Vision in Bad Weather
and in Murky Waters

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Support:
NSF, DARPA, ONR
Driving in Bad Weather

People tend to drive fast in fog!! – Nature, 1998
How often do we see Bad Weather?

Manhattan, Every Hour, 12 months

Clear & Sunny (77%)

Bad Weather (23%)

( Narasimhan et. al, ECCV 2002)
Other Poor Visibility Environments

Underwater

Dust

Smoke

Body Tissue
Computer Vision: What can Images Reveal about the Scene and the Atmosphere?
The Fundamental Assumption in Vision

Lighting

No Change in Surface Radiance

Surface

Camera
Attenuation + Airlight

\[ E(d) = E_0 e^{-\beta d} + E_{\infty} (1 - e^{-\beta d}) \]

( Bouguer’s Law, 1729 )
( Koschmeider, 1924 )

\[ (Koschmeider, 1924) \]

\[ (Bouguer’s Law, 1729) \]
Clear Day from Hazy Days

Unknown Hazy Conditions

Computed Clear Day Image

(Narasimhan et. al, IJCV 2002)
Gray World: Contrast Restoration and Structure

Misty Image (3:00pm)

Misty Image (4:00pm)

Dewathering

3D Visualization
Gray World: Contrast Restoration and Structure

Mild Fog, 5 PM

Dense Fog, 5:30 PM

Computed Depth Map
Quantized – 20 levels

Contrast Restored Image

(Narasimhan et. al, PAMI 2003)
Defogging Videos

Foggy Video

Defogged Video

Histogram Equalized Video
Instant Dehazing using Polarization

Haze

De-hazed
Instant Dehazing Using Polarization

Polarized Image (50 deg)  
Polarized Image (140 deg)  
Computed Depth Map  
Dehazed Image
Instant Dehazing Using Polarization

- Polarized Image (50 deg)
- Polarized Image (140 deg)
- Computed Depth Map
- Dehazed Image
Active illumination in Scattering Media

[Levoy et al., Narasimhan-Nayar, Kocak-Caimi, Jaffe et al., Schechner et al., Negahdaripour et al. ]
Floodlighting is Bad in Scattering Media

Structured Light Critical for Good Visibility
Light Stripe Range Finding in Clear Air

Light Stripe Range Finding in Scattering Media
Light Striping Algorithm in Scattering Media

Surface Intersection from Brightness Profile:

3D by Triangulation or Temporal Analysis: Same as in clear air.

Medium ($\beta, g$) from Fall-off: \(\min \| E_{medium} - L_0 e^{-\beta (x+y)} \frac{\beta}{4\pi} (1 + g \cos \alpha) \|_2\)

“Clear-Air” Scene Appearance: \(L_0 R = E_{surface} e^{+\beta(D_s+D_v)}\)
Photometric Stereo in Clear Air

Image Irradiance:

\[ E_{surface} = L_0 \rho n \cdot s \]

Three images required.

[ Woodham 80, Horn 86 ]
Photometric Stereo in Scattering Media

Image Irradiance:

\[ E_{\text{surface}} = L_0 \rho \, e^{-\beta D_s (1+\cos\alpha)} \cos^n \cdot s \]

\[ E_{\text{medium}} = L_0 (1 + g \cos \alpha) \, e^{-\beta D_s} (1 - e^{-\beta D_s \cos \alpha}) \]
Photometric Stereo in Scattering Media

5 Parameter Non-linear Optimization (4 per pixel, 1 global):

\[ \min \| E - (E_{\text{surface}} + E_{\text{medium}}) \| \]

Five Non-degenerate Sources are Necessary and Sufficient
Experiments: Teapot in Pure Water
Experiments: Teapot in Dilute Milk

Low Contrast, Flat Appearance
Results: Traditional Photometric Stereo

3D Shape from Normals
Too Flat

Albedos
Scattering effects present
Results: Our Five-Source Algorithm

3D Shape from Normals

Albedos
Results: Depth from Photometric Stereo

3D Shape from Normals

Depth map
Impossible using traditional method

<table>
<thead>
<tr>
<th>Milk Concentration</th>
<th>3 ml</th>
<th>4 ml</th>
<th>5 ml</th>
<th>6 ml</th>
<th>12 ml</th>
<th>15 ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>% RMS Error</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.3</td>
<td>5.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>
Rendering Participating Media

Accurate Rendering Critical for Realism
Our Measurement Setup

Camera

Glass Tank
Our Measurement Setup

Dimensions of Tank: 25cm x 30 cm x 30 cm
Problem: Multiple Scattering

- Causes significant **Blurring** of Incident Light
- Inverse Estimation is **Ill-conditioned** and **Not Unique**

[Ishimaru 75,97; McCormick et al., 79-83]
Problem: Multiple Scattering

• Causes significant Blurring of Incident Light

• Inverse Estimation is Ill-conditioned and Not Unique
  [Ishimaru 75,97; McCormick et al., 79-83]

• Key Idea: Avoid Multiple Scattering
  At “low” concentrations:
  - Single Scattering dominant
  - Multiple Scattering negligible
  [Ishimaru 97; Narasimhan et al 99-03]
So...dilute media “sufficiently” with water to simplify light transport.
Single Scattering Ray Geometry

- Range of Scattering Angles: [0 deg, 175 deg]
- Range of Path-lengths: [125 mm, 610 mm]
- All Path-length and Angle Combinations
Single Scattering Model and Estimation

- **Image Formation Model:**

\[
E(x, y, z) = \int \frac{I_0}{d_1^2} \exp(-\sigma d_1) \cdot \beta P(\alpha, g) \cdot \exp(-\sigma d_2) \, dz
\]

\[\cdot \quad \text{Scattering Coefficient} \quad \text{Phase function} \quad \text{Extinction Coefficient}\]
Single Scattering Model and Estimation

- **Image Formation Model:**
  \[
  E(x, y) = \int \frac{I_0}{d_1^2} \exp(-\sigma d_1) \cdot \beta P(\alpha, g) \cdot \exp(-\sigma d_2) \, dz
  \]

- **Parameter Estimation:** Nelder-Mead Search in Matlab
  \[
  \arg \min_{\sigma, \beta, g} \| E^{\text{measured}}(x, y) - E^{\text{model}}(x, y) \|\]
Single Scattering Model and Estimation

- **Image Formation Model:**

\[
E(x, y) = \int \frac{I_0}{d_1^2} \exp(-\sigma d_1) \cdot \beta P(\alpha, g) \cdot \exp(-\sigma d_2) \, dz
\]

- **Parameter Estimation:** Nelder-Meade Search in Matlab

\[
\arg \min_{\sigma, \beta, g} \| E_{\text{measured}}(x, y) - E_{\text{model}}(x, y) \| 
\]
How Much to Dilute?

Increasing Milk Concentration

Single Scattering

Multiple Scattering

\[
\frac{1}{d_2} \ln \frac{E}{E_0}
\]

Extinction Coefficient (per mm)

Concentration (ml per litre)
Database of 40 Common Materials

- **Alcoholic Beverages** – 3 wines, 3 beers…
- **Coffees** – black, with cream, cappuccino,…
- **Milks** – chocolate, whole, 2% fat, vitamin A & D,…
- **Juices** – grape, apple, cranberry,…
- **Soft-drinks** – coke, pepsi, lemonade…
- **Cleaning supplies** – detergents, shampoos,…
- **Powders and Crystals** – sugar, salt, tang,…
- **Pacific Ocean Water** – bay, different depths,…
Sample Photographs: Highly Scattering Media

- Pink Lemonade Powder
- Regular Chocolate Milk
- Low Fat Choc Milk
- Ruby Grapefruit Juice
- Salt Powder
- Espresso Coffee
- Cappuccino Powder
- Orange Powder
- Low Fat Milk
- Regular Milk
Sample Photographs: Highly Absorbing Media

Merlot Wine
Coke
Grape Juice
Yuengling Beer
Pacific Ocean Water

Chardonnay Wine
Era Detergent
Strawberry Shampoo
Lemon Tea Powder
Brown Sugar
## Sample Parameters: Highly Scattering Media

<table>
<thead>
<tr>
<th>Medium</th>
<th>Volume</th>
<th>Extinction Coefficient ((\sigma)) (x 10^{-2} \text{ mm}^{-1})</th>
<th>Scattering Coefficient ((\beta)) (x 10^{-2} \text{ mm}^{-1})</th>
<th>Average Cosine (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Fat Milk</td>
<td>16 ml</td>
<td>R 0.9126</td>
<td>0.9124</td>
<td>0.932</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G 1.0748</td>
<td>1.0744</td>
<td>0.902</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B 1.2500</td>
<td>1.2492</td>
<td>0.859</td>
</tr>
<tr>
<td>Regular Milk</td>
<td>15 ml</td>
<td>R 1.1874</td>
<td>1.1873</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G 1.3296</td>
<td>1.3293</td>
<td>0.714</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B 1.4602</td>
<td>1.4589</td>
<td>0.681</td>
</tr>
<tr>
<td>Regular Chocolate Milk</td>
<td>16 ml</td>
<td>R 0.7359</td>
<td>0.7352</td>
<td>0.862</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G 0.9172</td>
<td>0.9142</td>
<td>0.838</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B 1.0688</td>
<td>1.0588</td>
<td>0.806</td>
</tr>
</tbody>
</table>
## Sample Parameters: Highly Absorbing Media

<table>
<thead>
<tr>
<th>Medium</th>
<th>Volume</th>
<th>Extinction Coefficient ($\sigma$) ($\times 10^{-2} \text{ mm}^{-1}$)</th>
<th>Scattering Coefficient ($\beta$) ($\times 10^{-2} \text{ mm}^{-1}$)</th>
<th>Average Cosine (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yuengling Beer</strong></td>
<td>2900 ml</td>
<td>R: 0.1535</td>
<td>0.0495</td>
<td>0.969</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G: 0.3322</td>
<td>0.0521</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: 0.7452</td>
<td>0.0597</td>
<td>0.975</td>
</tr>
<tr>
<td><strong>Merlot Wine</strong></td>
<td>1500 ml</td>
<td>R: 0.7639</td>
<td>0.0053</td>
<td>0.974</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G: 1.6429</td>
<td>0.0000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: 1.9196</td>
<td>0.0000</td>
<td>-</td>
</tr>
<tr>
<td><strong>Era Detergent</strong></td>
<td>2300 ml</td>
<td>R: 0.7987</td>
<td>0.0553</td>
<td>0.949</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G: 0.5746</td>
<td>0.0586</td>
<td>0.950</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: 0.2849</td>
<td>0.0906</td>
<td>0.971</td>
</tr>
<tr>
<td>Medium</td>
<td>Time after collection</td>
<td>Extinction Coefficient ((\sigma)) (\times 10^{-2} \text{ mm}^{-1})</td>
<td>Scattering Coefficient ((\beta)) (\times 10^{-2} \text{ mm}^{-1})</td>
<td>Average Cosine ((g))</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Pacific Ocean Surface</td>
<td>1 hour</td>
<td>R: 3.3645</td>
<td>0.1800</td>
<td>0.902</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G: 3.3158</td>
<td>0.1834</td>
<td>0.825</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: 3.2428</td>
<td>0.2281</td>
<td>0.914</td>
</tr>
<tr>
<td>Mission Bay 10 ft deep</td>
<td>30 min</td>
<td>R: 3.4063</td>
<td>0.0990</td>
<td>0.726</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G: 3.3410</td>
<td>0.1274</td>
<td>0.820</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: 3.2810</td>
<td>0.1875</td>
<td>0.921</td>
</tr>
<tr>
<td>Mission Bay 10 ft deep</td>
<td>8 hours</td>
<td>R: 3.3997</td>
<td>0.1018</td>
<td>0.929</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G: 3.3457</td>
<td>0.1033</td>
<td>0.910</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: 3.2928</td>
<td>0.1611</td>
<td>0.945</td>
</tr>
</tbody>
</table>
Highly Scattering Media

- Merlot Wine
- Coke
- Era Detergent
- Orange Powder
- Strawberry Shampoo
- Pink Lemonade Powder
- Ruby Grape Fruit Juice
- Chardonnay
- Coors Light
- Ocean Water
- Sprite
- Low Fat Choc Milk
- Regular Choc Milk
- Low Fat Milk
- Regular Milk
<table>
<thead>
<tr>
<th>Material Name</th>
<th>Volume</th>
<th>Extinction Coefficient ((\sigma)) ((\times 10^{-2} \text{ mm}^{-1}))</th>
<th>Scattering Coefficient ((\beta)) ((\times 10^{-2} \text{ mm}^{-1}))</th>
<th>Average Cosine (g)</th>
<th>% RMS Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>G</td>
<td>B</td>
<td>R</td>
</tr>
<tr>
<td>Milk (lowfat)</td>
<td>16ml</td>
<td>0.9126</td>
<td>1.0748</td>
<td>1.2500</td>
<td>0.9124</td>
</tr>
</tbody>
</table>
Renderings with the "Kitchen" Environment Map

[Debevec et al]
Merlot

Chardonnay
Yuengling Beer

Coca-Cola
Renderings with a Single Directional Light Source
Yuengling Beer

Coca-cola
Chardonnay Wine

Orange Powder
Blending Parameters

75% Espresso + 25% Milk = Light Coffee
Blending Parameters

50% Wine  +  50% Milk  =  ?
Transitions between Media

Wine → Water → Milk → Espresso
Concentrations at which Parameters Measured
Acknowledgements

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