

DIP Final Project

Haze Removal

Qiuyi Zhang 12330402
joyeec9h3@gmail.com

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Contents

| | | |
|----------|---|----------|
| 1 | Introduction | 1 |
| 1.1 | Haze Removal Using Dark Channel Prior | 1 |
| 1.2 | Guided filter | 2 |
| 2 | Implementation | 2 |
| 3 | Results and Analysis | 3 |
| 4 | Discussion | 7 |

1 Introduction

1.1 Haze Removal Using Dark Channel Prior

In computer vision and computer graphics, the formation of a hazy image is usually described by the following model:

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

where \mathbf{I} is the observed intensity, \mathbf{J} is the scene radiance, \mathbf{A} is the global atmospheric light, and t is the medium transmission. With this model, the goal of haze removal is to recover \mathbf{J} , \mathbf{A} , and t when \mathbf{I} is given.

In [?], He proposed an approach to use the dark channel prior for haze removal. For an image \mathbf{J} , the dark channel of \mathbf{J} is defined as

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

When \mathbf{J} is a haze-free outdoor image, the intensity of J^{dark} in the non-sky region is close to zero. Using this prior, the transmission can be estimated by:

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

where $\omega \in (0, 1]$ is a constant parameter for keeping a certain amount of haze to make the output more natural. Here $\min_c(\min_{\mathbf{y} \in \Omega(\mathbf{x})}(\frac{I^c(\mathbf{y})}{A^c}))$ is actually the dark channel of the normalized haze image $\frac{I^c(\mathbf{y})}{A^c}$.

To automatically obtain \mathbf{A} from the input image, we can first pick the top $p\%$ brightest pixels in the dark channel, then, for each color channel, we chose the one with the highest intensity in the input image \mathbf{I} as its atmospheric light.

Now that we have $\tilde{t}(\mathbf{x})$, \mathbf{A} and \mathbf{I} , we can recover the haze-free image with:

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

where t_0 is a lower bound for t to preserve a certain amount of haze in dense haze regions.

1.2 Guided filter

Since a transmission map is just an alpha map, we can apply soft matting to refine the estimated transmission. An efficient approach, as proposed in [?], is to use the input image \mathbf{I} to guide the filter $\tilde{t}(\mathbf{x})$.

Define q as a linear transform of a color image \mathbf{I} in a window ω_k with radius r centered at the pixel k :

$$q_i = \mathbf{a}_k^T \mathbf{I}_i + b_k, \forall i \in \omega_k$$

where \mathbf{I}_k is a 3×1 color vector, \mathbf{a}_k is a 3×1 coefficient vector, b_k is a scalar coefficient. For a filter p , the coefficients \mathbf{a} and b can be computed with:

$$\begin{aligned} \mathbf{a}_k &= (\Sigma_k + \epsilon U)^{-1} \left(\frac{1}{|\omega|} \sum_{i \in \omega_k} \mathbf{I}_i p_i - \mu_k \bar{p}_k \right) \\ b_k &= \bar{p}_k - \mathbf{a}_k^T \mu_k \\ q_i &= \mathbf{a}_i^T \mathbf{I}_i + \bar{b}_i \end{aligned}$$

where Σ_k is the covariance matrix of \mathbf{I} in ω_k , ϵ is regularization parameter preventing \mathbf{a}_k from being too large, U is the 3×3 identity matrix, μ_k is the mean of \mathbf{I} in ω_k , $|\omega|$ is the number of pixels in ω_k , and \bar{p}_k is the mean of p in ω_k . Then, the resulting q is the desired filter under the guidance of \mathbf{I} .

2 Implementation

Algorithm 1 describes how to remove the haze from the image using the dark channel prior. To refine the transmission map, we implement Algorithm 2.

Algorithm 1 Haze Removal Using Dark Channel Prior

- 1: **function** DEHAZE(\mathbf{I} , t_{min} , A_{max} , w , p , ω , r , ϵ) $\triangleright \mathbf{I}$ is the hazy image
 - 2: Compute \mathbf{I}^{dark} with $\mathbf{I}^{dark}(\mathbf{x}) = \min_{c \in \{r, g, b\}} (\min_{\mathbf{y} \in \Omega(\mathbf{x})} (I^c(\mathbf{y})))$
 - 3: Find the indexes \mathbf{D} for highest $p\%$ pixels in \mathbf{I}^{dark}
 - 4: Compute atmosphere light \mathbf{A} with $\mathbf{A}_c = \max_{\mathbf{d} \in \mathbf{D}} (\mathbf{I}_c(\mathbf{d}))$
 - 5: Threshold \mathbf{A} with A_{max}
 - 6: Estimate transmission \tilde{t} with $\tilde{t}(\mathbf{x}) \leftarrow 1 - \omega \min_c (\min_{\mathbf{y} \in \Omega(\mathbf{x})} (\frac{I^c(\mathbf{y})}{A^c}))$
 - 7: $\tilde{t} \leftarrow \text{GUIDED_FILTER}(\mathbf{I}, \tilde{t}, r, \epsilon)$
 - 8: Recover \mathbf{J} with $\mathbf{J}(\mathbf{x}) = \frac{\mathbf{I}(\mathbf{x}) - \mathbf{A}}{\max(\tilde{t}(\mathbf{x}), t_0)} + \mathbf{A}$
 - 9: **return** \mathbf{J}
-

Algorithm 2 Guided Filter

```
1: function GUIDED FILTER( $\mathbf{I}, p, r, \epsilon$ )
2:   for each pixel  $k$  in  $p$  do
3:      $\omega_k$  is the window with radius  $r$  for pixel  $k$ 
4:     Compute  $\Sigma_k$ , the covariance matrix of  $\mathbf{I}$  in  $\omega_k$ 
5:     Compute  $|\omega|$ , the number of pixels in  $\omega_k$ 
6:     Compute  $\mu_k$ , the mean of  $\mathbf{I}$  in  $\omega_k$ 
7:     Compute  $\bar{p}_k$ , the mean of  $p$  in  $\omega_k$ 
8:      $\mathbf{a}_k = (\Sigma_k + \epsilon U)^{-1} (\frac{1}{|\omega|} \sum_{i \in \omega_k} \mathbf{I}_i p_i - \mu_k \bar{p}_k)$ 
9:      $b_k = \bar{p}_k - \mathbf{a}_k^T \mu_k$ 
10:     $q_k = \bar{\mathbf{a}}_k^T \mathbf{I}_k + b_k$ 
   return  $\mathbf{q}$ 
```

3 Results and Analysis

The results in Figure 1 - 4 are generated with $t_{min} = 0.2$, $A_{max} = 220$, $w = 15$, $p = 0.1$, $\omega = 0.95$, $r = 40$, $\epsilon = 10^{-3}$. From top to bottom are the input hazy image, the dark channel, the estimated transmission map, the refined transmission map, the image dehazed with raw transmission map, and the image dehazed with refined transmission map.

From the results, it is easy to see that this approach can remove most of the haze in the image. The refined transmission map, however, can lead to much better results than the raw estimates.

Since generating the dark channel is somewhat similar to applying a min filter to the image, areas with low intensity in the dark channel will greatly affect its neighboring pixels. Therefore, when there are drastic transitions in the dark channel (e.g. between the sky/fog and salient objects), the area with low intensities will “expand”. For example, in Figure 1, the twigs in the dark channel of the forest are much thicker than in the original image. The leaves with good visibility in the front have low values in the dark channel, resulting in those small squares (usually with the same size as the window) in the dark channel map. Since the raw transmission map is actually calculated with the dark channel of the normalized image, this effect directly leads to the translucent borders around the twigs in the image dehazed with this raw estimate. Other images with this kind of drastic transitions in the dark channel also have the same problems. For example, the distant cones in the second image and the leaves in the last image of Figure 1, the tall buildings in the first three images of Figure 2, the roofs in the first image and the trunk in the second image of Figure 3, etc. all have this kind of borders around them.

From the results it is obvious to see that after guiding the transmission map with the original image, the refined transmission map preserves much more detail than the raw estimate. Most objects become distinguishable in this refined map, and the edges in the transmission map are closer to those in the original image. Therefore, the images dehazed with this refined transmission map no longer have the weird borders as in those dehazed with the raw estimate.

Since the haze will usually increase the brightness of the image (because they are usually white or grayish), the images with a large amount of haze will become relatively darker after dehazing, e.g. the first image in Figure 1, the first two images in Figure 2, the last image in Figure 4. The images with just a thin layer of haze will have a better contrast after dehazing, e.g. the fourth image in Figure 1, the fourth image in Figure 2, the second and the third image in Figure 3, and the first image in Figure 4.

During the experiment, we discover that the choice of parameters is crucial in the quality of haze removal. When there are sky regions in the image, \mathbf{A} tends to be large. In this case, we need a higher t_{min} or lower A_{min} to threshold the computation so as to restrict the recovered \mathbf{J} in a reasonable range. To make the guidance more accurate, r should be larger than $w/2$. Larger r can lead to better results, but it will also slow down the process.

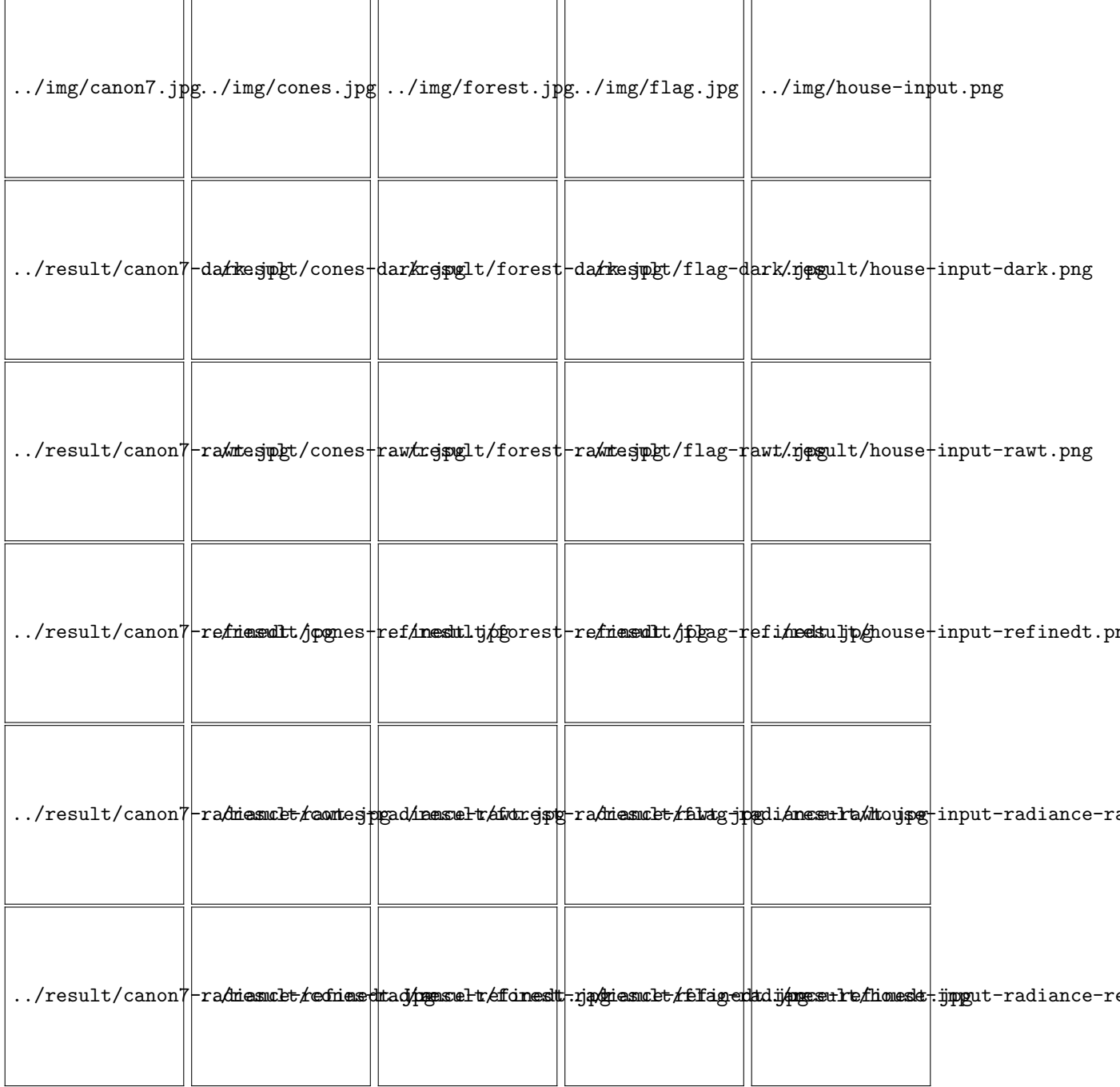


Figure 1: From top to bottom: input hazy image, dark channel, estimated transmission map, refined transmission map, image dehazed with raw estimate, image dehazed with refined estimate

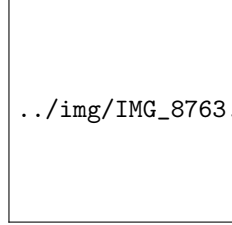
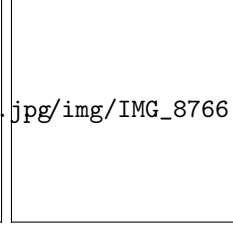
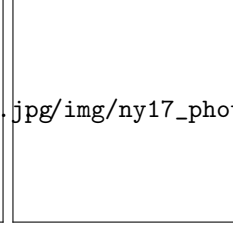
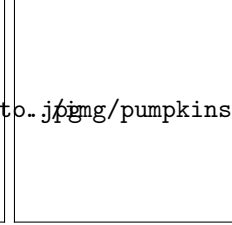
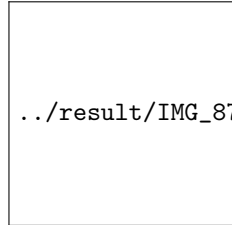
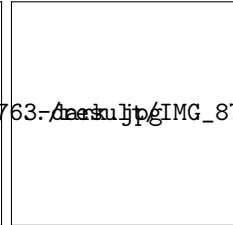
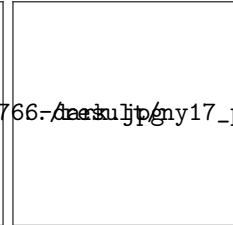

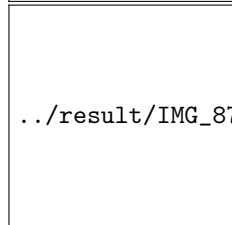
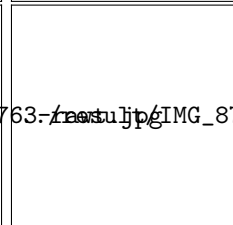
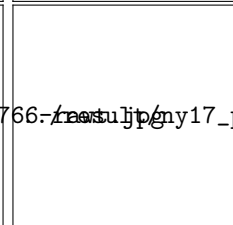

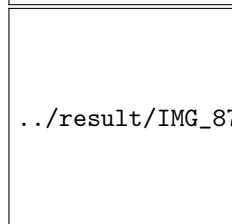
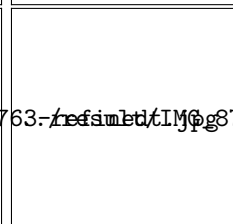
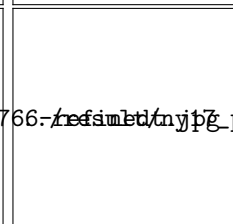

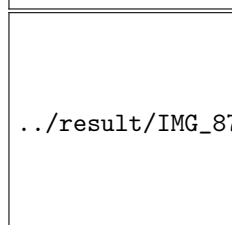
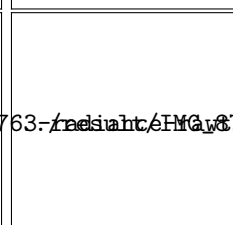
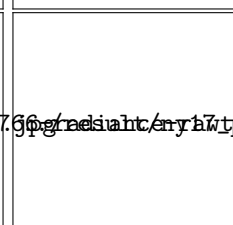
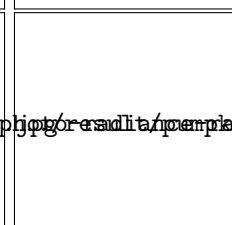
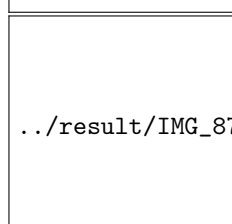
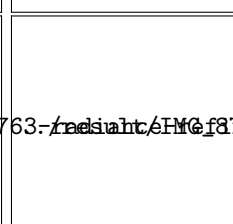
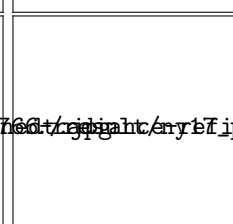
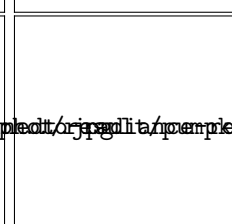
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Figure 2: From top to bottom: input hazy image, dark channel, estimated transmission map, refined transmission map, image dehazed with raw estimate, image dehazed with refined estimate

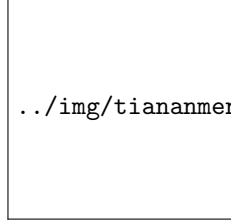
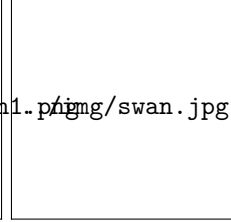
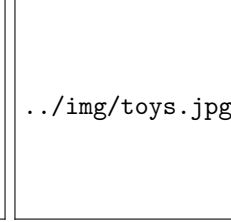
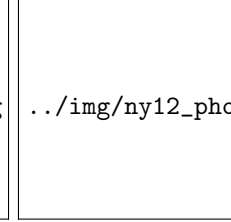
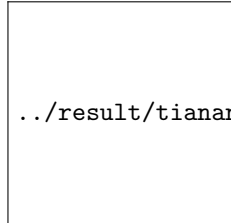
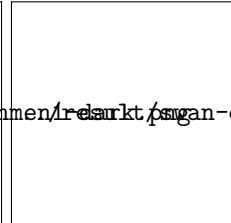
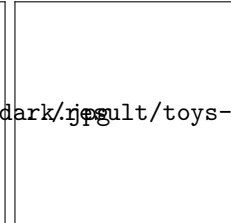
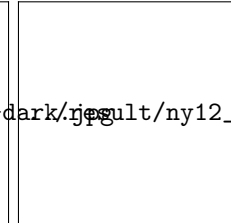
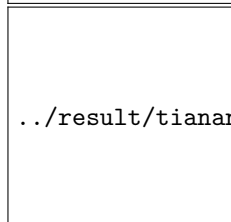
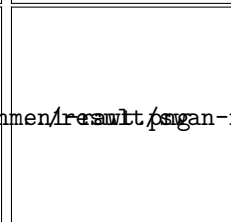
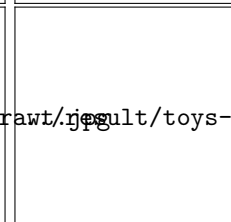
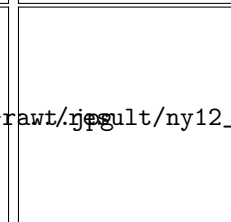
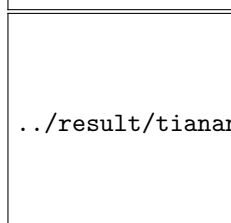
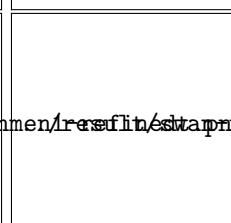
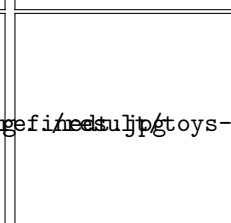
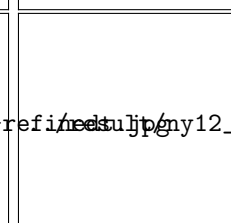
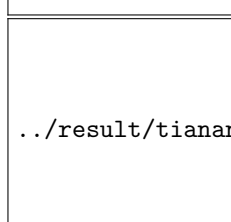
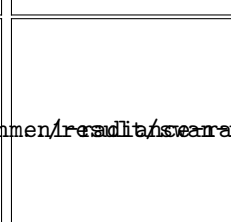
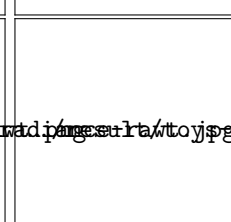
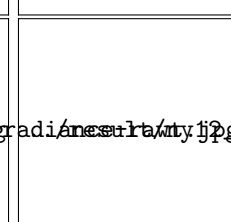
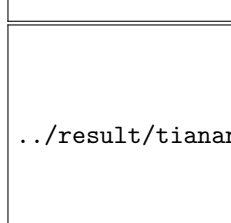
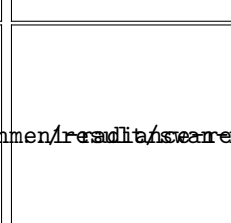
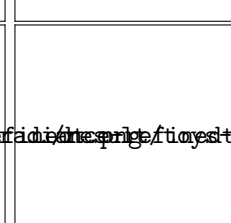
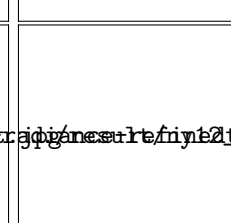
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Figure 3: From top to bottom: input hazy image, dark channel, estimated transmission map, refined transmission map, image dehazed with raw estimate, image dehazed with refined estimate

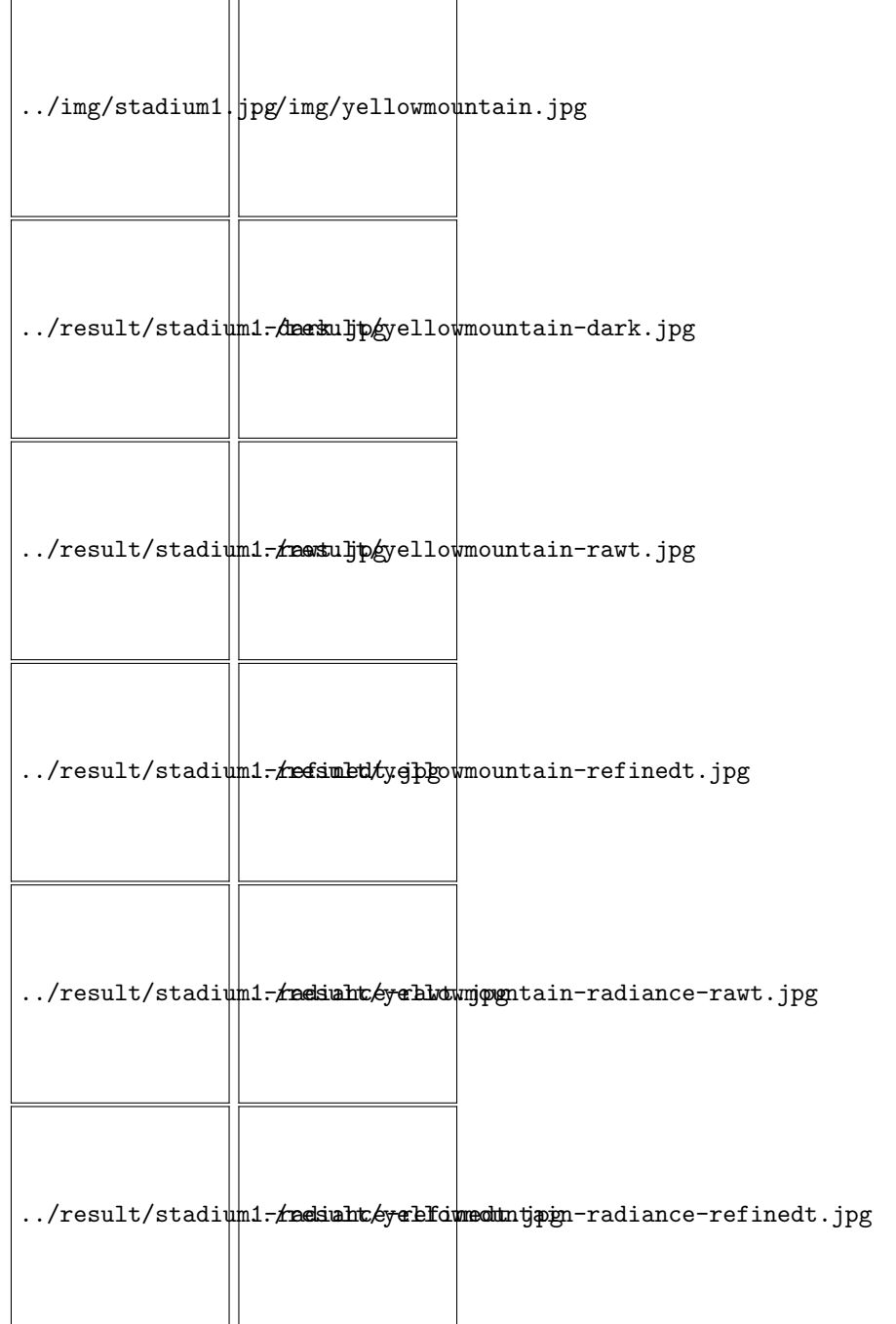


Figure 4: From top to bottom: input hazy image, dark channel, estimated transmission map, refined transmission map, image dehazed with raw estimate, image dehazed with refined estimate

4 Discussion

In the sky region, $\tilde{t} \rightarrow 0$ and $A^c \rightarrow L - 1$. Therefore the equation:

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

is prone to error in images with sky regions. One possible solution is to set a higher t_0 than the one (0.1) suggested in [?]. Another solution is to set a lower A_{max} (which is not mentioned in [?]). For different images, we need different t_0 and A_{max} to produce ideal results. Some results with different configuration of t_0 and A_{max} are listed in Figure 5 -8.

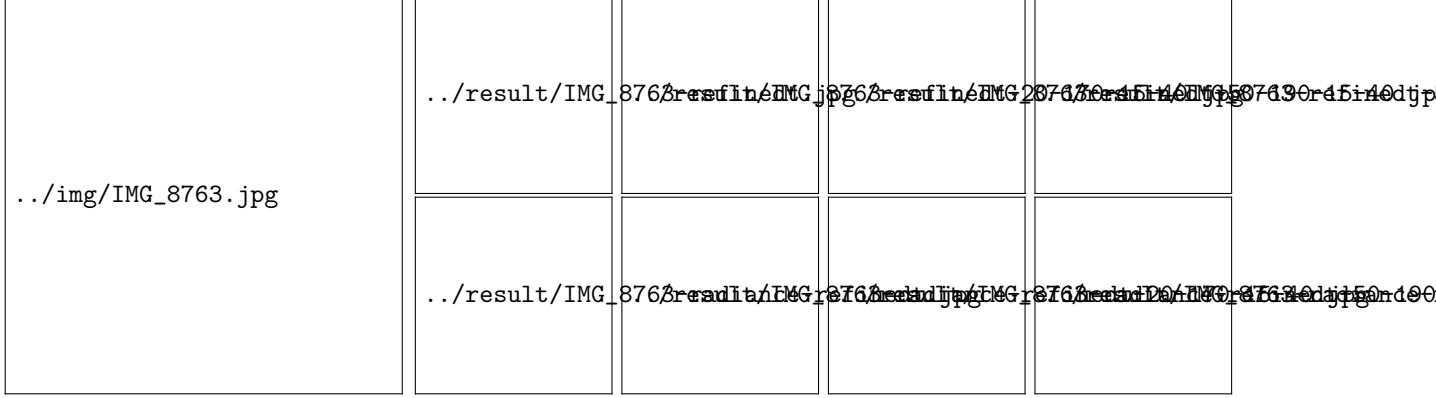


Figure 5: Leftmost image: the input hazy image. On the right side, the top row are transmission maps with $t_{min} = 0.2, A_{max} = 220$; $t_{min} = 0.2, A_{max} = 170$; $t_{min} = 0.5, A_{max} = 190$; $t_{min} = 0.5, A_{max} = 220$; the bottom row are corresponding dehazed images.

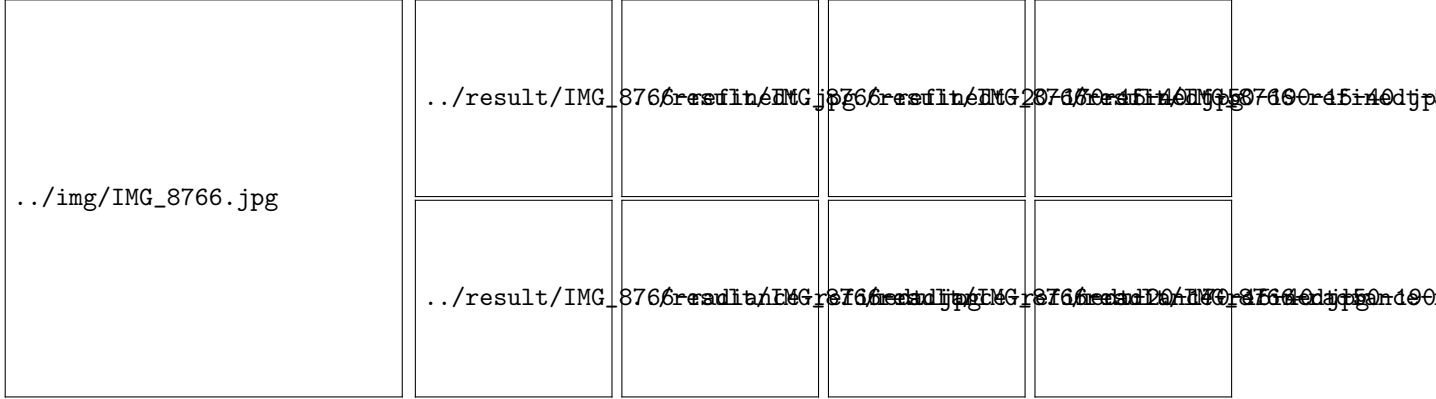


Figure 6: Leftmost image: the input hazy image. On the right side, the top row are transmission maps with $t_{min} = 0.2, A_{max} = 220$; $t_{min} = 0.2, A_{max} = 170$; $t_{min} = 0.5, A_{max} = 190$; $t_{min} = 0.5, A_{max} = 220$; the bottom row are corresponding dehazed images.

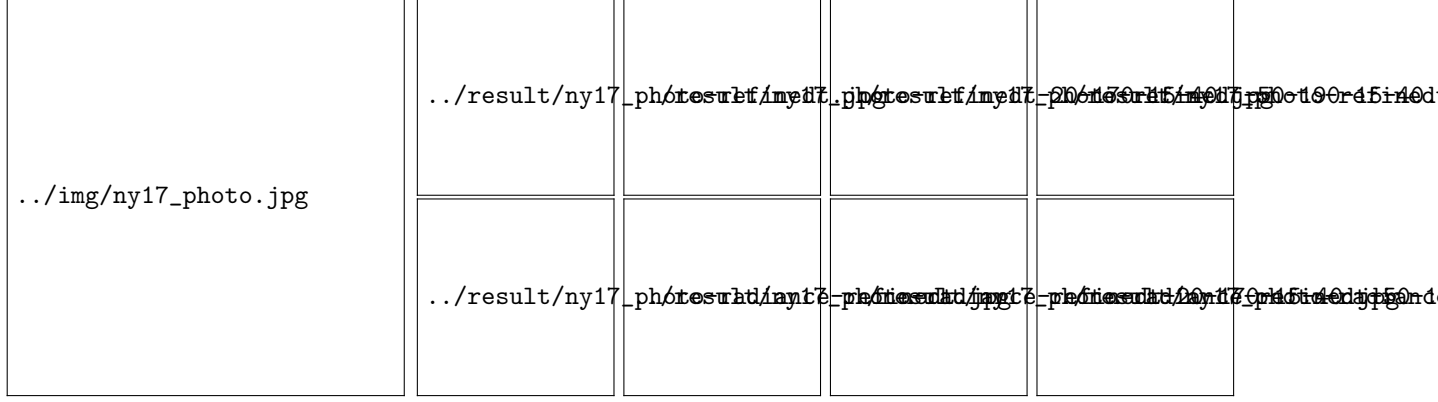


Figure 7: Leftmost image: the input hazy image. On the right side, the top row are transmission maps with $t_{min} = 0.2, A_{max} = 220$; $t_{min} = 0.2, A_{max} = 170$; $t_{min} = 0.5, A_{max} = 190$; $t_{min} = 0.5, A_{max} = 220$; the bottom row are corresponding dehazed images.



Figure 8: Leftmost image: the input hazy image. On the right side, the top row are transmission maps with $t_{min} = 0.2, A_{max} = 220$; $t_{min} = 0.2, A_{max} = 170$; $t_{min} = 0.5, A_{max} = 190$; $t_{min} = 0.5, A_{max} = 220$; the bottom row are corresponding dehazed images.