# Color Balance and Fusion for Underwater Image Enhancement

Codruta O. Ancuti, Cosmin Ancuti, Christophe De Vleeschouwer, and Philippe Bekaert

*Abstract*—**We introduce an effective technique to enhance the images captured underwater and degraded due to the medium scattering and absorption. Our method is a single image approach that does not require specialized hardware or knowledge about the underwater conditions or scene structure. It builds on the blending of two images that are directly derived from a color-compensated and white-balanced version of the original degraded image. The two images to fusion, as well as their associated weight maps, are defined to promote the transfer of edges and color contrast to the output image. To avoid that the sharp weight map transitions create artifacts in the low frequency components of the reconstructed image, we also adapt a multiscale fusion strategy. Our extensive qualitative and quantitative evaluation reveals that our enhanced images and videos are characterized by better exposedness of the dark regions, improved global contrast, and edges sharpness. Our validation also proves that our algorithm is reasonably independent of the camera settings, and improves the accuracy of several image processing applications, such as image segmentation and keypoint matching.**

*Index Terms*—**Underwater, image fusion, white-balancing.**

## I. Introduction and Overview

UNDERWATER environment offers many rare attractions such as marine animals and fishes, amazing landscape, and mysterious shipwrecks. Besides underwater photography, underwater imaging has also been an important source of interest in different branches of technology and scientific research [1], such as inspection of underwater infrastructures [2] and cables [3], detection of man made objects [4], control of underwater vehicles [5], marine biology research [6], and archeology [7].

Different from common images, underwater images suffer from poor visibility resulting from the attenuation of the propagated light, mainly due to absorption and scattering effects. The absorption substantially reduces the light energy, while the scattering causes changes in the light propagation direction. They result in foggy appearance and contrast degradation, making distant objects misty. Practically, in common sea water images, the objects at a distance of more than 10 meters are almost unperceivable, and the colors are faded because their composing wavelengths are cut according to the water depth.

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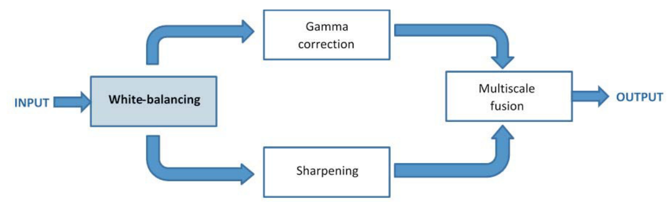


Fig. 1. Method overview: two images are derived from a white-balanced version of the single input, and are merged based on a (standard) multiscale fusion algorithm. the novelty of our approach lies in the proposed pipeline, but also in the definition of a white-balancing algorithm that is suited to our underwater enhancement problem.

There have been several attempts to restore and enhance the visibility of such degraded images. Since the deterioration of underwater scenes results from the combination of multiplicative and additive processes [8] traditional enhancing techniques such as gamma correction, histogram equalization appear to be strongly limited for such a task. In the previous works that are surveyed in Section II.B, the problem has been tackled by tailored acquisition strategies using multiple images [9], specialized hardware [10] or polarization filters [11]. Despite of their valuable achievements, these strategies suffer from a number of issues that reduce their practical applicability.

In contrast, this paper introduces a novel approach to remove the haze in underwater images based on a single image captured with a conventional camera. As illustrated in Fig. 1, our approach builds on the fusion of multiple inputs, but derives the two inputs to combine by correcting the contrast and by sharpening a white-balanced version of a single native input image. The white balancing stage aims at removing the color cast induced by underwater light scattering, so as to produce a natural appearance of the sub-sea images. The multi-scale implementation of the fusion process results in an artifact-free blending.

The rest of the paper is structured as follows. The next section briefly surveys the optical specificities of the underwater environment, before summarizing the work related to underwater dehazing. In Section III, we present our novel white-balancing approach, especially designed for underwater images. Section IV then describes the main components of our fusion-based enhancing technique, including inputs and associated weight maps definition. Before concluding, we present

# Single Image Dehazing by Multi-Scale Fusion

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***Abstract*— Haze is an atmospheric phenomenon that significantly degrades the visibility of outdoor scenes. This is mainly due to the atmosphere particles that absorb and scatter the light. This paper introduces a novel single image approach that enhances the visibility of such degraded images. Our method is a fusion-based strategy that derives from two original hazy image inputs by applying a white balance and a contrast enhancing procedure. To blend effectively the information of the derived inputs to preserve the regions with good visibility, we filter their important features by computing three measures (weight maps): luminance, chromaticity, and saliency. To minimize artifacts introduced by the weight maps, our approach is designed in a multiscale fashion, using a Laplacian pyramid representation. We are the first to demonstrate the utility and effectiveness of a fusion-based technique for dehazing based on a single degraded image. The method performs in a per-pixel fashion, which is straightforward to implement. The experimental results demonstrate that the method yields results comparative to and even better than the more complex state-of-the-art techniques, having the advantage of being appropriate for real-time applications.**

***Index Terms*— Single image dehazing, outdoor images, enhancing.**

## I. Introduction

OFTEN, the images of outdoor scenes are degraded by bad weather conditions. In such cases, atmospheric phenomena like haze and fog degrade significantly the visibility of the captured scene. Since the aerosol is misted by additional particles, the reflected light is scattered and as a result, distant objects and parts of the scene are less visible, which is characterized by reduced contrast and faded colors.

Restoration of images taken in these specific conditions has caught increasing attention in the last years. This task is important in several outdoor applications such as remote sensing, intelligent vehicles, object recognition and surveillance. In remote sensing systems, the recorded bands of reflected light are processed [1], [2] in order to restore the outputs. Multi-image techniques [3] solve the image dehazing problem by processing several input images, that have been taken in different atmospheric conditions. Another alternative [4] is to assume that an approximated 3D geometrical model of the scene is given. In this paper of Treibitz and Schechner [5] different angles of polarized filters are used to estimate the haze effects.

A more challenging problem is when only a single degraded image is available. Solutions for such cases have been introduced only recently [6]–[10].

In this paper we introduce an alternative single-image based strategy that is able to accurately dehaze images using only the original degraded information. An extended abstract of the core idea has been recently introduced by the authors in [11]. Our technique has some similarities with the previous approaches of Tan [7] and Tarel and Hautière [10], which enhance the visibility in such outdoor images by manipulating their contrast.

However, in contrast to existing techniques, we built our approach on a fusion strategy. We are the first to demonstrate the utility and effectiveness of a fusion-based technique for dehazing on a single degraded image. Image fusion is a well studied process [12], that aims to blend seamlessly several input images by preserving only the specific features of the composite output image. In this work, our goal is to develop a simple and fast technique and therefore, as will be shown, all the fusion processing steps are designed in order to support these important features. The main concept behind our fusion based technique is that we derive two input images from the original input with the aim of recovering the visibility for each region of the scene in at least one of them. Additionally, the fusion enhancement technique estimates for each pixel the desirable perceptual based qualities (called weight maps) that controls the contribution of each input to the final result. In order to derive the images that fulfill the visibility assumptions (good visibility for each region in at least one of the inputs) required for the fusion process, we analyze the optical model for this type of degradation. There are two major problems, the first one is the color cast that is introduced due to the airlight influence and the second is the lack of visibility into distant regions due to scattering and attenuation phenomena.

The first derived input ensures a natural rendition of the output, by eliminating chromatic casts that are caused by the airlight color, while the contrast enhancement step yields a better global visibility, but mainly in the hazy regions. However, by employing these two operations, the derived inputs taken individually still suffer from poor visibility (e.g. analyzing figure 3 it can be easily observed that the second input restores the contrast of the hazy inputs, but at the cost of altering the initial visibility of the closer/haze-free regions).

Therefore, to blend effectively the information of the derived inputs, we filter (in a per-pixel fashion) their important features, by computing several measures (weight maps). Consequently, in our fusion framework the derived inputs

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# Single-Scale Fusion: An Effective Approach to Merging Images

Codruta O. Ancuti, Cosmin Ancuti, Christophe De Vleeschouwer, and Alan C. Bovik, *Fellow, IEEE*

***Abstract*— Due to its robustness and effectiveness, multi-scale fusion (MSF) based on the Laplacian pyramid decomposition has emerged as a popular technique that has shown utility in many applications. Guided by several intuitive measures (weight maps) the MSF process is versatile and straightforward to implemented. However, the number of pyramid levels increases with the image size, which implies sophisticated data management and memory accesses, as well as additional computations. Here, we introduce a simplified formulation that reduces MSF to only a single level process. Starting from the MSF decomposition, we explain both mathematically and intuitively (visually) a way to simplify the classical MSF approach with minimal loss of information. The resulting single-scale fusion (SSF) solution is a close approximation of the MSF process that eliminates important redundant computations. It also provides insights regarding why MSF is so effective. While our simplified expression is derived in the context of high dynamic range imaging, we show its generality on several well-known fusion-based applications, such as image compositing, extended depth of field, medical imaging, and blending thermal (infrared) images with visible light. Besides visual validation, quantitative evaluations demonstrate that our SSF strategy is able to yield results that are highly competitive with traditional MSF approaches.**

***Index Terms*— Multi-scale image fusion, Laplacian pyramid, image enhancement.**

## I. Introduction

The advent of advanced image sensors has empowered effective and affordable applications such as digital photography, industrial vision, surveillance, medical applications, automotive, remote sensing, etc. However, in many cases the optical sensor is not able to accurately capture the scene content richness in a single shot. For example, the dynamic range of a real world scene is usually much higher than can be recorded with common digital imaging sensors, since the luminances of bright or highlighted regions can be 10,000 times greater than dark or shadowed regions. Therefore, such high dynamic range scenes captured by digital images are often degraded by under or over-exposed regions where details are completely lost. One solution to obtain a complete dynamic range depiction of scene content is to capture a sequence of LDR (low dynamic range) images captured with different exposure settings. The bracketed exposure sequence is then fused by preserving only well-exposed features from the different exposures. Similarly, night-time images are difficult to be processed due to poor illumination, making it difficult to capture a successful image even using the HDR (high dynamic range) method. However, by also capturing with a co-located infrared (IR) image sensor, it is possible to enrich the visual appearance of night-time by fusing complementary features from the optical and IR images.

Challenging problems like these require effective fusion strategies to blend information obtained from multiple-input imaging sources into visually agreeable images. Image fusion is a well-known concept that seeks to optimize information drawn from multiple images taken of the same sensor or different sensors. The aim of the fusion process is that the fused result yields a better depiction of the original scene, than any of the original source images.

Image fusion methods have been applied to a wide range of tasks including extended depth-of-field [1], texture synthesis [2], image editing [3], image compression [4], multi-sensor photography [5], context enhancement and surrealist video processing [6], image compositing [7], enhancing under-exposed videos [8], multi-spectral remote sensing [9], medical imaging [10].

Many different strategies to fuse a set of images have been introduced in the literature [11]. The simplest methods, including averaging and principal component analysis (PCA) [12], straightforwardly fuse the input images' intensity values. Multi-resolution analysis has also been extensively considered to match processing the human visual system. The discrete wavelet transform (DWT) was deployed by Li et al. [13] to accomplish multi-sensor image fusion. The DWT fusion method computes a composite multi-scale edge representation by selecting the most salient wavelet coefficients from among the inputs. To overcome the shift dependency of the DWT fusion approach, Rockinger [14] proposed using a shift

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# Effective Contrast-Based Dehazing for Robust Image Matching

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***Abstract*—In this letter we present a novel strategy to enhance images degraded by the atmospheric phenomenon of haze. Our single-based image technique does not require any geometrical information or user interaction enhancing such images by restoring the contrast of the degraded images. The degradation of the finest details and gradients is constrained to a minimum level. Using a simple formulation that is derived from the lightness predictor our contrast enhancement technique restores lost discontinuities only in regions that insufficiently represent original chromatic contrast of the scene. The parameters of our simple formulation are optimized to preserve the original color spatial distribution and the local contrast. We demonstrate that our dehazing technique is suitable for the challenging problem of image matching based on local feature points. Moreover, we are the first that present an image matching evaluation performed for hazy images. Extensive experiments demonstrates the utility of the novel technique.**

***Index Terms*—Dehazing, image matching, Scale Invariant Feature Transform (SIFT).**

## I. Introduction

GIVEN two or more images of the same scene, the process of image matching requires to find valid corresponding feature points in the images. These matches represent projections of the same scene location in the corresponding image. Since images are in general taken at different times, from different sensors/cameras and viewpoints this task may be very challenging. Image matching plays a crucial role in many remote sensing applications such as, change detection, cartography using imagery with reduced overlapping, fusion of images taken with different sensors. In the early remote sensing systems, this task required substantial human involvement by manually selecting some feature points of significant landmarks. Nowadays, due to the significant progress of local feature points detectors and descriptors, the tasks of matching and registration can be done in most of the cases automatically.

Many local feature points operator have been introduced in the last decade. By extracting regions that are covariant to a class of transformation [1], recent local feature operators are robust to occlusions being invariant to image transformations such as geometric (scale, rotation, affine) and photometric. A comprehensive survey of such local operators is included in the study of [2].

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However, besides the geometric and photometric variations, outdoor and aerial images that need to be matched are often degraded by the haze, a common atmospheric phenomenon. Obviously, remote sensing applications are dealing with such images since in many cases the distance between different sensors and the surface of earth is significant. Haze is the atmospheric phenomenon that dims the clarity of an observed scene due to the particles such as smoke, fog, and dust. A hazy scene is characterized by an important attenuation of the color that depends proportionally by the distance to the scene objects. As a result, the original contrast is degraded and the scene features gradually fades as they are far away from the camera sensor. Moreover, due to the scattering effects the color information is shifted.

Restoring such hazy images is a challenging task. The first dehazing approaches employ multiple images [3] or additional information such as depth map [4] and specialized hardware [5]. Since in general such additional information is not available to the users, these strategies are limited to offer a reliable solution for dehazing problem. More recent, several single image based techniques [6]–[11] have been introduced in the literature. Roughly, these techniques can be divided in two major classes: physically based and contrast-based techniques.

Physically based techniques [6], [9], [10] restore the hazy images based on the estimated transmission (depth) map. The strategy of Fattal [6] restores the airlight color by assuming that the image shading and scene transmission are locally uncorrelated. He *et al.* [9] estimate a rough transmission map version based on the dark channel [12] that is refined in a final step by a computationally expensive alpha-matting strategy. The technique of Nishino *et al.* [10] employs a Bayesian probabilistic model that jointly estimates the scene albedo and depth from a single degraded image by fully leveraging their latent statistical structures.

On the other hand, contrast-based techniques [7], [8], [11] aim to enhance the hazy images without estimating the depth information. Tan's [7] technique maximizes the local contrast while constraining the image intensity to be less than the global atmospheric light value. The method of Tarel and Hautière [8] enhances the global contrast of hazy images assuming that the depth-map must be smooth except along edges with large depth jumps. Ancuti and Ancuti [11] enhance the appearance of hazy images by a multiscale fusion-based technique that is guided by several measurements.

In this letter we introduce a novel technique that removes the haze effects of such degraded images. Our technique is a single-based image that aims to enhance such images by restoring the contrast of the degraded images. Different than

# Deblurring by Matching

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**Abstract**

*Restoration of the photographs damaged by the camera shake is a challenging task that manifested increasing attention in the recent period. Despite of the important progress of the blind deconvolution techniques, due to the ill-posed nature of the problem, the finest details of the kernel blur cannot be recovered entirely. Moreover, the additional constraints and prior assumptions make these approaches to be relative limited.*

*In this paper we introduce a novel technique that removes the undesired blur artifacts from photographs taken by hand-held digital cameras. Our approach is based on the observation that in general several consecutive photographs taken by the users share image regions that project the same scene content. Therefore, we took advantage of additional sharp photographs of the same scene. Based on several invariant local feature points, filtered from the given blurred/non-blurred images, our approach matches the keypoints and estimates the blur kernel using additional statistical constraints.*

*We also present a simple deconvolution technique that preserves edges while minimizing the ringing artifacts in the restored latent image. The experimental results prove that our technique is able to infer accurately the blur kernel while reducing significantly the artifacts of the spoilt images.*

Categories and Subject Descriptors (according to ACM CCS): Enhancement [I.4.3]: Sharpening and deblurring; —Image Processing and Computer Vision [I.4.9]: Applications—

## 1. Introduction

In recent years hand-held digital cameras have become very popular in many householders. A common problem that amateur photographs are faced with is the motion blur distortions due to the camera shake. Every slight shake during the exposure time increases the undesired blur artifacts. Only adjusting the exposure time may not solve entirely this trouble. For short exposure times, motion blur is still perceptible and, in addition, the darkness and the noise can destroy important details.

Image deblurring has long been a fundamental problem that preoccupied research community. Removing the undesired artifacts of a blurry image is translated into a deconvolution problem. However, the problem is mathematically under-constrained.

Even though the blur kernel is given, the problem, known also as *non-blind deconvolution*, is still ill-posed and therefore the finest details are irreversibly ruined.

On the other hand, restoring the original image without a priori knowledge of the blur kernel or PSF - *point spread function*, termed as *blind deconvolution*, is radically more challenging. In this case a twofold problem needs to be solved at the same time: estimate the blur kernel and recover the latent image. Despite of the progress in the field introduced by the recent techniques [FSH*06, LFDF07, YSQS08, SJA08], real blur kernels are complicated, being described by various distributions, that are difficult to infer accurately from a single image. Figure 3 presents the inferred blur kernels yielded by two recent state-of-the-art approaches [FSH*06, SJA08]. Images have been synthetically blurred and for generating the presented results we used the

# Enhancing Underwater Images and Videos by Fusion

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## Abstract

*This paper describes a novel strategy to enhance underwater videos and images. Built on the fusion principles, our strategy derives the inputs and the weight measures only from the degraded version of the image. In order to overcome the limitations of the underwater medium we define two inputs that represent color corrected and contrast enhanced versions of the original underwater image/frame, but also four weight maps that aim to increase the visibility of the distant objects degraded due to the medium scattering and absorption. Our strategy is a single image approach that does not require specialized hardware or knowledge about the underwater conditions or scene structure. Our fusion framework also supports temporal coherence between adjacent frames by performing an effective edge preserving noise reduction strategy. The enhanced images and videos are characterized by reduced noise level, better exposedness of the dark regions, improved global contrast while the finest details and edges are enhanced significantly. In addition, the utility of our enhancing technique is proved for several challenging applications.*

## 1. Introduction

Underwater imaging is challenging due to the physical properties existing in such environments. Different from common images, underwater images suffer from poor visibility due to the attenuation of the propagated light. The light is attenuated exponentially with the distance and depth mainly due to absorption and scattering effects. The absorption substantially reduces the light energy while the scattering causes changes in the light direction. The random attenuation of the light is the main cause of the foggy appearance while the the fraction of the light scattered back from the medium along the sight considerably degrades the scene contrast. These properties of the underwater medium yields scenes characterized by poor contrast where distant objects appear misty. Practically, in common sea water, the objects at a distance of more than 10 meters are almost indistinguishable while the colors are faded since their characteristic wavelengths are cut according to the water depth.

There have been several attempts to restore and enhance the visibility of such degraded images. Mainly, the problem can be tackled by using multiple images [21], specialized hardware [15] and by exploiting polarization filters [25]. Despite their effectiveness to restore underwater images, these strategies have demonstrated several important issues that reduce their practical applicability. First, the hardware solutions (e.g. laser range-gated technology and synchronous scanning) are relatively expensive and complex. The multiple-image solutions require several images of the same scene taken in different environment conditions. Similarly, polarization methods process several images that have different degrees of polarization. While this is relatively feasible for outdoor hazy and foggy images, for the underwater case, the setup of the camera might be troublesome. In addition, these methods (except the hardware solutions) are not able to deal with dynamic scenes, thus being impractical for videos.

In this paper, we introduce a novel approach that is able to enhance underwater images based on a single image, as well as videos of dynamic scenes. Our approach is built on the fusion principle that has shown utility in several applications such as image compositing [14], multispectral video enhancement [6], defogging [2] and HDR imaging [20]. In contrast to these methods, our fusion-based approach does not require multiple images, deriving the inputs and the weights only from the original degraded image. We aim for a straightforward and computationally inexpensive that is able to perform relatively fast on common hardware. Since the degradation process of underwater scenes is both multiplicative and additive [26] traditional enhancing techniques like white balance, color correction, histogram equalization shown strong limitations for such a task. Instead of directly filtering the input image, we developed a fusion-based scheme driven by the intrinsic properties of the original image (these properties are represented by the weight maps). The success of the fusion techniques is highly dependent on the choice of the inputs and the weights and therefore we investigate a set of operators in order to overcome limitations specific to underwater environments. As a result, in our framework the degraded image is firstly white balanced in order to remove the color

# Enhancing by Saliency-guided Decolorization

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## Abstract

*This paper introduces an effective decolorization algorithm that preserves the appearance of the original color image. Guided by the original saliency, the method blends the luminance and the chrominance information in order to conserve the initial color disparity while enhancing the chromatic contrast. As a result, our straightforward fusing strategy generates a new spatial distribution that discriminates better the illuminated areas and color features. Since we do not employ quantization or a per-pixel optimization (computationally expensive), the algorithm has a linear runtime, and depending on the image resolution it could be used in real-time applications. Extensive experiments and a comprehensive evaluation against existing state-of-the-art methods demonstrate the potential of our grayscale operator. Furthermore, since the method accurately preserves the finest details while enhancing the chromatic contrast, the utility and versatility of our operator have been proved for several other challenging applications such as video decolorization, detail enhancement, single image dehazing and segmentation under different illuminants.*

## 1. Introduction

Image decolorization is important in several applications (e.g. monochrome printing, medical imaging, monochrome image processing, stylization). Standard conversion, found in commercial image editing software, neglects the color distribution, and as a result it is commonly unable to conserve the discriminability of the original chromatic contrast (see figure 1). Mapping three dimensional color information onto a single dimension while still preserving the original appearance, contrast and finest details is not a trivial task.

In the last years several technique have been introduced in the literature. Roughly, the decolorization techniques can be grouped in local [10, 19, 3, 22] and global [11, 14] approaches. Among the techniques of the first class, Gooch et al. [10] introduced an optimization technique that iteratively searches the gray levels that best represent the color differences between all color pairs. Similarly, the method of Rasche et al. [19] seeks to optimize a quadratic objective function that incorporates both contrast preservation and luminance consistency. Smith et al. [22] developed a two-step algorithm that employs an unsharp mask-related strategy to emphasize the finest transitions. On the other hand, the global strategy of Grundland and Dodgson [11] performs a dimensionality reduction using the predominant component analysis. This approach does not take into consideration chromatic differences that are spatially distant, mapping in some cases different colors into very similar grayscale levels. Recently, Kim et al. [14] have optimized the Gooch et al. [10] method via nonlinear global mapping. Even more computationally effective, this strategy did not solve the problems of the Gooch et al. [10] approach risking to blur some of the fine details. In general, due to quantization strategies or prohibitive function optimization, the existing approaches fail to render the original image *look* and to preserve the finest details and the luminance consistency (shadows and highlights should not be reversed). Additionally, most of the existing approaches are computationally expensive.

Different than existing methods, we argue that the concept of image decolorization is not to generate a perfect optical match, but rather to obtain a plausible image that maintains the overall appearance and primary the contrast of the most salient regions. Our straightforward operator performs a global chromatic mapping that acts similarly as color filters [1]. In our scheme, the luminance level is progressively augmented by the chromatic variation of the salient information. Generally considered an important feature, saliency was not addressed directly in previous approaches. After the monochromatic luminance channel is filtered and stored as a reference, the luminance values are computed pixel-wise by mixing both saturation and hue values, creating a new spatial distribution with an increased contrast of the interest regions. All the precomputed values are normalized in order to fit the entire intensity range. The intensity is re-balanced in order to conserve the amount of glare in the initial image. For extreme lighting conditions, we apply several constraints in order to avoid clipping and fading of

# NIGHT-TIME DEHAZING BY FUSION

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**ABSTRACT**

We introduce an effective technique to enhance night-time hazy scenes. Our technique builds on multi-scale fusion approach that use several inputs derived from the original image. Inspired by the dark-channel [1] we estimate night-time haze computing the airlight component on image patch and not on the entire image. We do this since under night-time conditions, the lighting generally arises from multiple artificial sources, and is thus intrinsically non-uniform. Selecting the size of the patches is non-trivial, since small patches are desirable to achieve fine spatial adaptation to the atmospheric light, this might also induce poor light estimates and reduced chance of capturing hazy pixels. For this reason, we deploy multiple patch sizes, each generating one input to a multiscale fusion process. Moreover, to reduce the glowing effect and emphasize the finest details, we derive a third input. For each input, a set of weight maps are derived so as to assign higher weights to regions of high contrast, high saliency and small saturation. Finally the derived inputs and the normalized weight maps are blended in a multi-scale fashion using a Laplacian pyramid decomposition. The experimental results demonstrate the effectiveness of our approach compared with recent techniques both in terms of computational efficiency and quality of the outputs.

***Index Terms*—** night-time, hazy, dehazing, multi-scale fusion

## I. INTRODUCTION

Capturing good quality outdoor images poses interesting challenges since such scenes often suffer from poor visibility introduced by weather conditions such as haze or fog. The process dehazing has been tackled using such information as rough depth [2] of the scene or multiple images [3]. More recently, several techniques [4], [5], [1], [6], [7], [8], [9], [10], [11], [12], [13], [14], have introduced solutions that do not require any additional information than the single input hazy image.

While the effectiveness of these techniques has been extensively demonstrated on daylight hazy scenes, they suffer from important limitations on night-time hazy scenes. This is mainly due to the multiple light sources that cause a strongly non-uniform illumination of the scene. Night-time dehazing has been addressed only recently [15], [16], [17]. Pei and Lee [15] estimate the airlight and the haze thickness by applying a color transfer function before applying the dark channel prior [1], [18] refined iteratively by bilateral filtering as a post-processing step. The method of Zhang et al. [16] estimates non-uniform incident illumination and performs color correction before using the dark channel prior. Li et al.[17] employ an updated optical model by adding the atmospheric point spread function to model the glowing effect. A spatially varying atmospheric light map is used to estimate the transmission map based dark channel prior.

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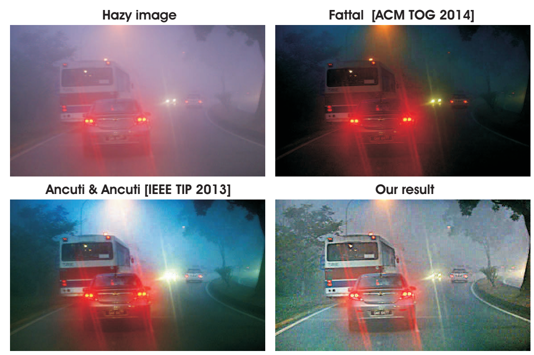


**Fig. 1**. *Night-time scene capture is a challenging task under difficult weather conditions and recent single-image dehazing techniques [11], [10] suffer from important limitations when applied to such images.*

We introduce a different approach to solving the problem of night-time dehazing. We develop the first fusion-based method of restoring hazy night-time images. Image fusion is a well-known concept that has been used for image editing [19], image compositing [20],image dehazing [10], HDR imaging [21], underwater image and video enhancement [22] and image decolorization [23]. The approach described here is built on our previous fusion-based daytime dehazing approach [10] that has been recently extended by Choi et al. in [24].

To deal with the problem of night-time hazy scenes (refer to Fig. 1), we propose a novel way to compute the airlight component while accounting for the non-uniform illumination presents in nighttime scenes. Unlike the well-known dark-channel strategy [18] that estimates a constant atmospheric light over the entire image, we compute this value locally, on patches of varying sizes. This is found to succeed since under night-time conditions, the lighting results from multiple artificial sources, and is thus intrinsically non-uniform. In practice, the local atmospheric light causes the color observed in hazy pixels, which are the brightest pixels of local dark channel patches. Selecting the size of the patches is non-trivial since small patches are desirable to achieve fine spatial adaptation to the atmospheric light, it might also lead to poor light estimates and reduced chance of capturing hazy pixels. For this reason, we

# D-HAZY: A DATASET TO EVALUATE QUANTITATIVELY DEHAZING ALGORITHMS

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## ABSTRACT

Dehazing is an image enhancing technique that emerged in the recent years. Despite of its importance there is no dataset to quantitatively evaluate such techniques. In this paper we introduce a dataset that contains 1400+ pairs of images with ground truth reference images and hazy images of the same scene. Since due to the variation of illumination conditions recording such images is not feasible, we built a dataset by synthesizing haze in real images of complex scenes. Our dataset, called **D-HAZY**, is built on the Middelbury [1] and NYU Depth [2] datasets that provide images of various scenes and their corresponding depth maps. Due to the fact that in a hazy medium the scene radiance is attenuated with the distance, based on the depth information and using the physical model of a hazy medium we are able to create a corresponding hazy scene with high fidelity. Finally, using D-HAZY dataset, we perform a comprehensive quantitative evaluation of several state of the art single-image dehazing techniques.

***Index Terms*—** dehazing, depth, quantitative evaluation

## I. INTRODUCTION

Image dehazing, a typical image enhancement technique studied extensively in the recent years, aims to recover the original light intensity of a hazy scene. While earlier dehazing approaches employ additional information such as multiple images [3] or a rough estimate of the depth [4], recent techniques have tackled this problem by using only the information of a single hazy input image [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16]. The existing techniques restore the latent image assuming the physical model of Koschmieder [17]. Since dehazing problem is mathematically ill-posed there are various strategies to estimate the two unknowns: the airlight constant and the transmission map.

Fattal [5] employs a graphical model that solves the ambiguity of airlight color assuming that image shading and scene transmission are locally uncorrelated. Tan's method [6] maximizes local contrast while constraining the image intensity to be less than the global atmospheric light value. He et al. [7], [18] introduce a powerful approach built on the statistical observation of the dark channel, that allows a rough estimation of the transmission map, further refined by an alpha matting strategy [19]. Tarel and Hautière [8] introduce a filtering strategy assuming that the depth-map must be smooth except along edges with large depth jumps. Kratz and Nishino [9] propose a Bayesian probabilistic method that jointly estimates the scene albedo and depth from a single degraded image by fully leveraging their latent statistical structures. Ancuti et al. [10] describe an enhancing technique built on a fast identification of hazy regions based on the *semi-inverse* of the image. Ancuti and Ancuti [12] introduce a multi-scale fusion procedure that restore such hazy image by defining proper inputs and weight maps. The method has been extended recently by Choi et al. [20]. Meng et al. [21] propose a regularization approach based on a novel boundary constraint applied on the transmission map. Fattal [13] presents a method inspired from color-lines, a generic regularity in natural images. Tang et al. [16] describe a framework that learns a set of feature for image dehazing.

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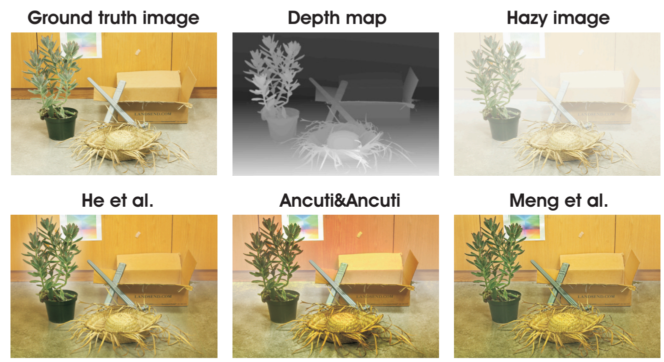


**Fig. 1**. *D-HAZY dataset provides ground truth images and the corresponding hazy image derived from the depth map (known). In the bottom row are shown results yielded by several recent dehazing techniques [18], [12], [21].*

There have been a few attempts to quantitatively evaluate dehazing methods. All of them have been defined as non-reference image quality assessment (NR-IQA) strategies. Hautiere et al. [22] propose a blind measure based on the ratio between the gradient of the visible edges between the hazy image and the restored version of it. Chen et al. [23] introduce a general framework for quality assessment of different enhancement algorithms, including dehazing methods. Their evaluation was based on a preliminary subjective assessment of a dataset which contains source images in bad visibility and their enhanced images processed by different enhancement algorithms. Moreover, general non reference image quality assessment (NR-IQA) strategies [24], [25], [26] have not been designed and tested for image dehazing.

However, none of these quality assessment approaches have been commonly accepted and as a consequence a reliable data set for dehazing problem is extremely important. Unlike other image enhancing problems for dehazing task capturing a valid ground

# Multi-scale Underwater Descattering

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***Abstract*—Underwater images suffer from severe perceptual/visual degradation, due to the dense and non-uniform medium, causing scattering and attenuation of the propagated light that is sensed. Typical restoration methods rely on the popular Dark Channel Prior to estimate the light attenuation factor, and subtract the back-scattered light influence to invert the underwater imaging model. However, as a consequence of using approximate and global estimates of the back-scattered light, most existing single-image underwater descattering techniques perform poorly when restoring non-uniformly illuminated scenes. To mitigate this problem, we introduce a novel approach that estimates the back-scattered light locally, based on the observation of a neighborhood around the pixel of interest. To circumvent issue related to selection of the neighborhood size, we propose to fuse the images obtained over both small and large neighborhoods, each capturing distinct features from the input image. In addition, the Laplacian of the original image is provided as a third input to the fusion process, to enhance texture details in the reconstructed image. These three derived inputs are seamlessly blended via a multi-scale fusion approach, using saliency, contrast, and saturation metrics to weight each input. We perform an extensive qualitative and quantitative evaluation against several specialized techniques. In addition to its simplicity, our method outperforms the previous art on extreme underwater cases of artificial ambient illumination and high water turbidity.**

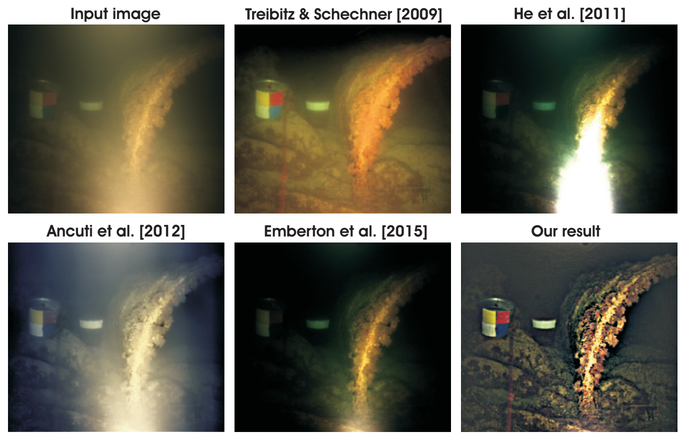


Fig. 1. ***Underwater scene restoration.*** Special-purpose single-image dehazing method of He et al. [21] and also specialized underwater dehazing methods of Ancuti et al. [15] and Emberton et al. [20] are limited in their ability to recover the visibility of challenging underwater scenes. While the polarization-based technique (uses multiple images) of Treibitz and Schechner [7] is competitive, our approach better restores both color and contrast (local and global) in the underwater image.

## I. Introduction

Underwater imaging is required in many applications [1] such as control of underwater vehicles [2], marine biology research [3], inspection of the underwater infrastructure [4] and archeology [5]. However, as compared with computer vision and image processing applications in the surface environment, image analysis underwater is a much more difficult problem, awing to the dense and strongly non-uniform medium where light scatters, i.e. is forced to deviate from its straight trajectory. The poor visual quality of underwater images is mainly due to the attenuation and back-scattering of illumination sources. Back-scattering refers to the diffuse reflection of light, in the direction from which it emanated.

Early underwater imaging techniques employed specialized hardware [6] and multiple images polarized over diverse angles [7], resulting in either expensive or impractical acquisition systems. Recently, inspired by outdoor dehazing [8], [9], [10], [11], [12], [13], [14], several single-image based underwater image enhancement solutions [15], [16], [17], [18], [19], [20] have been introduced. Chiang and Chen [17] first segment the foreground of the scene based on a depth estimate resulting from the Dark Channel Prior (DCP) [9], [21], then perform color correction based on the amount of attenuation expected for each light wavelength. Galdran et al. [19] introduce the Red Channel to recover colors associated with short wavelengths in underwater. Ancuti et al. [15] derives two color corrected inputs and merge them using a multi-scale fusion technique [22]. While the technique proposed in this paper is also based on a multi-scale fusion strategy, here, we derive three distinct inputs that are robust in the presence of highly non-uniform illumination of the scenes (see Fig. 1).

Despite these recent efforts, existing single-image underwater techniques exhibit significant limitations in the presence of turbulent water and/or artificial ambient illumination (see Fig. 1). This is mainly due to poor estimation of the back-scattered light, which is generally assumed to be uniform over the entire image. A unique global value of back-scattered light is only valid in relatively simple underwater scenes having nearly uniform illumination, as is encountered in most outdoor hazy scenes.

In this paper we introduce a novel approach based on local estimation of the back-scattering influence. Following the optical underwater model [23], we first compute the back-scattered light by searching for the brightest location along each image patch. By simply inverting the optical model using