Single Image Haze Removal Using Dark Channel Prior

Chaeeun Ryu (cr3413)

Table of Contents

01

Introduction

INTRODUCTION

“Proposes a simple but effective image prior - ***dark channel prior*** *to r<u>emove haze</u> from a single input image.”*

Hazy image

INTRODUCTION

“Proposes a simple but effective image prior - ***dark channel prior*** *to remove haze from a single input image.”*

Hazy image

Use dark channel prior to remove haze

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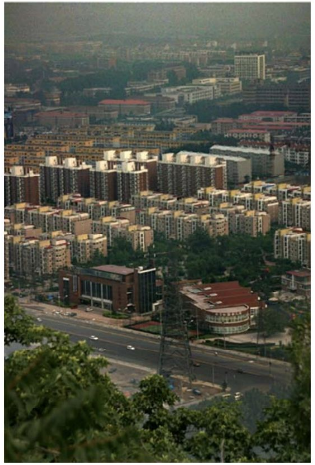


Haze-free Image

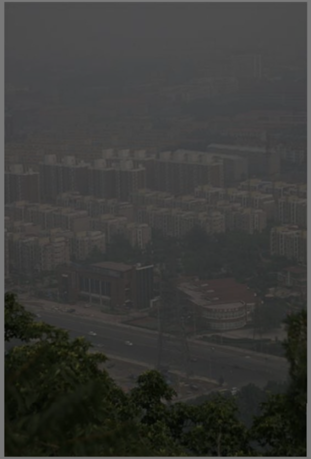
INTRODUCTION

“Proposes a simple but effective image p ***rior*** *to remove haze from a single input image.”*

Dark Channel Prior:
a kind of statistics of outdoor haze-free images

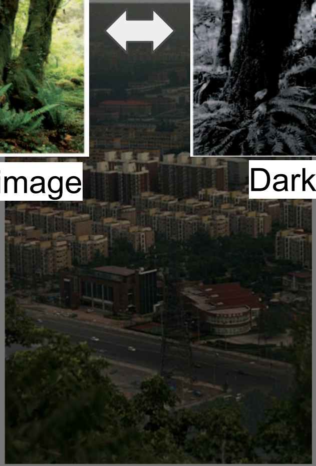
Outdoor haze-free image

Dark channel prior



Hazy image

Use **dark channel prior** to remove haze



Haze-free Image

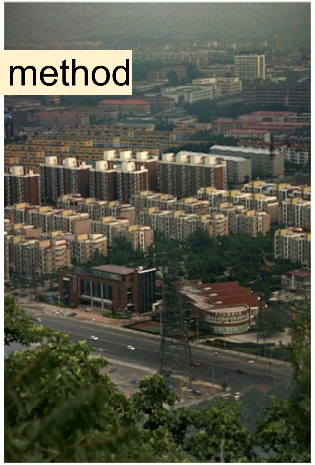
INTRODUCTION

*"Proposes a simple but effective image prior - **dark channel prior** to remove haze from a single input image."*

1) Haze imaging model
2) Soft matting interpolation method

Hazy image

Use dark channel prior to remove haze



Haze-free Image

INTRODUCTION

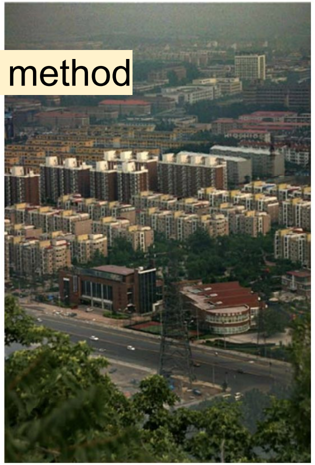
"Proposes a simple but effective image prior - ***dark channel prior*** *to remove haze from a single input image."*

"Accurate estimation of haze transmission"

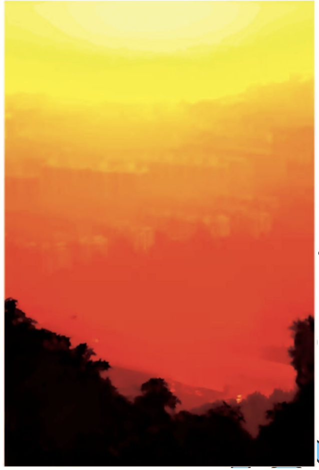
1) Haze imaging model
2) Soft matting interpolation method

Hazy image

Use dark channel prior to remove haze



High quality Haze-free Image



Good Depth map

02

Background

Formulation of a hazy image

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x})),$$

- $\mathbf{I}$: the observed intensity
- $\mathbf{J}$: the scene radiance
- $\mathbf{A}$: the global atmospheric light
- $\mathbf{t}$: the medium transmission describing the portion of the light that is not scattered and reaches the camera

Given $3\mathrm{N}$ constraints, $4\mathrm{N}+3$ unknowns,
The goal of haze removal is to recover $\mathbf{J}$, $\mathbf{A}$, and $\mathbf{t}$ from $\mathbf{I}$.

Formulation of a hazy image

$$\boxed{\mathbf{I}(\mathbf{x})} = \mathbf{J}(\mathbf{x})t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x})),$$

Hazy image

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Formulation of a hazy image

$$\mathbf{I}(\mathbf{x}) = \boxed{\mathbf{J}(\mathbf{x})}t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x})),$$

Hazy image **The haze-free image**

- $\mathbf{I}$: the observed intensity
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Formulation of a hazy image

How much fog there is

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})\boxed{t(\mathbf{x})} + \mathbf{A}(1 - \boxed{t(\mathbf{x})}),$$

Hazy image

The haze-free image

t(x) closer to 0: more haze, lower transmission
t(x) closer to 1: less haze, more transmission

- $\mathbf{I}$: the observed intensity
- $\mathbf{J}$: the scene radiance
- $\mathbf{A}$: the global atmospheric light
- $\mathbf{t}$: the medium transmission describing the portion of the light that is not scattered and reaches the camera

Given $3N$ constraints, $4N+3$ unknowns,
The goal of haze removal is to recover $\mathbf{J}$, $\mathbf{A}$, and $\mathbf{t}$ from $\mathbf{I}$.

Formulation of a hazy image

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})t(\mathbf{x}) + \boxed{\mathbf{A}}(1 - t(\mathbf{x})),$$

Hazy image

The haze-free image

Color of the fog

How much fog there is

- $\mathbf{I}$: the observed intensity
- $\mathbf{J}$: the scene radiance
- $\mathbf{A}$: the global atmospheric light
- $\mathbf{t}$: the medium transmission describing the portion of the light that is not scattered and reaches the camera

Given $3\mathrm{N}$ constraints, $4\mathrm{N}+3$ unknowns,
The goal of haze removal is to recover $\mathbf{J}$, $\mathbf{A}$, and $\mathbf{t}$ from $\mathbf{I}$.

Formulation of a hazy image

Given (3N)

Find (4N + 3)

$$\mathbf{I}(\mathbf{x}) = \boxed{\mathbf{J}(\mathbf{x})t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x})),}$$

Hazy image

The haze-free image (3N)

Color of the fog (3)

How much fog there is (N)

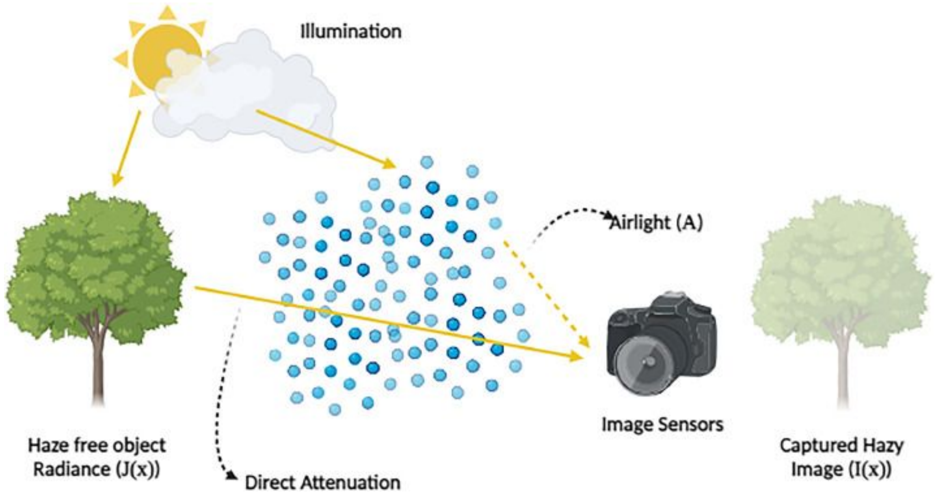
- $\mathbf{I}$: the observed intensity
- $\mathbf{J}$: the scene radiance
- $\mathbf{A}$: the global atmospheric light
- $\mathbf{t}$: the medium transmission describing the portion of the light that is not scattered and reaches the camera

Given $3\mathrm{N}$ constraints, $4\mathrm{N}+3$ unknowns,
The goal of haze removal is to recover $\mathbf{J}$, $\mathbf{A}$, and $\mathbf{t}$ from $\mathbf{I}$.

Formulation of a hazy image

$$\mathbf{I}(\mathbf{x}) = \boxed{\mathbf{J}(\mathbf{x})t(\mathbf{x})} + \boxed{\mathbf{A}(1 - t(\mathbf{x}))},$$

Direct Attenuation **Airlight**

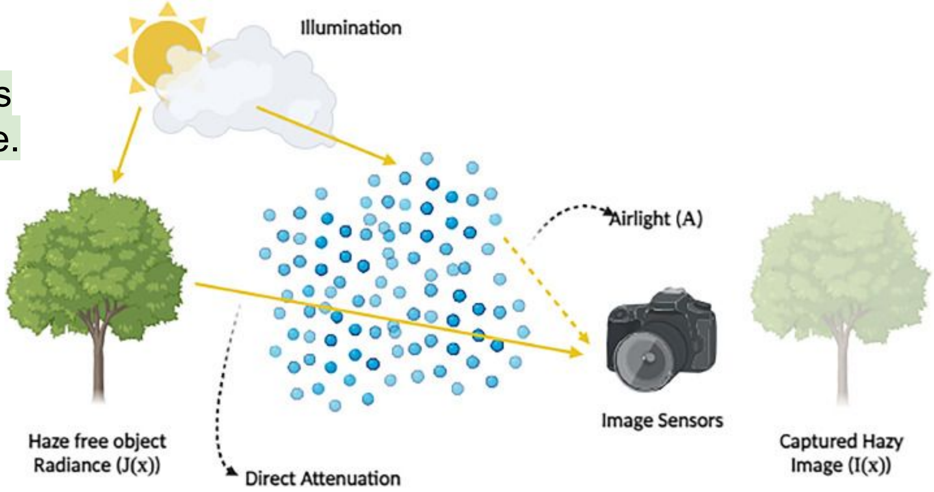


Formulation of a hazy image

$$\mathbf{I}(\mathbf{x}) = \underbrace{\boxed{\mathbf{J}(\mathbf{x})t(\mathbf{x})}}_{\text{Direct Attenuation}} + \underbrace{\boxed{\mathbf{A}(1 - t(\mathbf{x}))}}_{\text{Airlight}},$$

Direct Attenuation **Airlight**

Light from the scene is attenuated (weakened) as it travels through the haze.
-> making distant objects appear faded



Formulation of a hazy image

$$\mathbf{I}(\mathbf{x}) = \boxed{\mathbf{J}(\mathbf{x})t(\mathbf{x})} + \boxed{\mathbf{A}(1 - t(\mathbf{x}))},$$

Direct Attenuation **Airlight**

Light from the scene is attenuated (weakened) as it travels through the haze.
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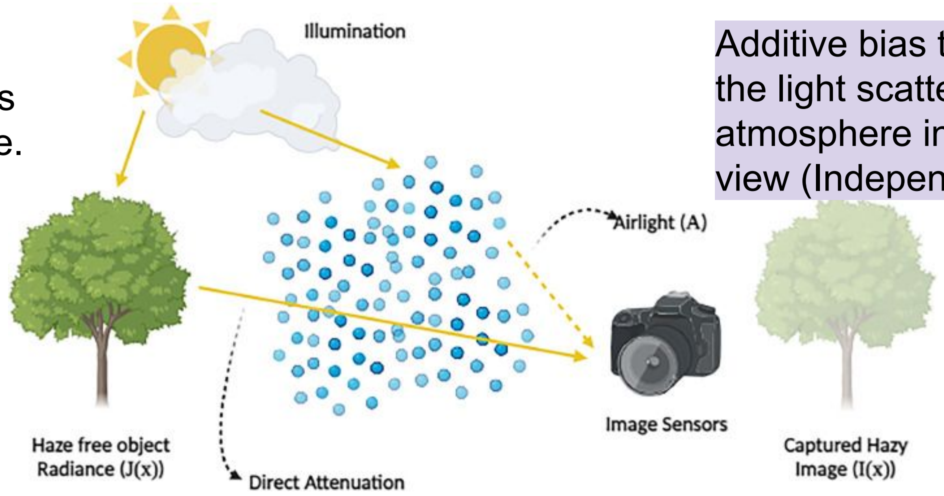
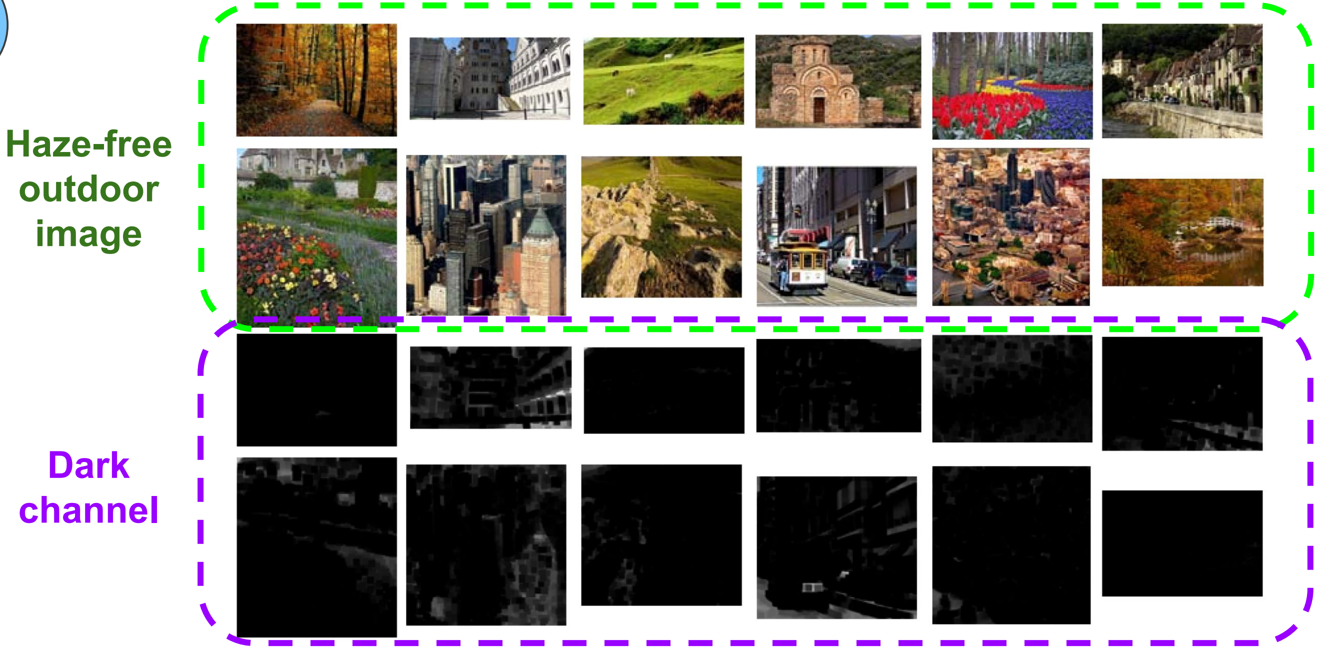


Additive bias that represents the light scattered by the atmosphere into the camera's view (Independent of J)

03

Dark Channel Prior



Observation

In most of the non-sky patches, at least one color channel has some pixels whose intensity are very low and close to zero.

Dark Channel Prior Formulation

For an arbitrary image $\mathbf{J}$, its dark channel is given by:

$$J^{\text{dark}}(\mathbf{x}) = \min_{\mathbf{y}\in\Omega(\mathbf{x})} \left(\min_{c\in\{r,g,b\}} J^c(\mathbf{y}) \right)$$

J^c : color channel of J

$\Omega(\mathbf{x})$: a local patch centered at x

$\min_{\mathbf{y}\in\Omega(\mathbf{x})}$: a minimum filter

Dark Channel Prior Formulation

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J^c : color channel of J

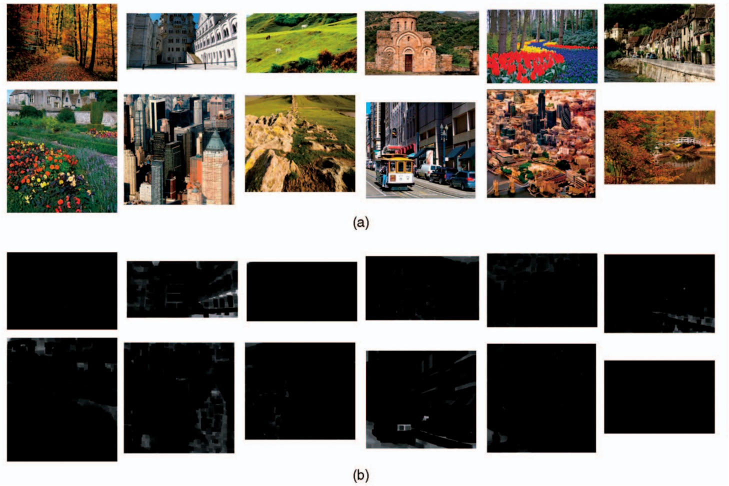
$\Omega(\mathbf{x})$: a local patch centered at x

$\min_{\mathbf{y}\in\Omega(\mathbf{x})}$: a minimum filter

$$J^{\text{dark}} \rightarrow 0.$$

If J is an outdoor haze-free image, except for the sky region, the intensity of J's dark channel is low and tends to be zero

Dark Channel Prior Formulation



Due to:

a) Shadows
b) Colorful objects or surfaces
c) Dark objects or surfaces

As the natural outdoor images are usually colorful and full of shadows, **the dark channels of these images are really dark!**

$$J^{\text{dark}} \to 0.$$

If J is an outdoor haze-free image, except for the sky region, the intensity of J's dark channel is low and tends to be zero

Statistics of the observation

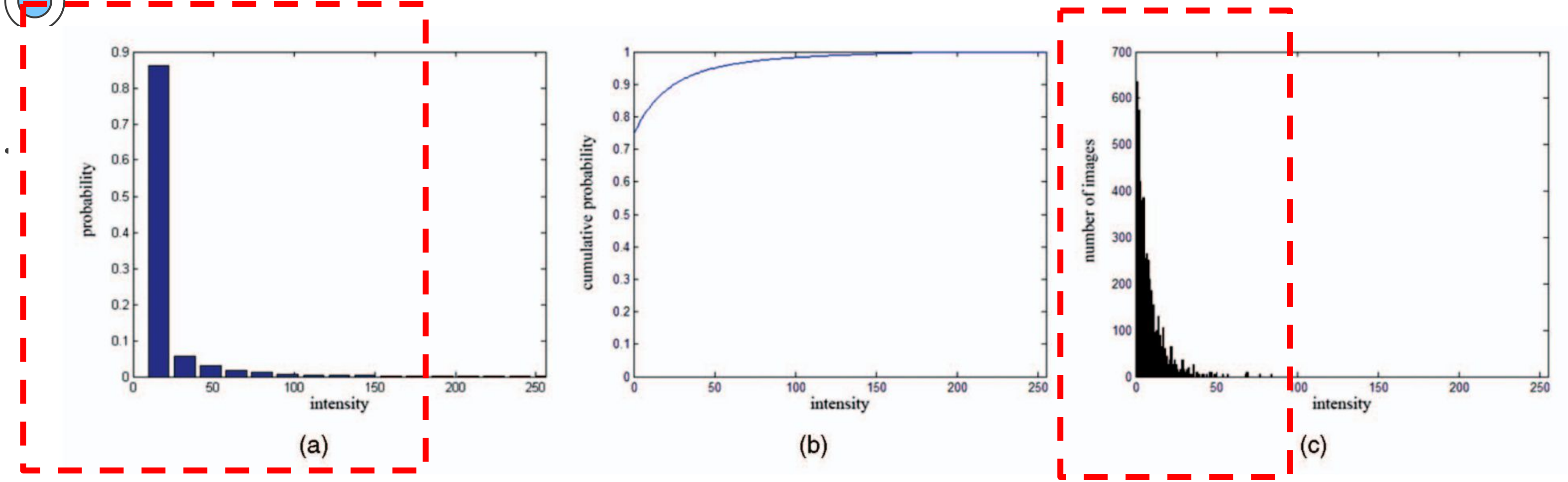
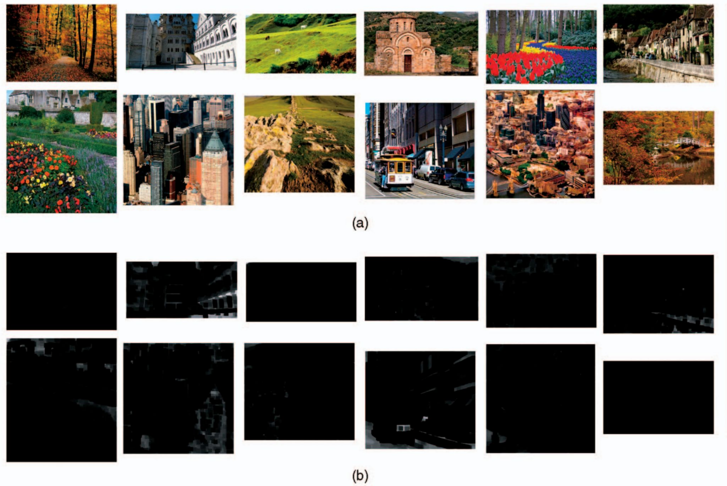


Fig. 5. Statistics of the dark channels. (a) Histogram of the intensity of the pixels in all of the 5,000 dark channels (each bin stands for 16 intensity levels). (b) Cumulative distribution. (c) Histogram of the average intensity of each dark channel.

About 75 percent of the pixels in the dark channels have zero values, and the intensity of 90 percent of the pixels is below 25.

Dark Channel Prior

Haze-free images

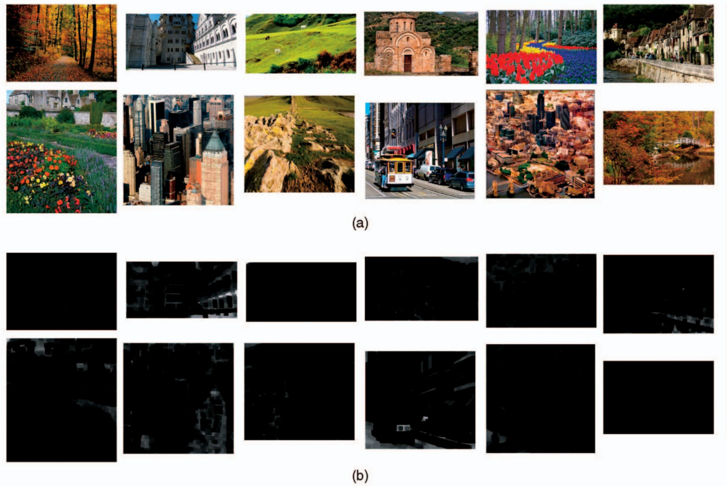


Hazy image

Due to the additive airlight, a hazy image is brighter than its haze-free version where the transmission t is low. So, **the dark channel of a hazy image will have higher intensity in regions with denser haze.**

Dark Channel Prior

Haze-free images



Hazy image

the intensity of the dark channel is a rough approximation of the thickness of the haze.

Due to the additive airlight, a hazy image is brighter than its haze-free version where the transmission t is low. So, **the dark channel of a hazy image will have higher intensity in regions with denser haze.**

Haze Removal Using Dark Channel Prior

Sample Image

01 Estimating the Transmission

02 Soft Matting

03 Estimating the Atmospheric Light

04 Recovering the Scene Radiance

Haze Removal Using Dark Channel Prior

Sample Image

01 Estimating the Transmission

02 Soft Matting

03 Estimating the Atmospheric Light

04 Recovering the Scene Radiance

Haze Removal Using Dark Channel Prior

Sample Image

Dehazed Image

01 Estimating the Transmission

02 Soft Matting

03 Estimating the Atmospheric Light

04 Recovering the Scene Radiance

1) Estimating the transmission

- Assume that the atmospheric light A is given

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x}))$$

$$\Downarrow$$

normalize each color channel independently

$$\frac{I^c(\mathbf{x})}{A^c} = t(\mathbf{x})\frac{J^c(\mathbf{x})}{A^c} + 1 - t(\mathbf{x}).$$

1) Estimating the transmission

Assume that the atmospheric light A is given

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x}))$$

normalize each color channel independently

$$\frac{I^c(\mathbf{x})}{A^c} = t(\mathbf{x})\frac{J^c(\mathbf{x})}{A^c} + 1 - t(\mathbf{x}).$$

calculate dark channel prior

$$\min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\min_c \frac{I^c(\mathbf{y})}{A^c}\right) = \tilde{t}(\mathbf{x}) \min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\min_c \frac{J^c(\mathbf{y})}{A^c}\right) + 1 - \tilde{t}(\mathbf{x}).$$

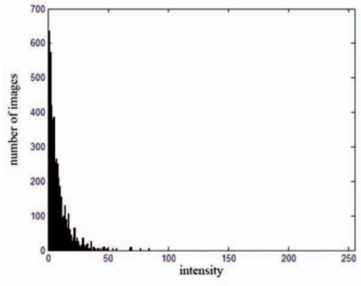
$\tilde{t}(\mathbf{x})$: transmission for the patch (assuming **constant** value)

1) Estimating the transmission

$$\min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\min_c \frac{I^c(\mathbf{y})}{A^c}\right) = \tilde{t}(\mathbf{x}) \boxed{\min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\min_c \frac{J^c(\mathbf{y})}{A^c}\right)} + 1 - \tilde{t}(\mathbf{x}).$$

$\rightarrow 0$

As the scene radiance J is a haze-free image, the dark channel of J is close to zero due to the dark channel prior



1) Estimating the transmission

We can calculate estimation by:

$$\tilde{t}(\mathbf{x}) = 1 - \min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\min_{c}\frac{I^c(\mathbf{y})}{A^c}\right)$$

Aerial Perspective
In practice, even on clear days the atmosphere is not absolutely free of any particle. So the haze still exists when we look at distant objects. Moreover, the presence of haze is a fundamental cue for human to perceive depth. **If we remove the haze thoroughly, the image may seem unnatural and we may lose the feeling of depth.**

So, we can optionally keep a very small amount of haze for the distant objects by introducing a constant parameter **w**!

1) Estimating the transmission

We can calculate estimation by:

$$\tilde{t}(\mathbf{x}) = 1 - \min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\min_{c}\frac{I^c(\mathbf{y})}{A^c}\right) \longrightarrow \tilde{t}(\mathbf{x}) = 1 - \omega \min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\min_{c}\frac{I^c(\mathbf{y})}{A^c}\right)$$

Aerial Perspective
In practice, even on clear days the atmosphere is not absolutely free of any particle. So the haze still exists when we look at distant objects. Moreover, the presence of haze is a fundamental cue for human to perceive depth. **If we remove the haze thoroughly, the image may seem unnatural and we may lose the feeling of depth.**

So, we can optionally keep a very small amount of haze for the distant objects by introducing a constant parameter **w**!

1) Estimating the transmission

When we apply step 1) …

Original Image I(x)

Estimated transmission

$\tilde{t}(\mathbf{x})$

1) Estimating the transmission

When we apply step 1) …

Original Image I(x)

Estimated transmission

$$\tilde{t}(\mathbf{x})$$

Output Image

1) Estimating the transmission

When we apply step 1) …

Original Image I(x)

Estimated transmission

$$\tilde{t}(\mathbf{x})$$

Output Image

Some halos and block artifacts because the transmission is not always constant in a patch.
-> propose a **soft matting method** to refine the transmission maps.

2) Soft Matting

Denote the refined transmission map as t, the cost function is formalized as:

$$E(\mathbf{t}) = \mathbf{t}^T \mathbf{L} \mathbf{t} + \lambda(\mathbf{t} - \tilde{\mathbf{t}})^T (\mathbf{t} - \tilde{\mathbf{t}})$$

2) Soft Matting

Denote the refined transmission map as t, the cost function is formalized as:

$$E(\mathbf{t}) = \underbrace{\mathbf{t}^{\mathrm{T}}\mathbf{L}\mathbf{t}}_{\text{smoothness term}} + \lambda \underbrace{(\mathbf{t}-\tilde{\mathbf{t}})^{\mathrm{T}}(\mathbf{t}-\tilde{\mathbf{t}})}_{\text{data term}}$$

smoothness term

"Measures how bumby the estimated fog map is"

data term

"Tries to stay close to the previously estimated fog map"

weight

When λ is big: try stay close to original t
When λ is small: care more about the smoothness

2) Soft Matting

Denote the refined transmission map as t, the cost function is formalized as:

$$E(\mathbf{t}) = \mathbf{t}^{\mathrm{T}}\mathbf{L}\mathbf{t} + \lambda(\mathbf{t} - \tilde{\mathbf{t}})^{\mathrm{T}}(\mathbf{t} - \tilde{\mathbf{t}})$$

the matting Laplacian matrix

$$\sum_{k|(i,j)\in w_k}\left(\delta_{ij} - \frac{1}{|w_k|}\left(1 + (\mathbf{I}_i - \mu_k)^T\left(\Sigma_k + \frac{\varepsilon}{|w_k|}\mathrm{U}_3\right)^{-1}(\mathbf{I}_j - \mu_k)\right)\right)$$

where $\mathbf{I}_i$ and $\mathbf{I}_j$ are the colors of the input image $\mathbf{I}$ at pixels i and j, δ_{ij} is the Kronecker delta, μ_k and Σ_k are the mean and covariance matrix of the colors in window w_k, U_3 is a 3×3 identity matrix, ε is a regularizing parameter, and $|w_k|$ is the number of pixels in the window w_k.

For each local window that contains pixel i and j, calculate how smooth the fog map is

2) Soft Matting

Denote the refined transmission map as t, the cost function is formalized as:

$$E(\mathbf{t}) = \mathbf{t}^{\mathrm{T}}\mathbf{L}\mathbf{t} + \lambda(\mathbf{t}-\tilde{\mathbf{t}})^{\mathrm{T}}(\mathbf{t}-\tilde{\mathbf{t}})$$

the matting Laplacian matrix

$$\sum_{k|(i,j)\in w_k}\left(\delta_{ij} - \frac{1}{|w_k|}\left(1 + \boxed{(\mathbf{I}_i-\mu_k)^T\left(\Sigma_k+\frac{\varepsilon}{|w_k|}\mathrm{U}_3\right)^{-1}(\mathbf{I}_j-\mu_k)}\right)\right)$$

Color similarity term

where $\mathbf{I}_i$ and $\mathbf{I}_j$ are the colors of the input image $\mathbf{I}$ at pixels i and j, δ_{ij} is the Kronecker delta, μ_k and Σ_k are the mean and covariance matrix of the colors in window w_k, U_3 is a 3×3 identity matrix, ε is a regularizing parameter, and $|w_k|$ is the number of pixels in the window w_k.

1 if i and j are same pixels and 0 otherwise

2) Soft Matting

Denote the refined transmission map as t, the cost function is formalized as:

$$E(\mathbf{t}) = \mathbf{t}^{\mathrm{T}}\mathbf{L}\mathbf{t} + \lambda(\mathbf{t} - \tilde{\mathbf{t}})^{\mathrm{T}}(\mathbf{t} - \tilde{\mathbf{t}})$$

the matting Laplacian matrix

$$\sum_{k|(i,j)\in w_k}\left(\delta_{ij} - \frac{1}{|w_k|}\left(1 + \boxed{(\mathbf{I}_i - \mu_k)^T\left(\Sigma_k + \frac{\varepsilon}{|w_k|}U_3\right)^{-1}(\mathbf{I}_j - \mu_k)}\right)\right)$$

Color similarity term

where $\mathbf{I}_i$ and $\mathbf{I}_j$ are the colors of the input image $\mathbf{I}$ at pixels i and j, δ_{ij} is the Kronecker delta, μ_k and Σ_k are the mean and covariance matrix of the colors in window w_k, U_3 is a 3×3 identity matrix, ε is a regularizing parameter, and $|w_k|$ is the number of pixels in the window w_k.

1 if i and j are same pixels and 0 otherwise

If pixels i and j have colors that are consistent with the color distribution in the patch/window w, the term tends to be smaller

2) Soft Matting

Denote the refined transmission map as t, the cost function is formalized as:

$$E(\mathbf{t}) = \mathbf{t}^{\mathrm{T}}\mathbf{L}\mathbf{t} + \lambda\boxed{(\mathbf{t} - \tilde{\mathbf{t}})^{\mathrm{T}}(\mathbf{t} - \tilde{\mathbf{t}})}$$

Difference between t and previous t

When λ is big: try stay close to original t
When λ is small: care more about the smoothness

2) Soft Matting

Denote the refined transmission map as t, the cost function is formalized as:

$$E(\mathbf{t}) = \mathbf{t}^{\mathrm{T}}\mathrm{L}\mathbf{t} + \lambda(\mathbf{t} - \tilde{\mathbf{t}})^{\mathrm{T}}(\mathbf{t} - \tilde{\mathbf{t}})$$

After solving: (U: an identity matrix of the same size as L)

$$(\mathrm{L} + \lambda\mathrm{U})\mathbf{t} = \lambda\tilde{\mathbf{t}}$$

We can find the refined map!

2) Soft Matting

Original Image I(x)

Estimated transmission
$\tilde{t}(\mathbf{x})$

Output Image ☹

Refine w/ Soft Matting

Refined transmission
$t(\mathbf{x})$

Final Image ☺

Estimating the Atmospheric Light

$$\mathbf{I}(\mathbf{x}) = \boxed{\mathbf{J}(\mathbf{x})}t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x})),$$

Hazy image

The haze-free image

Sunshine

$$J(\mathbf{x}) = R(\mathbf{x})(S + A)$$

where $R \leq 1$ is the reflectance of the scene points

Estimating the Atmospheric Light

$$\mathbf{I}(\mathbf{x}) = \boxed{\mathbf{J}(\mathbf{x})}t(\mathbf{x}) + \mathbf{A}(1 - t(\mathbf{x})),$$

Hazy image

The haze-free image

Sunshine

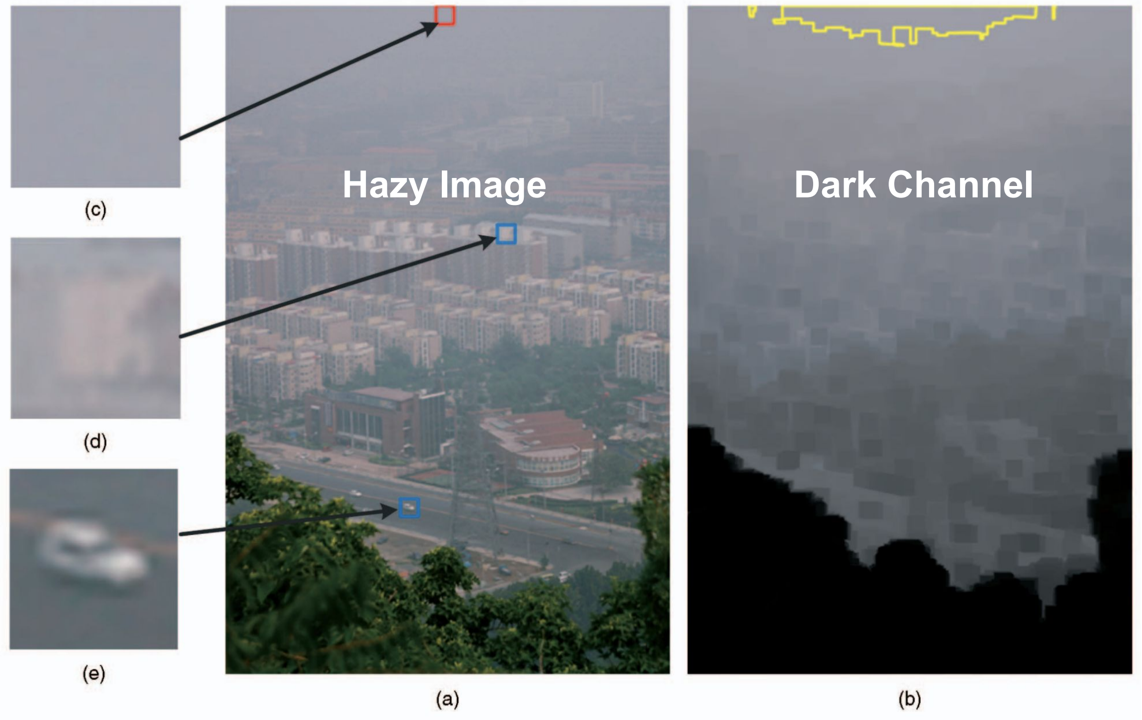
$$J(\mathbf{x}) = R(\mathbf{x})(S + A)$$

where $R \leq 1$ is the reflectance of the scene points

$$I(\mathbf{x}) = \underbrace{R(\mathbf{x})St(\mathbf{x}) + R(\mathbf{x})At(\mathbf{x})}_{\mathbf{J(x)}} + (1 - t(\mathbf{x}))A$$

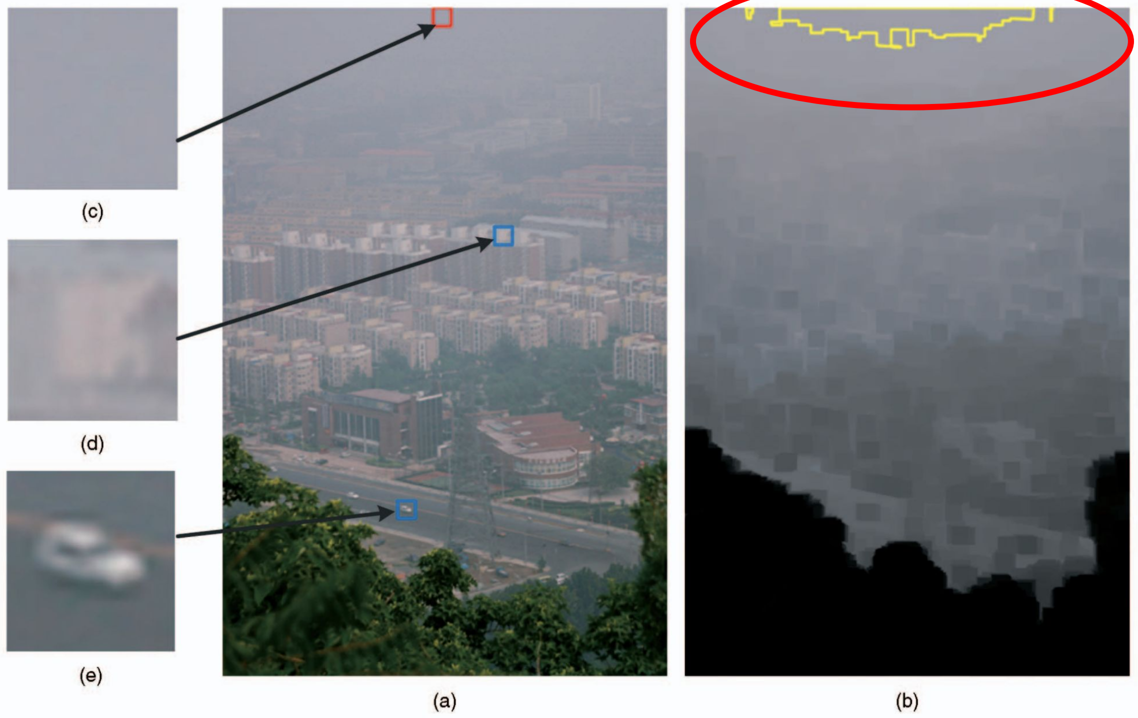
Estimating the Atmospheric Light

$$I(\mathbf{x}) = R(\mathbf{x})St(\mathbf{x}) + R(\mathbf{x})At(\mathbf{x}) + (1 - t(\mathbf{x}))A$$



Estimating the Atmospheric Light

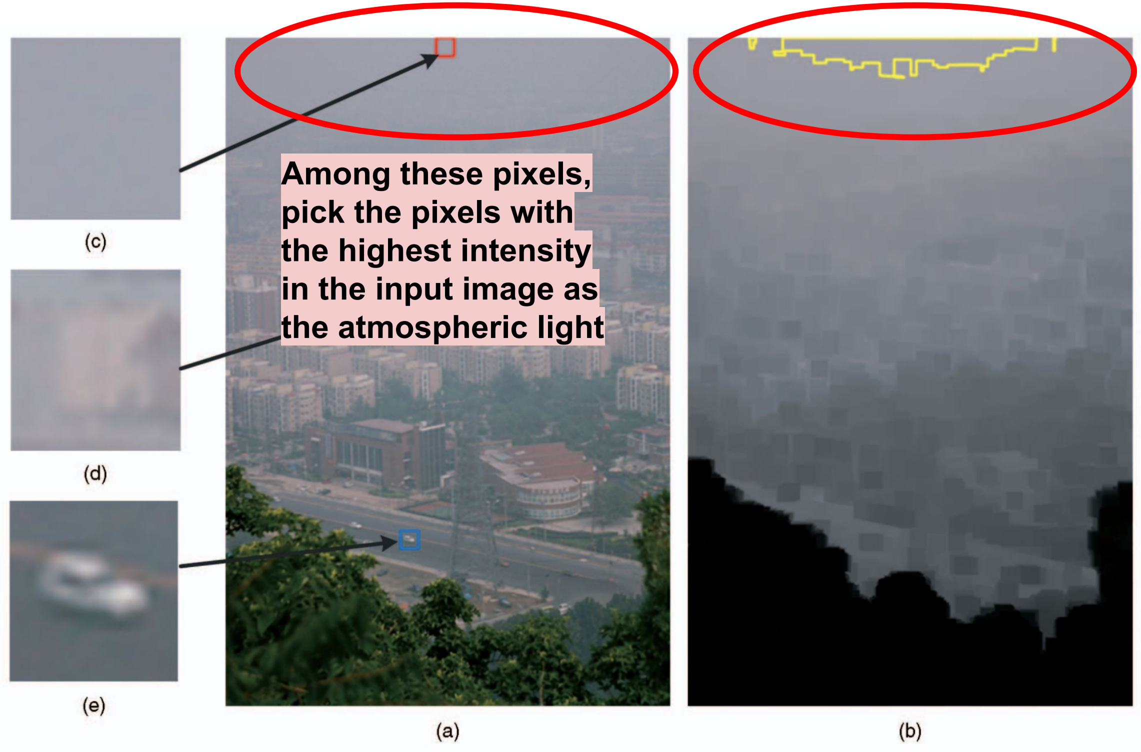
$$I(\mathbf{x}) = R(\mathbf{x})St(\mathbf{x}) + R(\mathbf{x})At(\mathbf{x}) + (1 - t(\mathbf{x}))A$$



First pick the top 0.1 percent brightest pixels in the dark channel

Estimating the Atmospheric Light

$$I(\mathbf{x}) = R(\mathbf{x})St(\mathbf{x}) + R(\mathbf{x})At(\mathbf{x}) + (1 - t(\mathbf{x}))A$$



First pick the top 0.1 percent brightest pixels in the dark channel

Recovering Scene Radiance

$$\mathbf{I}(\mathbf{x}) = \boxed{\mathbf{J}(\mathbf{x})t(\mathbf{x})} + \mathbf{A}(1 - t(\mathbf{x})),$$

Can be close to 0 when t is close to 0
-> Makes J prone to noise

So, we provide a lower bound t_0 to preserve a small amount of haze in very dense haze regions)

$$\mathbf{J}(\mathbf{x}) = \frac{\mathbf{I}(\mathbf{x}) - \mathbf{A}}{\max(t(\mathbf{x}), t_0)} + \mathbf{A}$$

A typical value of t_0 is 0.1

04

Experimental Results

Qualitative Analysis

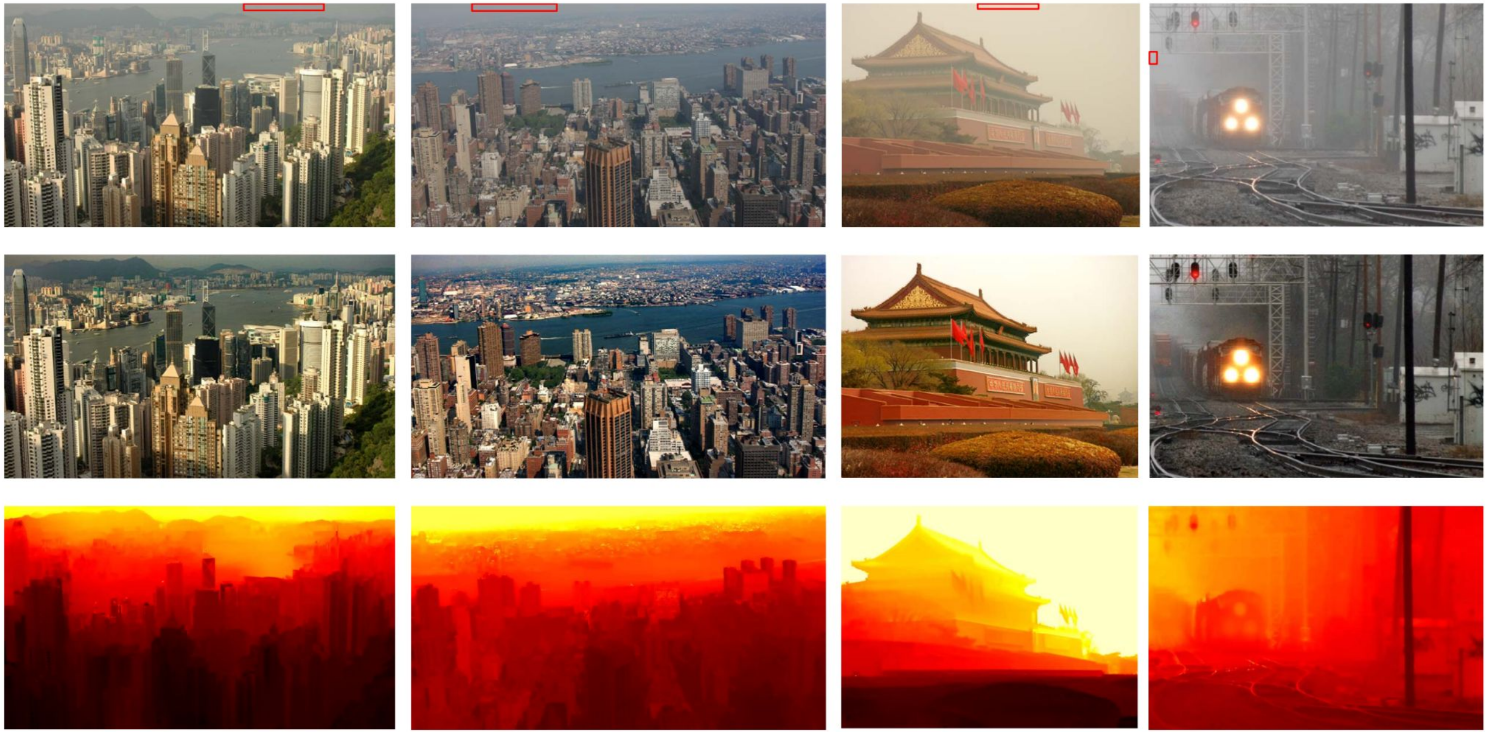


Figure 7. Haze removal results. Top: input haze images. Middle: restored haze-free images. Bottom: depth maps. The red rectangles in the top row indicate where our method automatically obtains the atmospheric light.

Dependent on patch sizes

Fig. 9. A haze-free image (600×400) and its dark channels using 3×3 and 15×15 patches, respectively.

Dependent on patch sizes

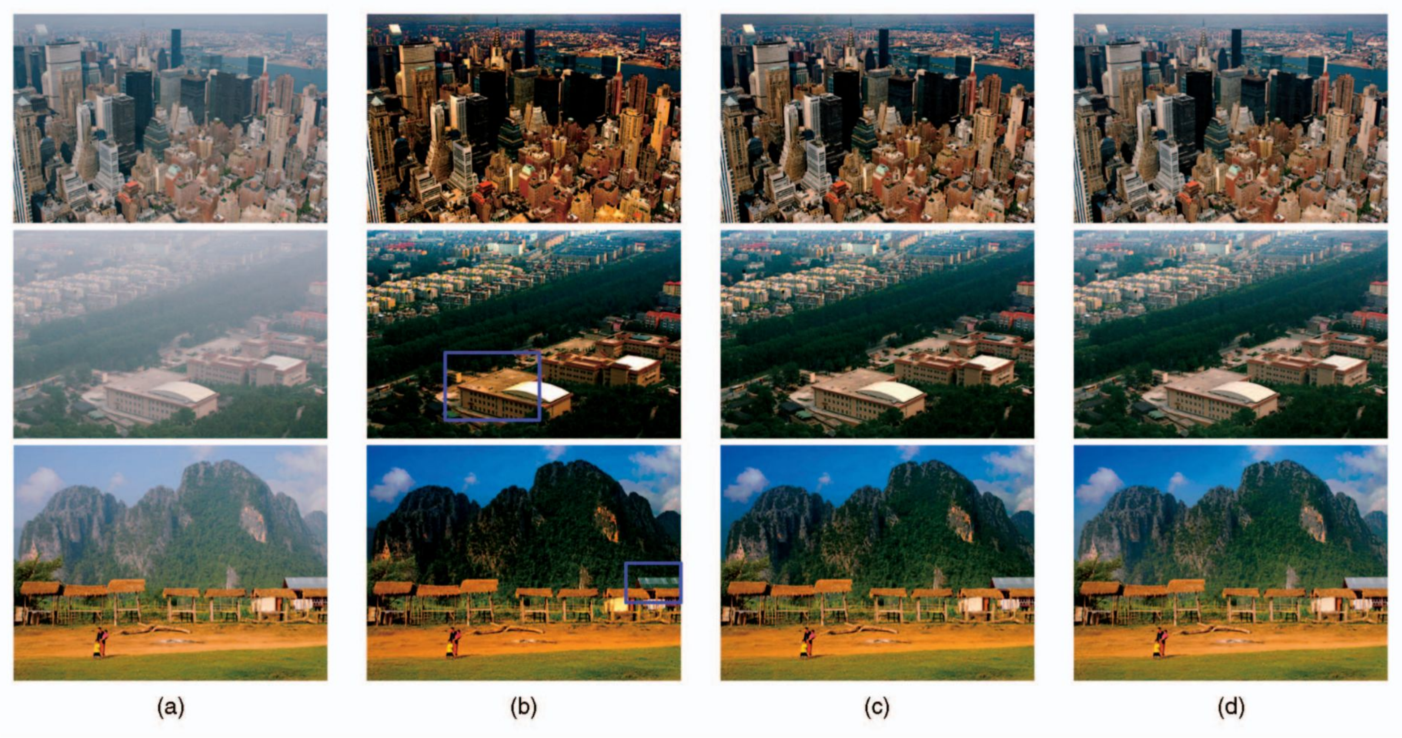


Fig. 11. Recovering images using different patch sizes (after soft matting). (a) Input hazy images. (b) Using 3×3 patches. (c) Using 15×15 patches. (d) Using 30×30 patches.

Underestimated case

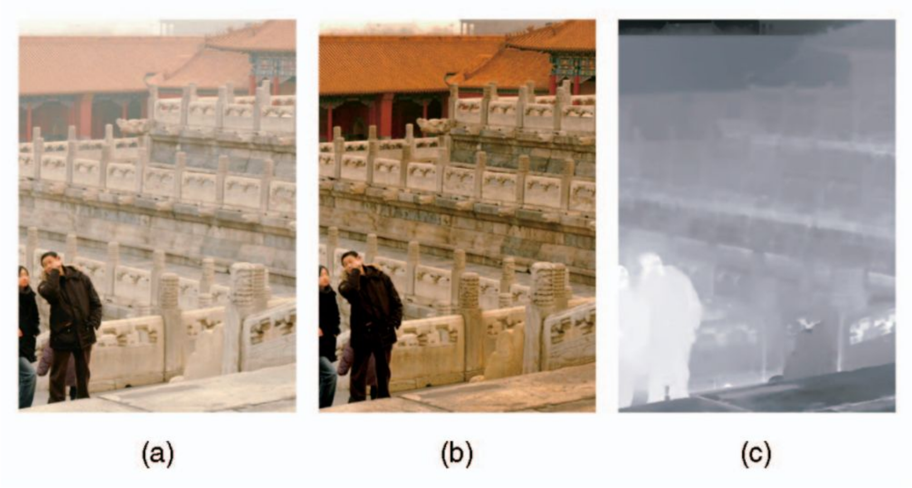
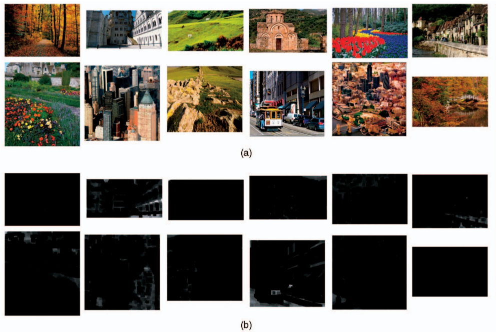


Fig. 18. Failure of the dark channel prior. (a) Input image. (b) Our result. (c) Our transmission map. The transmission of the marble is underestimated.

Underestimated case

(a) (b) (c)

[Assumption on dark channel prior]



Due to:

a) Shadows
b) Colorful objects or surfaces
c) Dark objects or surfaces

Thank you