A Survey of Modelling and Rendering of the Earth’s Atmosphere

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Talk Outline

- Introduction.
- Models of the atmosphere.
- Atmosphere composition.
- Light transfer through the atmosphere.
- Rendering of the atmosphere.
Motivation

- **Photo-realistic image synthesis of outdoor scenes**
  - most of scene objects illumination comes directly from the sun and sky
  - sky forms the background of the scene
  - atmosphere causes change of colors of distant objects

- **Instance of participating media simulation problem**
  - long distances make the effects of atmosphere visible
Models of the Atmosphere

- **Plane-parallel model**  
  - approximates the atmosphere as a set of plane-parallel layers  
  - neglects the sphericity of Earth  
  - introduces large errors near the horizon

- **Spherical model**  
  - Nishita et al. [20,21], Irwin [8], Jackel et al. [10]  
  - for each atmospheric component one submodel  
  - submodel = a set of non-interleaving spherical layers
Composition of the Atmosphere

- **Major atmospheric constituents**
  - clean dry air
  - aerosols
  - ozone
  - water vapour, rain drops and ice crystals

- **Constituents characteristics at point P**
  - extinction coefficient $\sigma_{e\lambda}(P)$ (losses by absorption and scattering)
  - scattering function $p_{\lambda}(P, \theta)$ (angular distribution of scattered light)
  - single scattering albedo $\varpi_{\lambda}(P)$

  (relation between absorption and scattering $\varpi_{\lambda}(P) = \frac{\int_{\Omega} p_{\lambda}(P, \theta) d\theta}{\sigma_{e}}$)
Composition of the Atmosphere – cont.

- Constituents properties depend on
  - particle size
  - wavelength of incident light $\lambda$
  - refractive index of the particle
  - number of particles in unit volume

- Sources of constituents properties
  - Mie scattering theory
  - Rayleigh scattering theory
  - geometric optics
  - measured data
Mie Scattering Theory

- general theory - valid for all particle sizes
- strong forward scattering
- absorption of energy occurs
- scattering function depends on particle size and wavelength
Rayleigh Scattering Theory

- approximation for particles smaller than wavelength of light
- no absorption of light
- simple scattering function
- radiance of scattered light is proportional to the ratio $\sim \frac{1}{\lambda^4}$
  - blue color of the sky
  - color of the sun (yellow $\rightarrow$ orange $\rightarrow$ red)
\[ L_\lambda(P(s_0), \vec{s}) = L_\lambda(P_0, \vec{s}) \tau(s_0, s_{E}) + \int_{s_0}^{s_E} J_\lambda(P(s), \vec{s}) \tau(s_0, s) \sigma_{e\lambda}(P(s)) \, ds \]

- Initial ray radiance \( L_\lambda(P_0, \vec{s}) \) attenuated along the viewing ray by transmittance \( \tau \).
- Integral of skylight radiance scattered towards the observer by volume elements along the viewing ray attenuated by \( \tau \).
Source function

\[ J_{\lambda}(P, \vec{s}) = \frac{1}{4\pi} \iiint_{\Omega} \left[ \sum_{i=1}^{n} \varpi_\lambda^i(P) p_\lambda^i(P, \theta) \right] L_\lambda(P, \vec{s}') \, d\omega' \]
Boundary condition at the top of the atmosphere

\[ L_\lambda(P_0, \vec{s}) = \begin{cases} 
  f_\lambda \left[ 1 - u \left( 1 - \sqrt{1 - \frac{d^2}{r_s^2}} \right) \right] & \text{ray hits the solar disc} \\
  0.0 & \text{outside the solar disc}
\end{cases} \]
Boundary condition for ground reflection

\[
L_\lambda(P_0, \vec{s}) = \frac{1}{\pi} \int_\Omega \int \rho_\lambda(\vec{s}, \vec{s}') L_\lambda(P_0, \vec{s}') \cos \vartheta \, d\omega,
\]
For rendering we need

- function \( F(P, \vec{dir}, date, atm\_cond) \rightarrow \text{spectral radiance} \)
  to simulate the color of the sky and sun

- function \( G(P, \vec{dir}, date, atm\_cond, L_r(P_r)) \rightarrow \text{spectral radiance} \)
  to simulate the change of color of distant objects observed through the atmosphere

\( F \) and \( G \) are based on the light transfer equation
Rendering of the Atmosphere – cont.

Rendering of the sky color

- For every pixel covered by the sky do
  - evaluate $LTE$ to determine amount of spectral radiance
  - convert spectral radiance $\rightarrow$ CIE XYZ color space
  - apply tone mapping techniques
  - convert CIE XYZ color $\rightarrow$ RGB color to be displayed

Simulation of the aerial perspective

- For all pixels not covered by the sky
  - find intersection with the scene object
  - calculate amount of light reflected towards the observer
  - evaluate $LTE$ to calculate gains and losses of reflected light
  - tone mapping and conversion to the RGB color
Methods to solve the light transfer equation

- **analytic methods**
  + fast and easy to use
  - hardly extendable
- **numerical methods**  
  Nishita et al.[13,20,21], Jackel et al.[9,10]
  - still very difficult to solve
  - require a lot of computational time
  + work with arbitrarily complex atmospheric conditions

Simplifying assumptions

- uniform medium, simple geometry or very small albedo
- restriction of order of scattering $\rightarrow$ single scattering methods
Hybrid methods

- numerical solution $\Rightarrow$ analytical approximation
- sky approximated by hemisphere with a large radius
- numerical solution
  $\Rightarrow$ sky spectral radiance distribution for several sun altitudes
  $\Rightarrow$ approximation by a series of basis functions / simple parametrically fitted formulas
  $\Rightarrow$ weights / parameters values are stored in tables
Rendered Images

Preetham et al. [23]  Walter and Jackel [9,10]
Summary

We discussed

- two models of the atmosphere
- atmosphere composition and properties of the major atmospheric constituents
- light transfer equation
- overview of methods used for rendering of the atmosphere
QUESTIONS ?
i-th spherical layer
combination of
submodel 1 and 2
=+
submodel 2
submodel 1

H1

H2

ground

ground

submodel 1

submodel 2

combination of
submodel 1 and 2
scattering volumes

beams of sunlight penetrating the atmosphere

incident skylight radiance along direction \( \vec{s} \)

skylight scattered along direction \( \vec{s} \) towards the observer

phase function

\[
L_\lambda(P_0, \vec{s})
\]

\[
\tau(s_0, s_E)
\]

\[
\lambda
\]

\[
J_\lambda(P, \vec{s})
\]

\[
P_0
\]

\[
P
\]

\[
\theta
\]
irradiance decrease factor

distance from the center of solar disc [km]

limb darkening

solar irradiance

L_\lambda(P_0, \vec{s})

atmosphere

\vec{s}

\textbf{f}_{\lambda}

0.4
0.5
0.6
0.7
0.8
0.9
1
0 100000 200000 300000 400000 500000 600000
irradiance decrease factor
distance from the center λ
λ
solar irradiance
black body at 5777K
atm_cond

F(...)

G(...)

L_r (P_r)

P_r

P