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**A perceptually driven hybrid additive-multiplicative watermarking technique in the wavelet domain**

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# A perceptually driven hybrid additive-multiplicative watermarking technique in the wavelet domain

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## ABSTRACT

This paper presents a hybrid watermarking technique which mixes additive and multiplicative watermark embedding with emphasis on its robustness versus the imperceptibility of the watermark. The embedding is performed in six wavelet sub-bands using independently three embedding equations and two parameters to modulate the embedding strength for multiplicative and additive embedding. The watermark strength is independently modulated into distinct image areas. Specifically, when a multiplicative embedding is used, the visibility threshold is first reached near the image edges, whereas using an additive embedding technique the visibility threshold is first reached into the smooth areas. A subjective experiment has been used to provide the optimal watermark strength for three distinct embedding equations. Observers were asked to tune the watermark amplitude and to set the strength at the visibility threshold. The experimental results showed that using an hybrid watermarking technique significantly improves the robustness performance. This work is a preliminary study for the design of an optimal wavelet domain Just Noticeable Difference (JND) mask.

## 1. INTRODUCTION

Most of the early watermarking methods were based on an additive embedding principle. In additive watermarking, the watermark is multiplied with a global embedding strength and added to the spatial-domain or transformed-domain image coefficients. The global embedding strength is adjusted such that the watermark is imperceptible. More recent watermarking techniques use a multiplicative or proportional embedding procedure where the watermarks, embedded into the transformed-domain coefficients are locally modulated proportional to the strength (or square of the strength [1]) of the coefficients. The rationale behind this embedding rule is that it makes the watermark more image-adaptive and thus results in a better perceptual impact. The multiplicative watermark embedding is widely used and it is shown to be quite efficient with respect to imperceptibility and robustness. In addition to that, the multiplicative watermarking offers better security [2]. The commonly used additive and multiplicative embedding equations are given in Equation 1 [3].

$$\begin{aligned} y_{m,n} &= x_{m,n} + \alpha \times w_{m,n}, \\ y_{m,n} &= x_{m,n}\left(1 + \alpha \times w_{m,n}\right), \end{aligned} \tag{1}$$

where $y_{m,n}$ is a watermarked coefficient, $x_{m,n}$ is the original coefficient, $\alpha$ is the embedding strength, and $w_{m,n}$ is commonly a noise-like watermark. Besides the use of various embedding formulas and embedding domains, several works have focused on the computation of Just Noticeable Difference (JND) masks to improve the robustness performances while maintaining the imperceptibility of the watermark. JND masks provide the maximum allowable modification to each image coefficients such that the watermark is imperceptible. Among the early adaptation of JND masks for watermarking, [4] and [5] use the visibility thresholds of discrete wavelet transform (DWT) coefficients and the discrete cosine transform (DCT) quantization matrix, both were originally proposed for image coding. In [4], three different JND masks for multiplicative watermark embedding have been proposed. Among the three masks, one exploits multiple-channel human visual system (HVS) model, another exploits some HVS sensitivity properties (e.g. luminance sensitivity, frequency sensitivity etc.) and the third one was based on the computation of local variances. In [5], the authors propose a DWT-domain masking model,

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based on some empirical assumptions such as the brightness sensitivity of the HVS and the visibility of noise in textured/smooth areas of an image.

For most, if not all of the cited JND masks, the watermark strength is higher in the image high activity areas, whether it is on edges or textured areas. To the best of our knowledge, no JND mask have ever tried to optimally tune the watermark strength in the smooth areas of the image. In this regard, the authors studied [6] the comparative performance of three wavelet-domain multiplicative watermark embedding equations on the imperceptibility-robustness trade-off perspective. The three embedding equations were special cases of the general multiplicative embedding rule. The watermark embedding strength in those equations was proportional to the absolute value of the wavelet coefficients, square of the wavelet coefficients and square-root of the wavelet coefficients, respectively. It was found that the square-root embedding equation, which spreads the watermark away from the image edges, as compared to the other two embedding equations, provided the best overall robustness performance. Nevertheless, in this previous study, only wavelet domain multiplicative embedding was considered, and thus, the flat portions of the image were discarded during the watermark embedding.

In this work, we study the possibility of further improving the robustness performance by using a hybrid additive-multiplicative watermark embedding. To the best of the authors' knowledge no work have ever tried to combine the additive and multiplicative watermark embedding methods. Our main motivation is to establish a perceptually optimal embedding in every portion of the image, whether the watermark is embedded into high activity areas, or in the smoother areas, or in both regions simultaneously. Determining such a near visibility threshold watermarking technique would be an important step towards the design of an efficient JND mask.

There are actually two distinct approaches we can use to ensure the watermark invisibility, we can either exploit objective quality metrics to determine when the tuned watermark reaches the visibility threshold, and would thus provide the best robustness versus invisibility trade-off, or, we can run a subjective experiment, during which human observers are asked to determine whether the embedded watermark is visible or not. Researchers commonly use statistical quality metrics (such as the PSNR or SSIM) to evaluate the quality of marked images [7] [8]. However, Objective quality metrics are generally designed to assess the perceived quality for a wide range of distortions, and they may not be very accurate when the distortions occurs near the visibility threshold. In this work, we use a subjective experiment where the observers can modulate the watermark strength until the visibility threshold is reached.

The remaining of the paper is organized as follows. The details of the watermark embedding equations and the detection method is described in Section 2, the subjective experimental setup is detailed in Section 3, experimental results are analyzed in Section 4 and the conclusion is given in Section 5.

## 2. WATERMARKING TECHNIQUE

The watermark embedding is performed in the wavelet domain. In this work, the optimal watermark strength in every of the selected wavelet sub-bands was tuned by human observers during a subjective experiment (details on the experiments are given in section 3). Like in our previous study [6], six wavelet sub-bands have been selected for the watermark embedding. The six selected sub-bands are represented in gray shade on Figure 1.

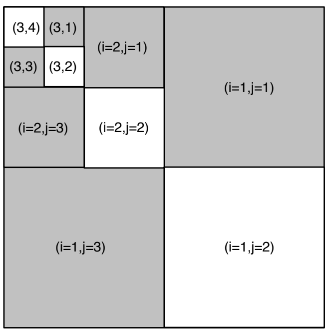


**Figure 1.** Embedding wavelet sub-bands, with their corresponding index

As the aim of this work is to compare the performance of hybrid multiplicative-additive watermark embedding scenario with respect to the general additive and multiplicative watermark embedding frameworks, we consider the following generalized watermark embedding equation :

$$y^{i,j}_{m,n} = x^{i,j}_{m,n} + \left(a \times |x^{i,j}_{m,n}|^k + b\right) \times w^{i,j}_{m,n} \tag{2}$$

where $y^{i,j}_{m,n}$ is the marked wavelet coefficient, $x^{i,j}_{m,n}$ is the host wavelet coefficient,and $w^{i,j}_{m,n}$ is a zero-mean Gaussian watermark at location $(m, n)$ in the sub-band$(i, j)$. In this work, although color images were used during the subjective experiment, the watermark was only embedded onto the luminance component. The following 7 special cases of Equation 2 are considered in this work :

| | |
|---|---|
| additive embedding | $(a = 0, b \neq 0)$ |
| multiplicative-1 embedding | $(k = 1, a \neq 0, b = 0)$ |
| multiplicative-2 embedding | $(k = 2, a \neq 0, b = 0)$ |
| multiplicative-3 embedding | $(k = 0.5, a \neq 0, b = 0)$ |
| hybrid-1 embedding | $(k = 1, a \neq 0, b \neq 0)$ |
| hybrid-2 embedding | $(k = 2, a \neq 0, b \neq 0)$ |
| hybrid-3 embedding | $(k = 0.5, a \neq 0, b \neq 0)$ |

The goal of this study being to analyse the robustness of a hybrid watermarking technique with as a final aim, the design of a wavelet domain JND mask, we did not focus on the detection technique performances, and therefore a simple non blind detection method is used. The correlation coefficient was computed between the extracted watermark $(\tilde{y}^{i,j}_{m,n} - x^{i,j}_{m,n})$ and the original watermark $\left(w^{i,j}_{m,n}\right)$, $\tilde{y}^{i,j}_{m,n}$ being the marked (and possibly distorted) wavelet sub-band. The detection threshold was experimentally determined by computing the detector response for every embedding equation and within every wavelet sub-band. In this work, no attempt was made to derive an optimal detector for every embedding scenario, as our target is to provide a wavelet domain JND mask, if such a mask is derived, any embedding technique that ensures the watermarked coefficients remain below the mask can be considered along with it's optimal detector.

## 3. SUBJECTIVE EXPERIMENT

In this study, a subjective experiment was set under normalized viewing conditions (according to the ITU-R BT.500-11 recommendations [9]). The display monitor was a 22" iMac with a $1920 \times 1080$ resolution, 50Hz, and with a minimum and maximum of respectively 0.26 and 213 $Cd/m^2$. A threshold detection protocol* has been specifically designed. Sixty four observers were enrolled and were asked to tune independently the $a$ and $b$ parameters of equation 2 until the visibility threshold was reached. All observers were screened for normal acuity (using the Monoyer chart) and correct color vision (using Ishihara color plates). Every observer was asked to determine the visibility threshold for a given embedding equation and for 5 input images watermarked in six embedding sub-bands. Therefore, every session was composed of 30 images, which made the experiment duration within a 30 minutes time frame. Overall, ten original color images, of size $768 \times 512$ were selected from the KODAK image database†. Every image was watermarked using Equation 2 with either $k = 0.5$, $k = 1$ or $k = 2$ independently in one of the 6 selected sub-bands. For every displayed image, the experiment was composed of two successive steps. In a first step, the observers had to tune the $a$ parameter using the "UP" and "DOWN" arrows of the keyboard, once the visibility threshold was reached, the "LEFT" and "RIGHT" arrows were used for modifying parameter $b$. Finally, the observers validated their choices with the "RETURN" key. The initial values for both $a$ and $b$ was set to 0.00002 and any stroke on the "UP" or "RIGHT" arrows multiplied $a$ or $b$ by a factor of 2 (respectively, any stoke on the "DOWN" or "LEFT" arrows divided the parameters by 2). The average $a$ and $b$ values provided by the observers (denoted as $\bar{a}$ and $\bar{b}$) are used in the following experiments. Note that in this work, we did not run an additive only subjective test, and thus, the results depicted here use the maximum $\bar{b}$ parameter from the hybrid-1, hybrid-2 and hybrid-3 scenarios.

*The source code for the subjective experiment is available on-line: http://www.irccyn.ec-nantes.fr/~autrusse/jnd/

†http://www.cipr.rpi.edu/resource/stills/kodak.html

During the subjective experiment, it was observed that while the increase of the $a$ parameter made the watermark more evident at a first stage near the image edges, the increase of the $b$ parameter made the distortions appear first in the smooth areas of the image. It is important to notice that the higher is the $k$ parameter, the narrower gets the watermark energy along the edges.

## 4. EXPERIMENTAL ANALYSIS

The optimal watermark strengths provided by the observers were thus collected from the subjective experiment. In this section, we analyse the robustness of the 7 considered scenarios (see section 2). We furthermore make an attempt to determine the visibility threshold by using a quality metric (13 objective quality metrics were tested, and PSNR results are presented here).

### 4.1. Robustness analysis

The aim of this study being to compare the robustness performances of additive, multiplicative and hybrid embedding techniques, we show on Figure 2 the correlation coefficient for 35 selected attacks and for the three embedding scenarios (additive, multiplicative and hybrid watermarking). The ten input images were watermarked using $\bar{a}$ and $\bar{b}$ obtained from the subjective experiment. Each marked image was attacked using 35 distortions. The selected distortions are: JPEG 2000 coding (with bit-rates ranging from 0.04 bpp to 0.5 bpp), JPEG coding (quality factor from 10 to 70 %), noise addition (Gaussian noise with a variance ranging from 0.001 to 0.011), and various filtering methods (sharpening, $3 \times 3$ Gaussian filtering with variances between 0.5 and 1.1, and median filtering).

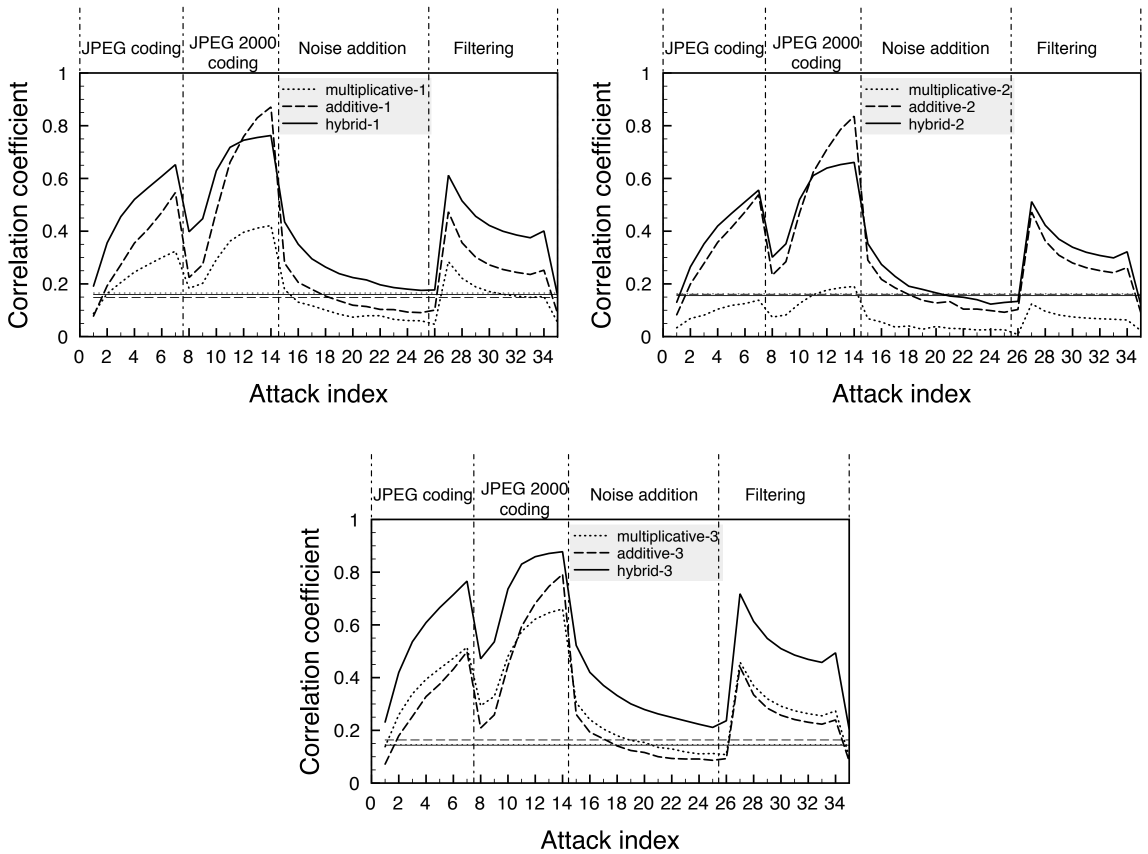


**Figure 2.** Comparison between additive, multiplicative and hybrid embedding scenarios for 35 selected attacks and for the three selected equations (brief details on the attacks are given above each plot).

The multiplicative embedding is represented with the dotted line, the dashed line represents the detection for the additive embedding and the hybrid technique is plotted with a solid line. The three figures respectively stands for $k = 1$ (Figure 2, top left panel), $k = 2$ (Figure 2, top right) and $k = 0.5$ (Figure 2, bottom panel). The horizontal lines on each plot represents the detection threshold for a particular scenario. The thresholds were computed for every equation and within every wavelet sub-band by plotting the detector response; 1000 watermarks were used within every wavelet level. In this figure, only the lowest frequency sub-band (wavelet Level 3) was watermarked, however similar results were observed in other frequency levels. The curves are averaged for the 10 input images, and the 2 selected orientations. It clearly appears that using the hybrid scenario (both the $a$ and $b$ parameters) significantly improves the overall robustness. It is also interesting to notice that, surprisingly, the additive embedding overall provides better robustness performances than the multiplicative watermarking scenario. The three computed thresholds, corresponding to each embedding formula, being very close to each other. Finally, it appears on Figure 2 that using $k = 0.5$ globally improves the detection performances for all three considered frameworks (additive, multiplicative and hybrid embedding).

In order to have a better idea of the robustness performances for every embedding level, the percentage of correct detection was computed for every wavelet sub-band and the average for every wavelet level is plotted in Figure 3. For every level, the first three bars (darkest bars) represent the multiplicative embedding scenario, whereas the last three bars (lightest ones) represent the hybrid scenario. As previously noticed on Figure 2, this plot clearly shows better robustness performances for the hybrid scenario. The robustness results for the additive embedding are depicted with a white diamond. Typically, for the linear embedding method ($k = 1$) in the third decomposition level, the use of the multiplicative embedding framework leads to 48% correct detection (against 35 attacks) the additive embedding reaches 60% correct detections whereas using the hybrid embedding brings the detection rate to 91%. Again, it is interesting to notice that the average robustness is better with the additive embedding scenario than for the "multiplicative-1" embedding (black bar).

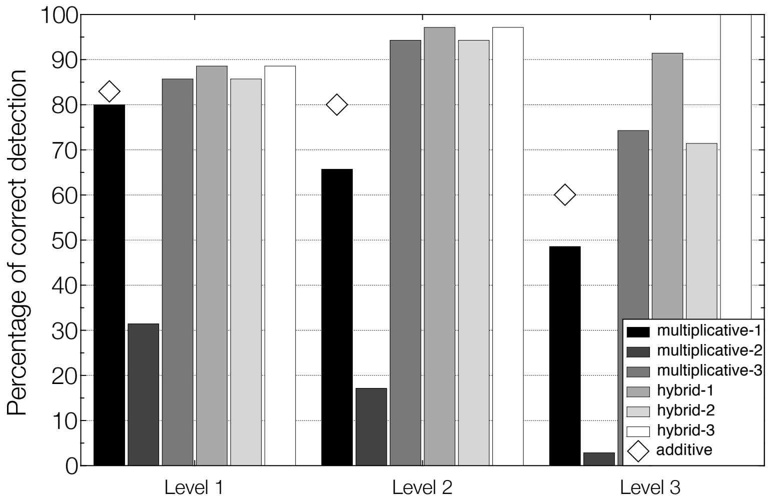


**Figure 3.** Percentage of correct detection for the additive, multiplicative and hybrid scenarios.

## 4.2. Objective metrics for Visibility Threshold modeling

In the robustness analysis, the parameters $\bar{a}$ and $\bar{b}$ of the embedding equations were obtained using subjective experiment. Even though the subjective experiment will give the most accurate value of the embedding parameters at the visibility threshold, it is very time consuming and thus impractical in most of the applications. An alternative way to find the optimal embedding parameters is to use objective quality metrics. In such a scenario, the embedding parameters have to be tuned until a target metric value is reached. Figure 4 shows the PSNR values of 10 test images marked using the hybrid-3 embedding technique at the visibility threshold. It can be observed that there is a lot of variation in the PSNR values of watermarked images in each level and also across different wavelet sub-band decomposition levels. So the PSNR may not be suitable for modeling the embedding parameters. We have also tested the suitability of other objective quality metrics, including the 12 metrics in the Metrix Mux package[‡] and the CPA metric [10], in modeling the embedding parameters. However, none of the tested metrics were found to be suitable for this purpose due to the wide variation of metric values.

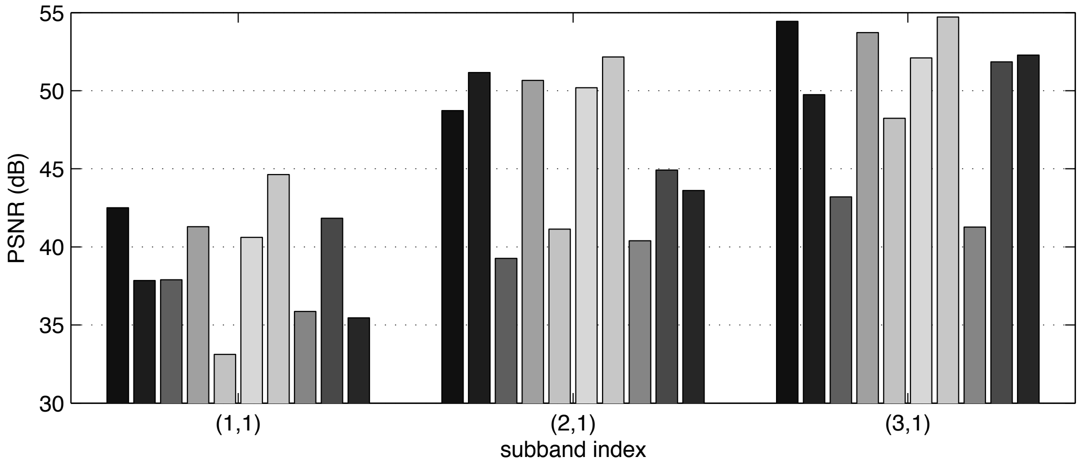


**Figure 4.** PSNR values of 10 marked images using hybrid-3 embedding in three wavelet levels.

In order to further understand the impact of target metric scenario on the perceptual quality of the watermarked images, we tested the quality of images marked using target PSNR. For this experiment, a target PSNR was fixed at 40dB, and the $a$ embedding coefficient was increased until the target PSNR was reached (the $b$ parameter was discarded in this experiment). The resulting watermarked images are depicted on Figure 5 for the "plane" image watermarked within sub-band $(3, 1)$. We can observe that for all three marked images using the target PSNR (left images and top right image), the distortions induced by the watermark are clearly visible, whereas if the $\bar{a}$ parameter is used (bottom right image), the distortions are invisible. We have depicted a zoom on the plane's helix in order to highlight the induced distortions (represented by the insets located at the top right of every image).

## 5. CONCLUSION

In this work, we have presented a hybrid watermark embedding technique, which mixes both additive and multiplicative embedding scenarios. We have shown that mixing these two techniques significantly improves the robustness performances. Three embedding equations were used in order to enhance the watermark strength in various portions of the wavelet coefficients. On the 35 tested attacks, the percentage of correct detection can be improved by more than 40 percent for the commonly used multiplicative embedding scenario in the third wavelet level. Based on the experimental analysis, it was found that using a square-root embedding significantly increases the robustness performance, and moreover using the hybrid additive-multiplicative embedding framework provided overall the best robustness, and thus, the hybrid embedding could be considered for JND modeling. It was also observed that the additive embedding provided better robustness than the multiplicative watermarking on the selected attacks. The watermark strength was determined from a subjective experiment where the observers were asked to tune the strength at the visibility threshold. Further research is required to model the embedding parameters in order to automatically determine the optimal embedding strength for a given input image.

[‡]http://foulard.ece.cornell.edu/gaubatz/metrix_mux/

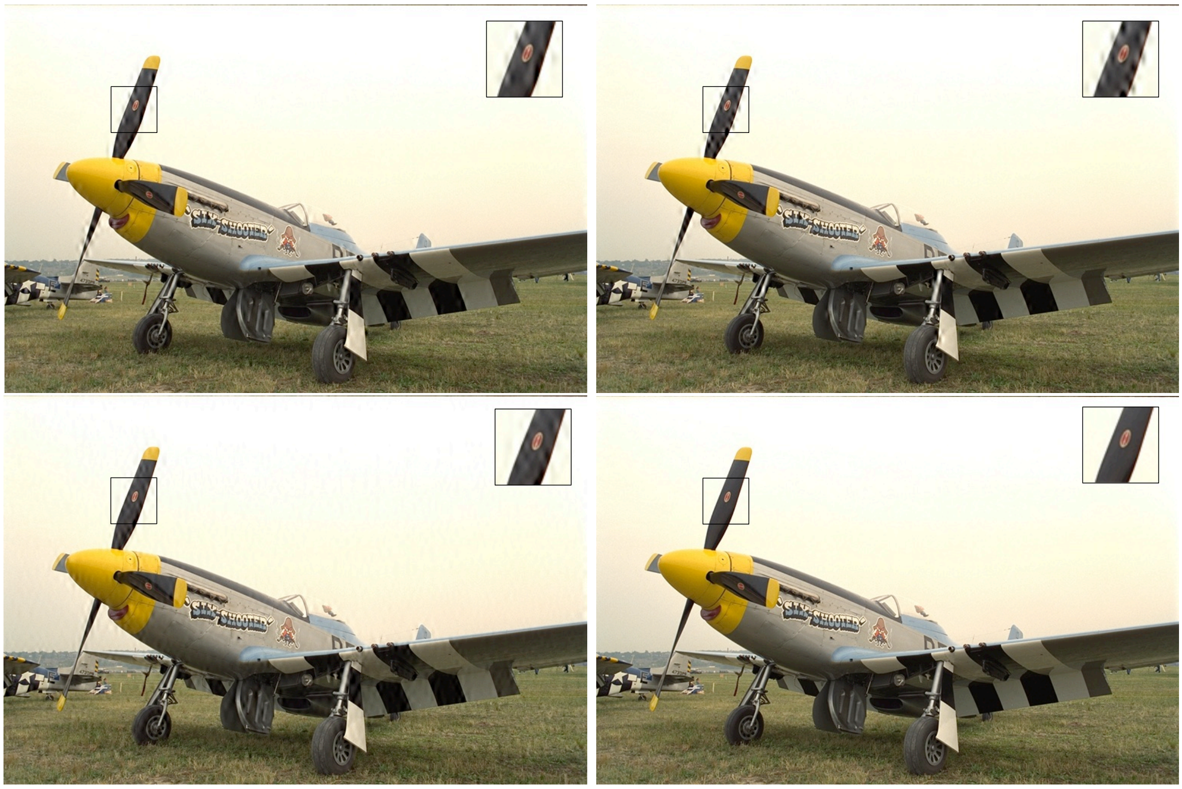

**Figure 5.** Watermarked images when a target PSNR was set to 40dB using $k = 1$ (top left), $k = 2$ (top right), $k = 0.5$ (bottom left) and $\bar{a}$ provided by the observers during the subjective experiment (bottom right).

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