Single Image Haze Removal Using Dark Channel Prior

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Hazy Images






- Low visibility
- Faint colors

Goals of Haze Removal

depth

- Scene restoration
- Depth estimation

Haze Imaging Model

Atmospheric light

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

Hazy image

Scene radiance

Transmission

Haze Imaging Model

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

Depth

$$d = -\beta \ln t$$

Transmission

Ambiguity in Haze Removal

scene
radiance

input

depth

....

Previous Works

- Using additional information
  - Polarization filter [Shwartz et al., CVPR'06]
  - Multiple images [Narasimhan & Nayar, CVPR'00]
  - Known 3D model [Kopf et al., Siggraph Asia'08]
  - User-assistance [Narasimhan & Nayar, CPMCV'03]

Previous Works

- Single image
  - Maximize local contrast [Tan, CVPR 08]

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  - Independent Component Analysis [Fattal, Siggraph 08]

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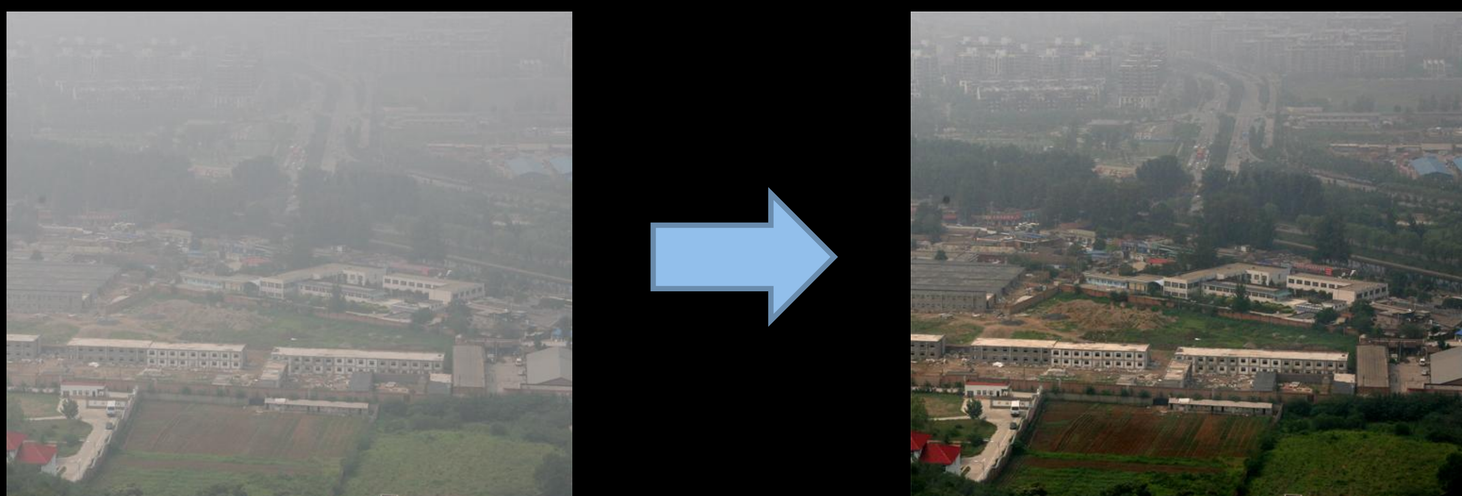
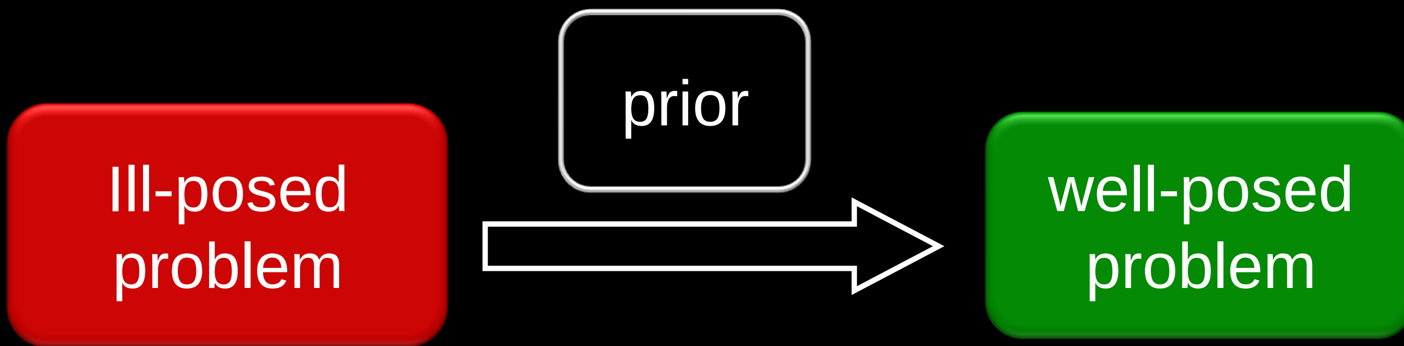


Priors in Computer Vision



- Smoothness prior
- Sparseness prior
- Exemplar-based prior

Dark Channel Prior

Dark Channel

- min (rgb, local patch)

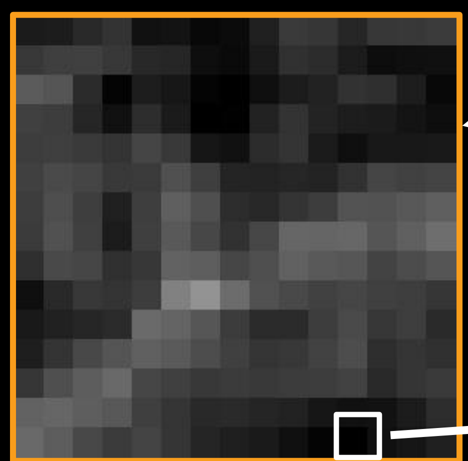
Dark Channel

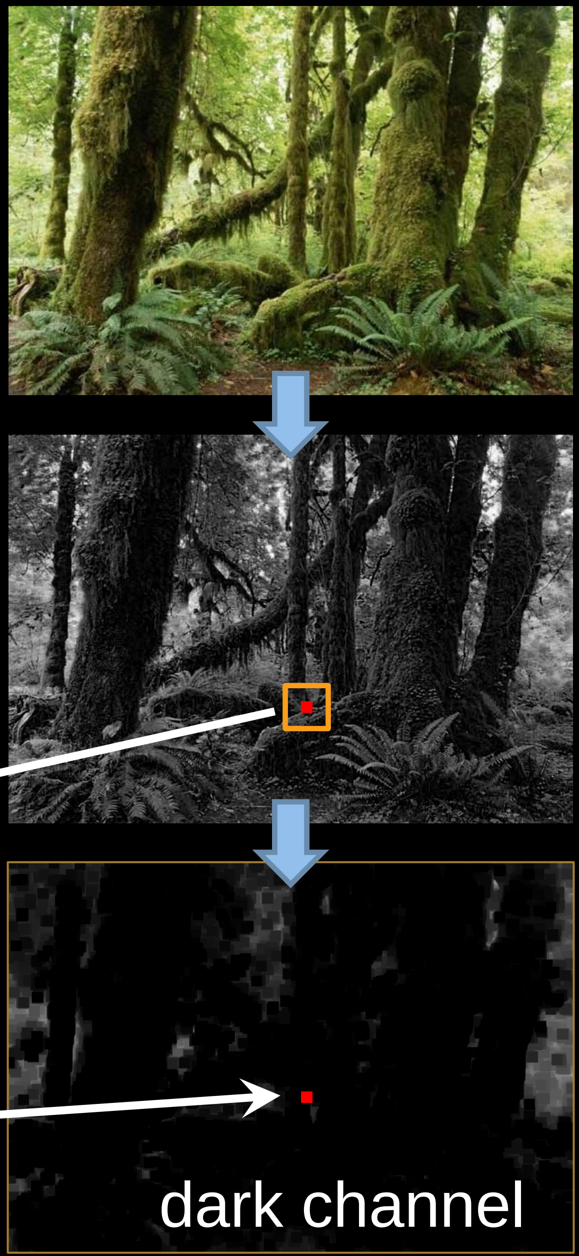
- min (rgb, local patch)
  - min (r, g, b)

min (r, g, b)

Dark Channel

- min (rgb, local patch)
  - min (r, g, b)
  - min (local patch) = min filter



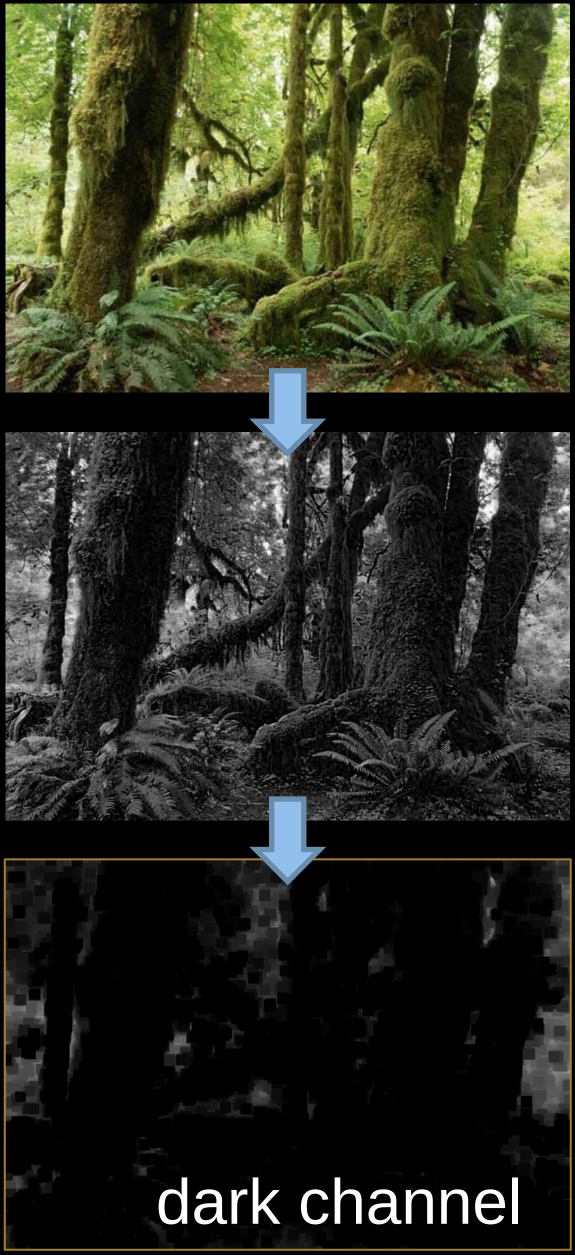


Dark Channel

- min (rgb, local patch)
  - min (r, g, b)
  - min (local patch) = min filter

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

- J^c: color channel of $\mathbf{J}$
- J^{dark}: dark channel of $\mathbf{J}$

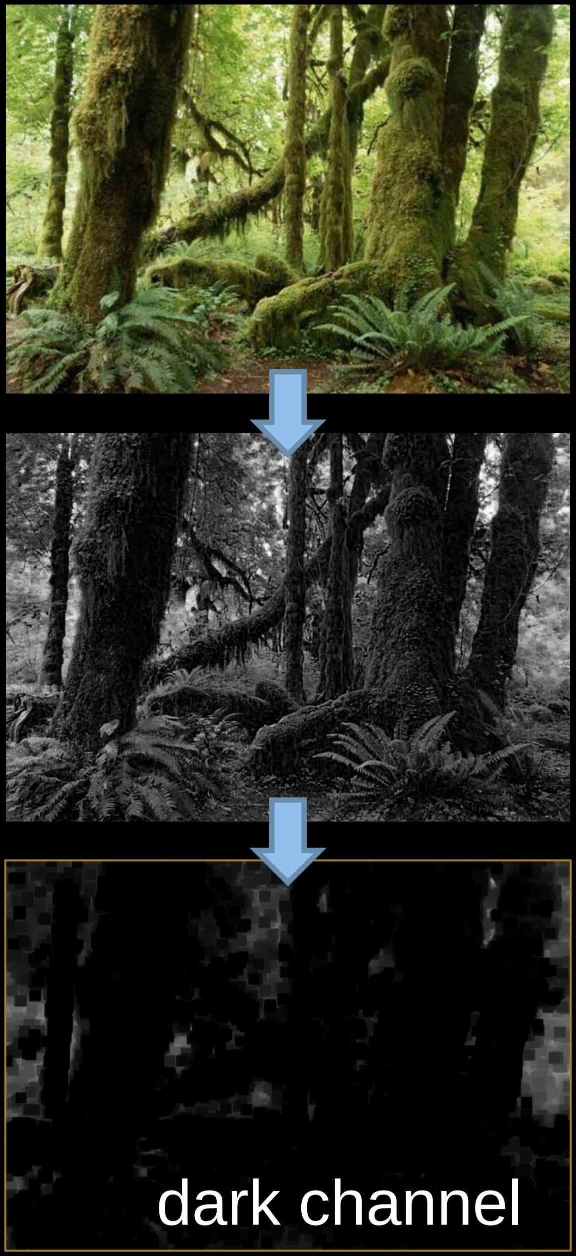


Dark Channel

- min (rgb, local patch)
  - min (r, g, b)
  - min (local patch) = min filter

$$J^{dark} = \min_{\Omega} \left(\min_{c} J^{c} \right)$$

  - J^c: color channel of $\mathbf{J}$
  - J^{dark}: dark channel of $\mathbf{J}$



A Surprising Observation

Haze-free

A Surprising Observation

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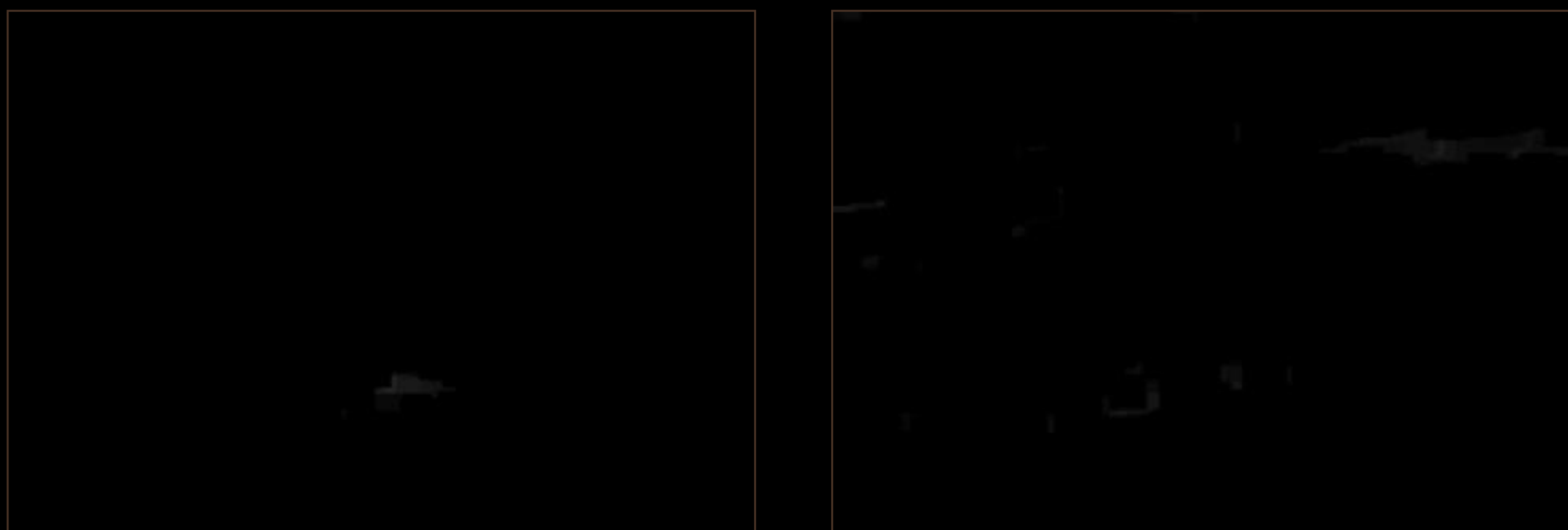

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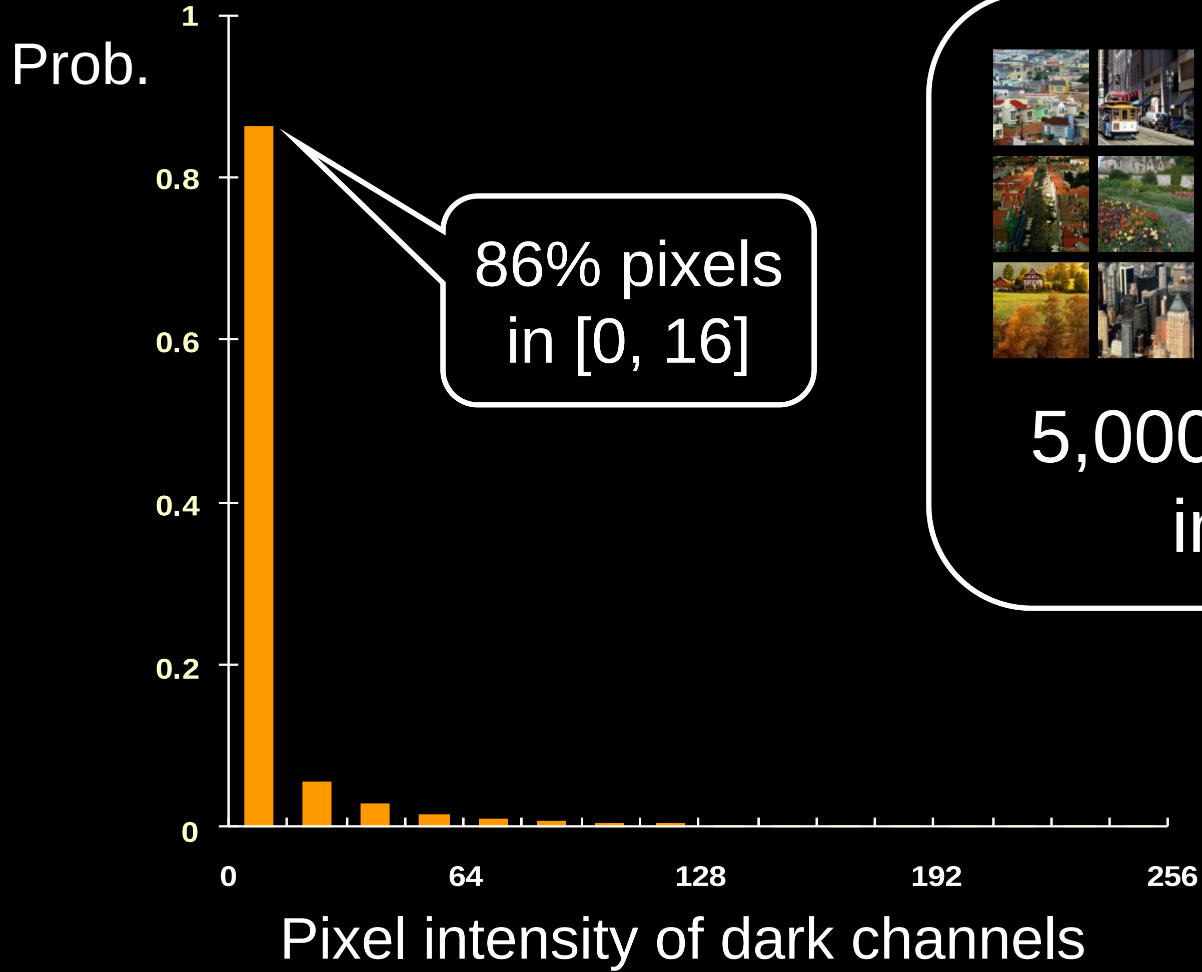
A Surprising Observation



5,000 haze-free images

Dark Channel Prior

- For outdoor haze-free images

$$\min_{\Omega}\left(\min_{c} J^{c}\right) \rightarrow 0$$

What makes it dark?

- Shadow

- Colorful object

- Black object

Dark Channel of Hazy Image

hazy image

dark channel

- The dark channel is no longer dark.

Transmission Estimation

Haze imaging model $\mathbf{I} = \mathbf{J} \cdot t + \mathbf{A} \cdot (1 - t)$

Normalize

$$\frac{\mathrm{I}^c}{\mathrm{A}^c} = \frac{\mathrm{J}^c}{\mathrm{A}^c} t + 1 - t$$

Compute dark channel

$$\min_{\Omega}(\min_{c} \frac{\mathrm{I}^c}{\mathrm{A}^c}) = \left\{\min_{\Omega}(\min_{c} \frac{\mathrm{J}^c}{\mathrm{A}^c})\right\} t + 1 - t$$

Transmission Estimation

Dark Channel Prior

$$\min_{\Omega}(\min_{c} J^{c}) \rightarrow 0$$

Compute dark channel

$$\min_{\Omega}(\min_{c} \frac{I^{c}}{A^{c}}) = \boxed{\left\{\min_{\Omega}(\min_{c} \frac{J^{c}}{A^{c}})\right\}} t + 1 - t$$

$$\rightarrow 0$$

Transmission Estimation

Estimate transmission

$$t = 1 - \min_{\Omega}\left(\min_{c} \frac{I^c}{A^c}\right)$$

Compute dark channel

$$\min_{\Omega}\left(\min_{c} \frac{I^c}{A^c}\right) = \left\{\min_{\Omega}\left(\min_{c} \frac{J^c}{A^c}\right)\right\} t + 1 - t$$

Transmission Estimation

Estimate transmission

$$t = 1 - \min_{\Omega}\left(\min_{c} \frac{I^c}{A^c}\right)$$

input I

estimated t

Transmission Optimization

Haze imaging model $\mathbf{I} = \mathbf{J} \cdot t + \mathbf{A} \cdot (1 - t)$

Matting model $\mathbf{I} = \mathbf{F} \cdot \alpha + \mathbf{B} \cdot (1 - \alpha)$

+

tri-map

α

+

Refined transmission

Transmission Optimization

$$\mathrm{E}(\mathbf{t}) = \underbrace{\lambda \left\| \mathbf{t} - \tilde{\mathbf{t}} \right\|^2}_{\text{Data term}} + \underbrace{\mathbf{t}^{\mathrm{T}} \mathbf{L} \mathbf{t}}_{\text{Smoothness term}}$$

- $\mathbf{L}$ - matting Laplacian [Levin et al., CVPR '06]
- Constraint - soft, dense (matting - hard, sparse)

Transmission Optimization

before optimization

Transmission Optimization

after optimization

Atmospheric Light Estimation

Scene Radiance Restoration

Atmospheric light

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

Hazy image

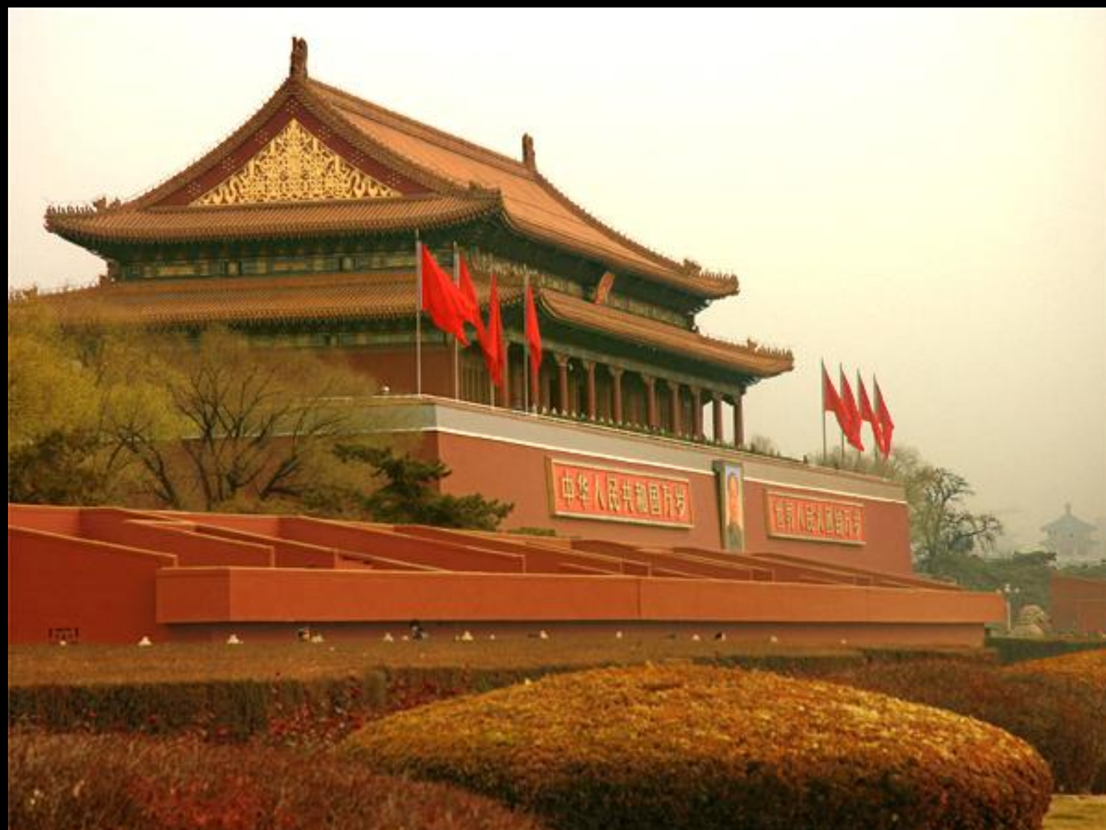
Scene radiance

Transmission

Results

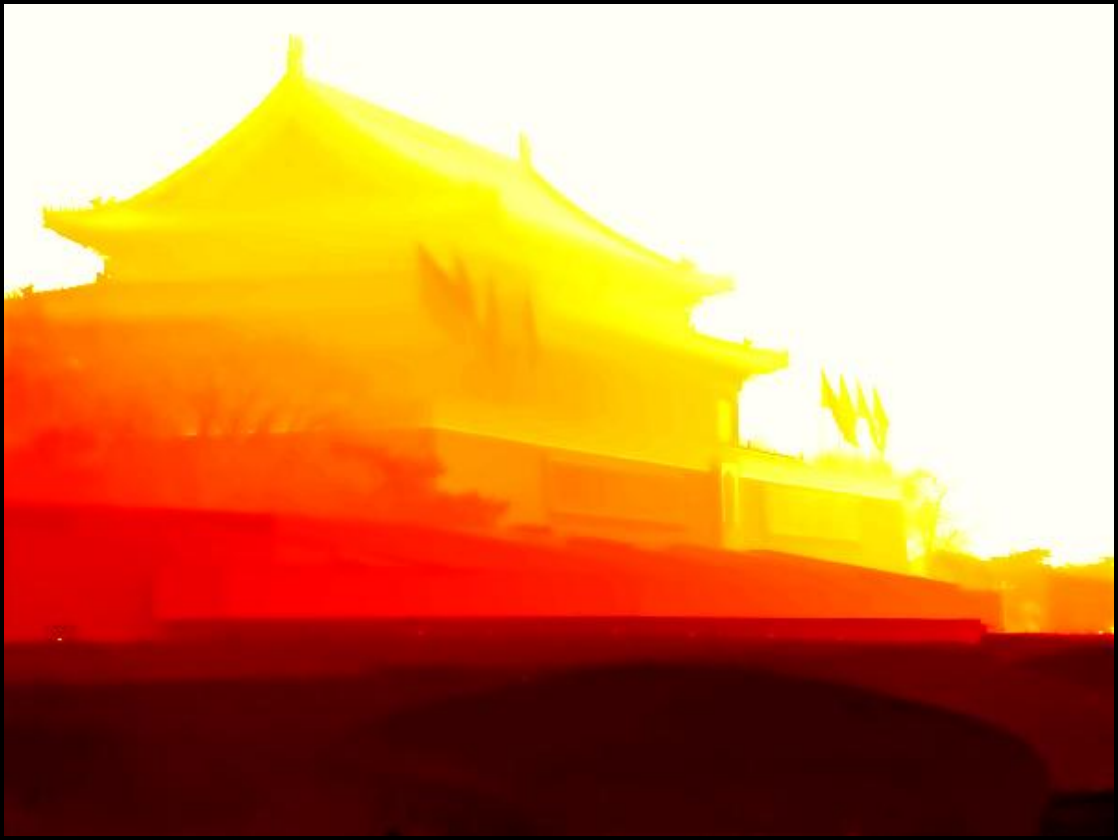
input

Results



recovered image

Results



depth

Results

input

Results

recovered image

Results

depth

Results

input

Results

recovered image

Results

depth

Comparisons

input

[Fattal Siggraph 08]

Comparisons

input

our result

Comparisons

input

[Tan, CVPR 08]

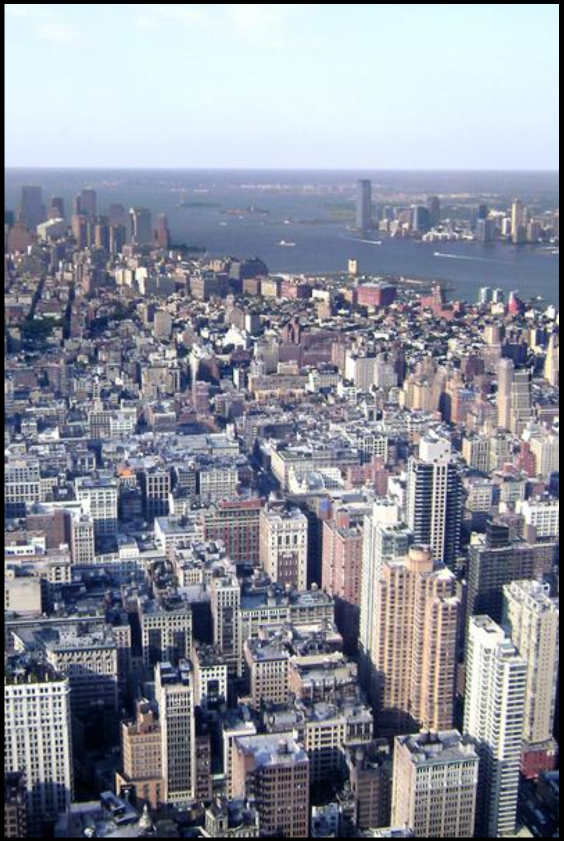
Comparisons

input

our result

Comparisons

input



[Kopf et al, Siggraph Asia 08]

our result

Results: De-focus

recovered scene radiance

input

depth

Results: De-focus

de-focus

input

depth

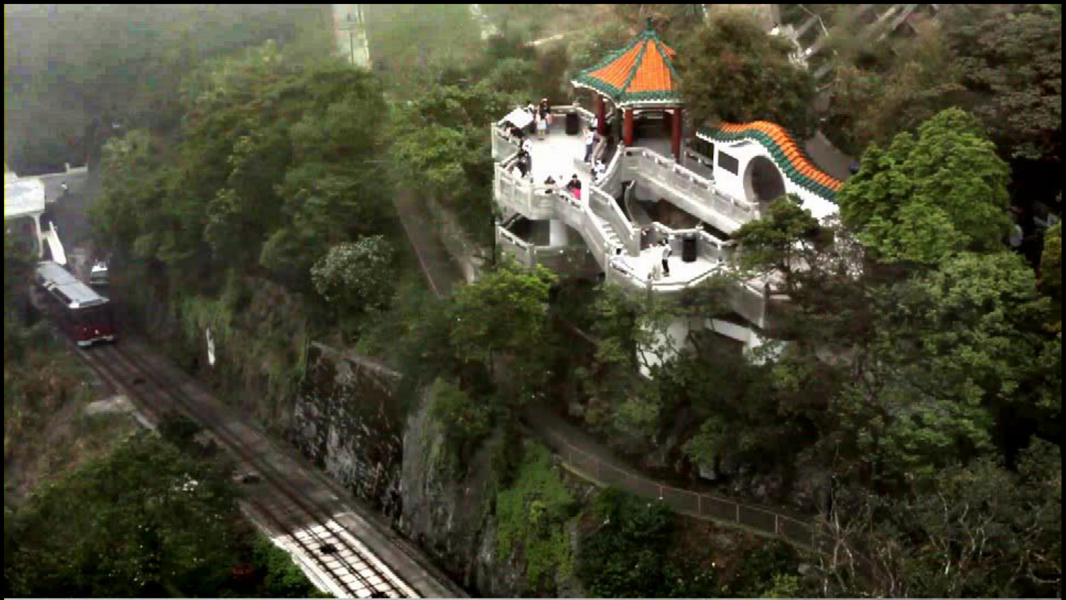
Results: Video

output

input

Results: Video

output



input

Limitations

- Inherently white or grayish objects

input

our result

transmission

Limitations

- Haze imaging model is invalid
  - e.g. non-constant $\mathbf{A}$

input

our result

Summary

- Dark channel prior
  - A natural phenomenon
  - Very simple but effective
  - Put a bad image to good use

Thank you