIM



M-DCT

Figure 9. Comparison of the scatter plots for M-DCT, PSNR, Q, and MSSIM. In each plot, the y-axis represents the Mean Opinion Score (MOS), the x-axis represents the quantitative measure, and each mark represents one distorted image. The mapping between the distortion types and the marks is as follows: JPEG (□), JPEG 2000 (Δ), Gaussian blur (o), Gaussian noise (◊), Sharpening (x).

Table 9 displays the overall performance of the measures using two criteria: Correlation Coefficient (CC) and Root Mean Squared Error (RMSE) between MOS and objective prediction.

Table 9. Comparison of four measures

Criteria\Measure	PSNR	Q	MSSIM	M-DCT
CC	0.8038	0.8482	0.8282	0.8743
RMSE	7.0857	6.3096	6.6749	5.7821

The performance of the measures within each distortion type and across different distortion types are given in Tables 10 and 11, respectively.

We observe that the overall performance of M-DCT is better than the other three measures. For only Gaussian blur, the performance of M-DCT is slightly worse than the performances of Q and MSSIM. Across each distortion level, M-DCT outperforms all the other measures in comparison.

Table 10. (a) CC-based performance within each distortion type

Distortion type\Measure	PSNR	Q	MSSIM	M-DCT
JPEG	0.8877	0.9136	0.8768	0.9470
JPEG2000	0.7799	0.7810	0.8354	0.9156
Gaussian blur	0.8773	0.9124	0.9248	0.8868
Gaussian noise	0.9947	0.9585	0.9766	0.9955
Sharpening	0.9513	0.9662	0.9627	0.9931

(b) RMSE-based performance within each distortion type

Distortion type\Measure	PSNR	Q	MSSIM	M-DCT
JPEG	4.7647	4.2082	4.9762	3.3238
JPEG2000	3.5505	3.5387	3.1151	2.2783
Gaussian blur	6.1557	5.2497	4.8780	5.9259
Gaussian noise	0.9181	2.5556	1.9291	0.8485
Sharpening	1.0498	0.8783	0.9215	0.3984

Table 11. (a) CC-based performance across each distortion level

Distortion level\Measure	PSNR	Q	MSSIM	M-DCT
1	0.8024	0.7783	0.8436	0.9326
2	0.8246	0.8405	0.8542	0.9178
3	0.8361	0.8408	0.8402	0.8790
4	0.8422	0.8601	0.8549	0.8853
5	0.8358	0.8818	0.8755	0.8850

(b) RMSE-based performance across each distortion level

Distortion level\Measure	PSNR	Q	MSSIM	M-DCT
1	2.1151	2.2253	1.9028	1.2793
2	3.3381	3.1974	3.0679	2.3430
3	4.6552	4.5944	4.6026	4.0473
4	5.6156	5.3127	5.4026	4.8427
5	6.7775	5.8218	5.9646	5.7474

3. CONCLUSIONS

We presented three full-reference quality measures for color images. Each measure is based on a particular transform: (a) M-DFT uses the Discrete Fourier Transform, (b) M-DWT uses the Discrete Wavelet Transform, and (c) M-DCT uses the Discrete Cosine Transform. In all cases, the three measures, when the overall performance is considered, outperform the other measures (i.e., PSNR, Q, and MSSIM). The other experimental results can be summarized as follows:

- The performance of M-DFT is better than PSNR, Q, and MSSIM for each distortion type and distortion level.

- The performance of M-DWT is not as good as the performance of PSNR, Q, and MSSIM for three types of distortion (JPEG compression, JPEG compression, and Gaussian noise). However, the performance of M-DWT is considerably more consistent across distortion levels, providing higher CCs and lower RMSEs.
- The performance of M-DCT is slightly worse than the performances of Q and MSSIM for Gaussian blur. Across each distortion level, M-DCT outperforms all the other measures.

In future work, we will apply the proposed measures to watermarked images and video sequences.

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