Realtime Rendering of Planetary Atmospheres

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Talk outline

- Introduction
  - light, atmosphere, light scattering
- Examples of light scattering
- Calculation of light scattering
- Visualisation
  - precomputation
  - rendering
  - comparation
- Why bother?
- Interactive demonstration

Talk outline – part I

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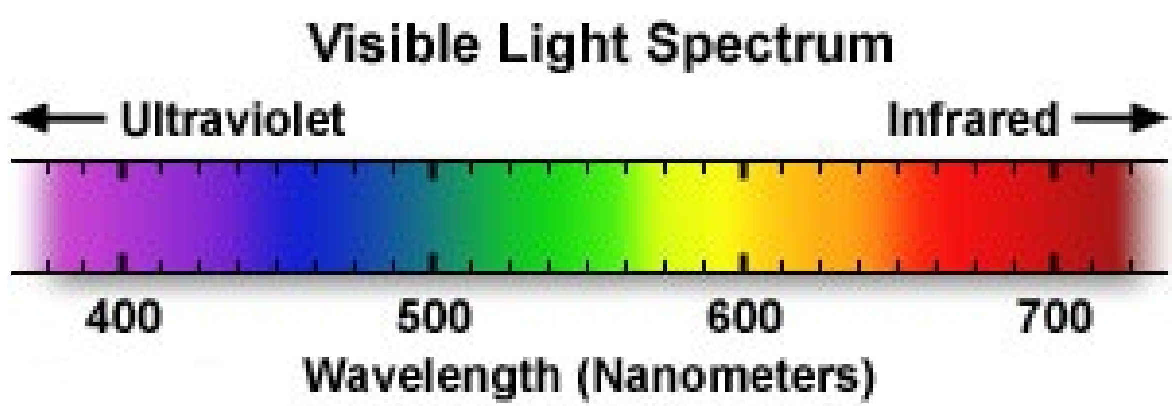
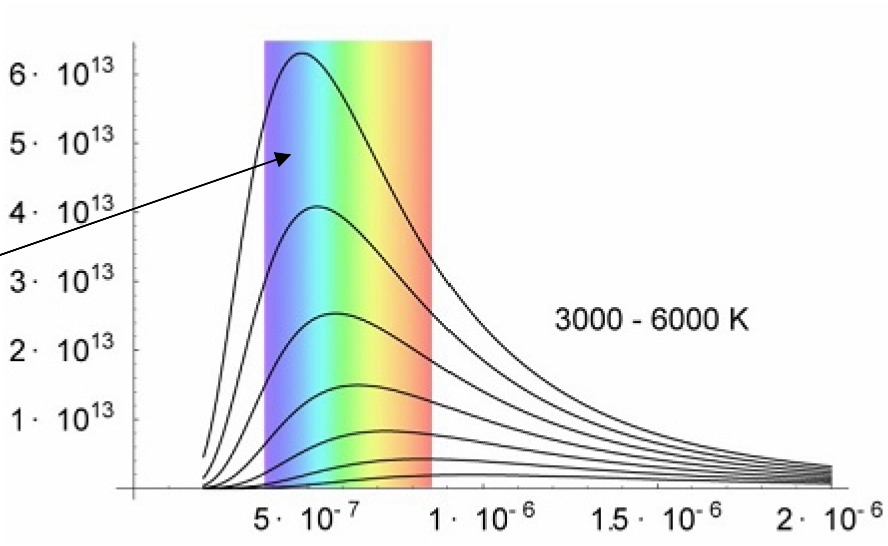
Light I

- Often simplified to RGB triplets
- “Light is electromagnetic radiation that is visible to the human eye.”
- Main attributes:
  - Amplitude → Intensity
  - **Wavelength → Colour**
  - Polarisation



Light II

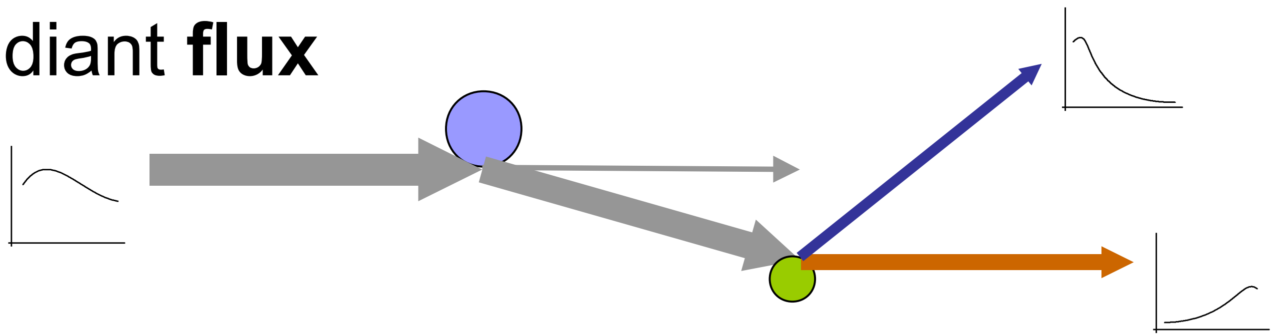
- Color determined by **spectral composition**
- Example: blackbody radiation from Sun



- Wave-particle duality – Albert Einstein 1900s
  - Wave – interference, scattering…
  - Particle – light pressure
  - Every particle is dual (de Broglie 1929)

Light III

- Common abstraction in realtime CG – ray
- Radiant **flux**



  - Can be diverged and attenuated
- Polarisation
  - Orientation of oscillations
    - <u>Linear</u>, circular or elliptical
  - Can lead to attenuation of light

Atmosphere

- Earth's atmosphere
  - Gas molecules
    - N_2, O_2, CO_2…
  - Larger (aerosol) particles
    - Water droplets, dust, ice crystals, ash…

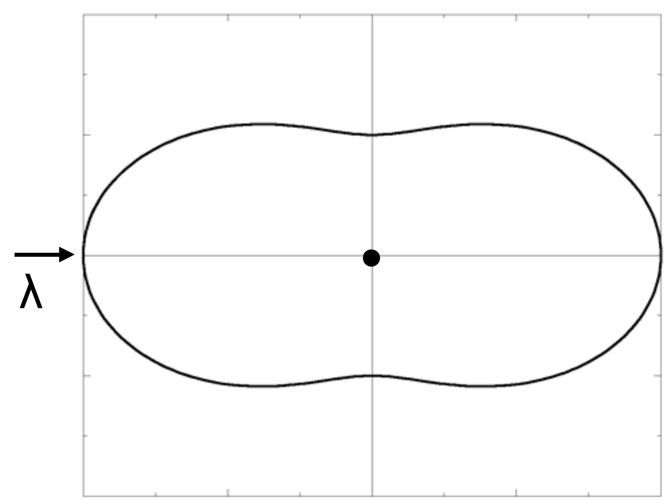
- The density (and pressure) drops down exponentially:

$$\rho = \exp\left(\frac{-h}{H_0}\right)$$

    - H_0 - scale height
      - Gases ~ 8km (5.6km for exp2())
      - Aerosols ~ 1.2km (1.7km for exp2())

Light scattering

- "Light scattering is process when the light passing through **participating medium** is forced to deviate from original trajectory."
- Reason of many phenomena, incl. color of atmosphere
- Denser medium ~ higher probability of scattering event
- Angular scattering pattern (distribution) given by **phase function**

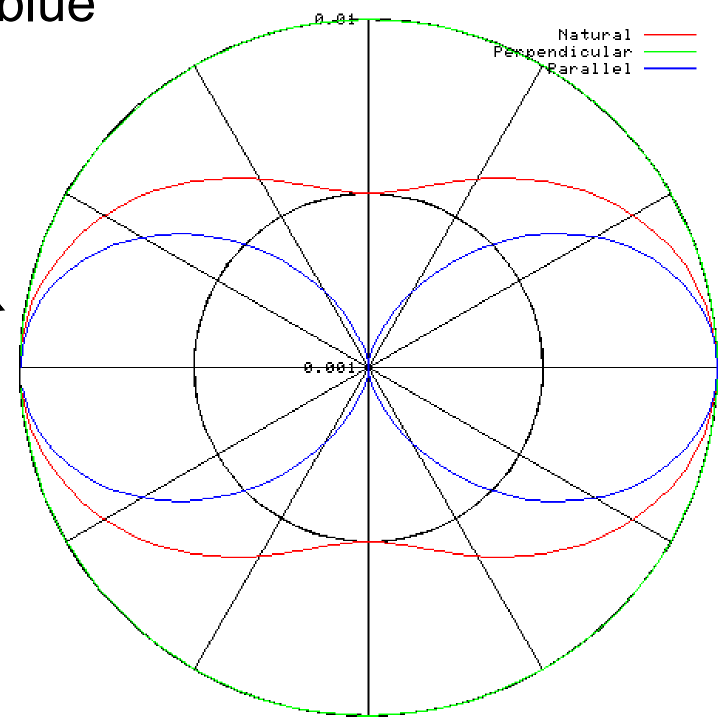


Light scattering classification

- Elastic
  - **Rayleigh scattering**
  - **Mie scattering**
  - Takes place in the atmosphere
- Inelastic (energy loss)
  - Raman scattering
  - Brillouin scattering
- Special
  - Rutherford scattering (α-particles on gold foil)

Rayleigh scattering

- J. W. Strut – 3rd Lord Rayleigh, 1871
- Light scattering on particles → $x \ll 1 \qquad x = \frac{2\pi r}{\lambda}$
  - At r~10nm transition to Mie scattering
- **$^{1}/_{\lambda^4}$ dependency**
  - $(730/380)^4$ = 13.6 times more blue than red light scattered
- y-**symetric** phase function



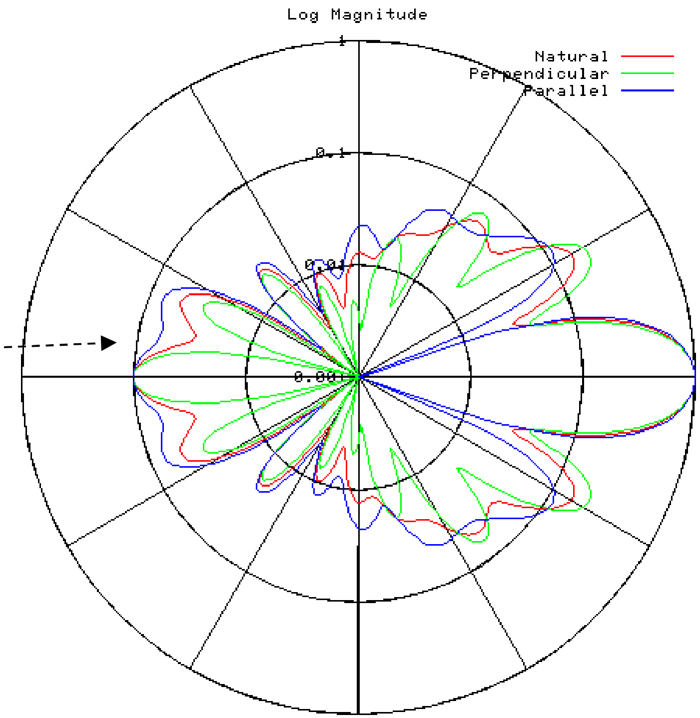
- Approximation:

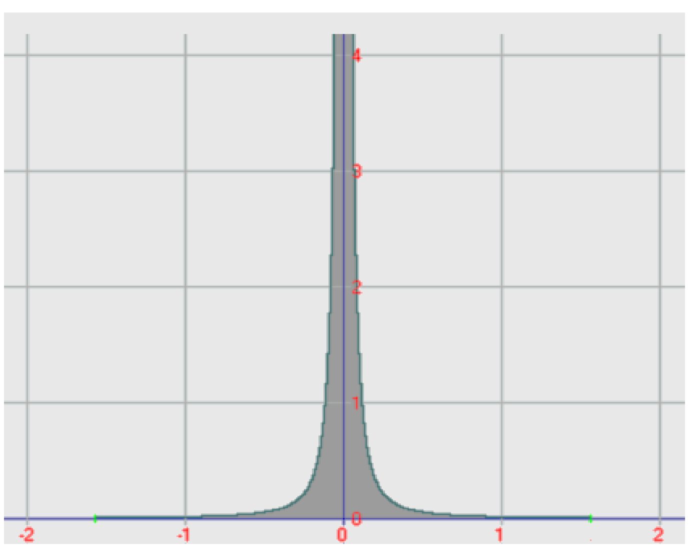
$$F_R(\theta) = \frac{3}{4}(1 + cos^2(\theta))$$

Mie scattering

- German physicist Gustav Mie, 1908
- Light scattering on larger particles (x ~1 and more)
- **No general λ dependency**
- Phase function

  strongly **anisotropic**





- Analytical approximation by Cornette-Shanks

Multiple scattering

- So far only single bounce discussed
- Rayleigh and Mie are elastic → 'infinite' number of bounces
- Main difference:
  - Single scattering – **random occurrence** (scatterer position uncertainity) – described by probability distribution
  - Multiple scattering – averaged **deterministic behaviour** to high degree
- Can turn strongly anisotropic scattering medium into isotropic in terms of global phase function (i.e. clouds – cca 30 bounces)

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- **<u>Examples of light scattering</u>**
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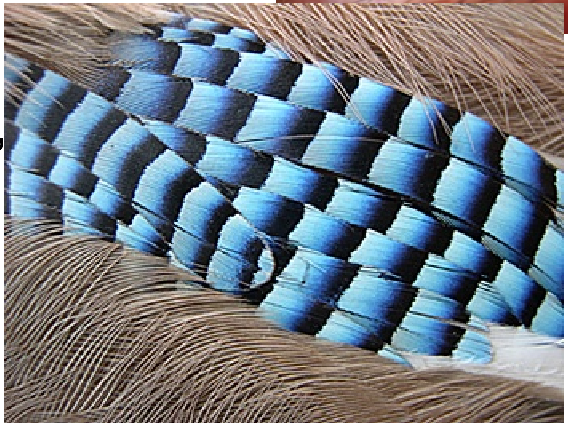
Examples of light scattering I

- Subsurface skin scattering
- Translucent materials (wax, marble…)

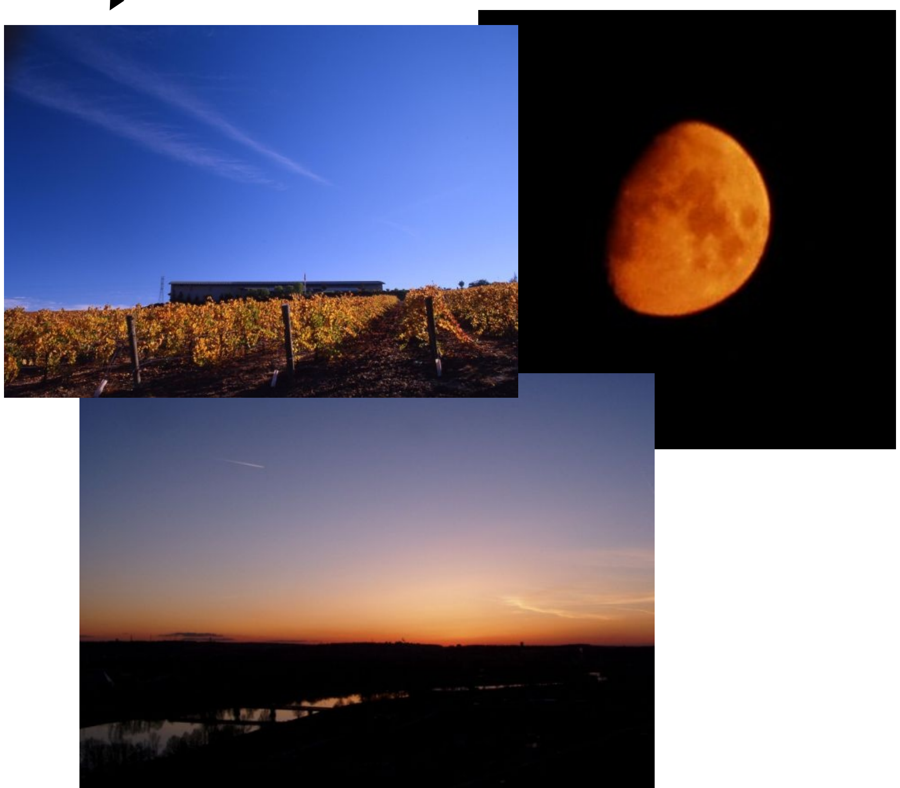
- Smoke, haze
- Human eyes (combined with absorptive reflectivity)

- Water blue (minor share)
- Animal realm (feathers, butterflies, reptiles – sharing colorfulness with interferential iridescence)



Examples of light scattering II

- **Colour of the atmosphere**
  - Rayleigh scattering – chromatic parts
  - Mie scattering – achromatic (λ-independence)



Talk outline – part III

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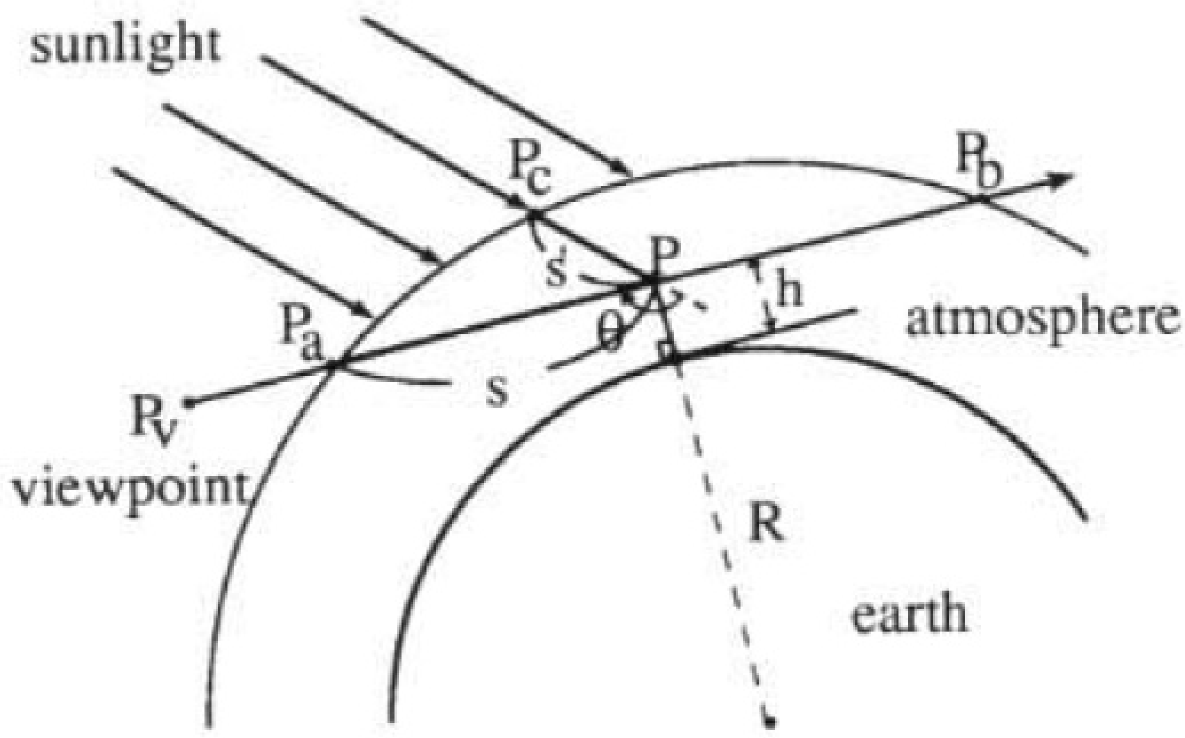
Scattering integral - sketch

$$I_V(\lambda) = I_i(\lambda) F_R(\theta) \frac{K}{\lambda^4} \int_{P_a}^{P_b} \rho(h) exp\left(-t(PP_c, \lambda) - t(PP_a, \lambda)\right) ds$$



Optical length

- Expresses attenuation along given path in participating medium

$$t(S,\lambda) = \frac{4\pi K}{\lambda^4} \int_0^S \rho(s)ds$$

- *S* …… path length
- *K* …… density constant (sea level)
- *ρ* …… density scale function ($0 \le \rho \le 1$)
- Without $^1/_{\lambda^4}$ for Mie scattering

Scattering integral

- Scattered light coming from certain direction (single scattering only!)

$$I_V(\lambda) = I_i(\lambda) F_R(\theta) \frac{K}{\lambda^4} \int_{P_a}^{P_b} \rho(h) exp\left(-t(PP_c, \lambda) - t(PP_a, \lambda)\right) ds$$

- I_V …… incoming scattered light
- Suitable for procedural calculation of light scattering

Scattering integral - analyse

$$I_V(\lambda) = I_i(\lambda) F_R(\theta) \frac{K}{\lambda^4} \int_{P_a}^{P_b} \rho(h) exp\left(-t(PP_c, \lambda) - t(PP_a, \lambda)\right) ds$$

- I_i …… incident light
- F_R …… phase function (at scattering angle θ)
- K …… atmosphere density constant

Scattering integral - analyse

$$I_V(\lambda) = I_i(\lambda) F_R(\theta) \frac{K}{\lambda^4} \int_{P_a}^{P_b} \rho(h) exp\left(-t(PP_c, \lambda) - t(PP_a, \lambda)\right) ds$$

- Integrating along view ray *S* – in-scattering phase
- P_a …… first point on *S* where *ρ(h)*>0
- P_b …… last point on *S* where *ρ(h)*>0

Scattering integral - analyse

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$$I_V(\lambda) = I_i(\lambda) F_R(\theta) \frac{K}{\lambda^4} \int_{P_a}^{P_b} \rho(h) exp\left(-t(PP_c, \lambda) - t(PP_a, \lambda)\right) ds$$

- Attenuation function at sample point *P* – out-scattering phase
- PP_c …… path in direction of light
- PP_a …… path to observer

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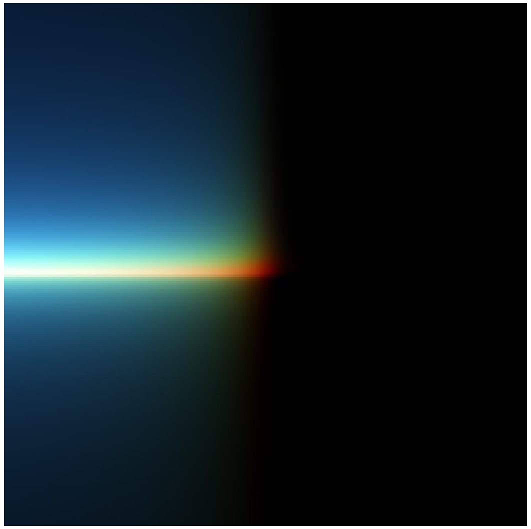
Precomputation

- ‘Compute & store’ concept
  - In some data structure (kD texture on graphics HW)
- Critical assumptions:
  - Sensible behaviour of target function (classical sampling problem)
  - Sensible dimensionality of TF
    - ‘Sensible’ means at most 4-5 DoF
    - Otherwise data will grow too large
- Fetch data during rendering
  - Assuming ‘fetch’ is fast enough



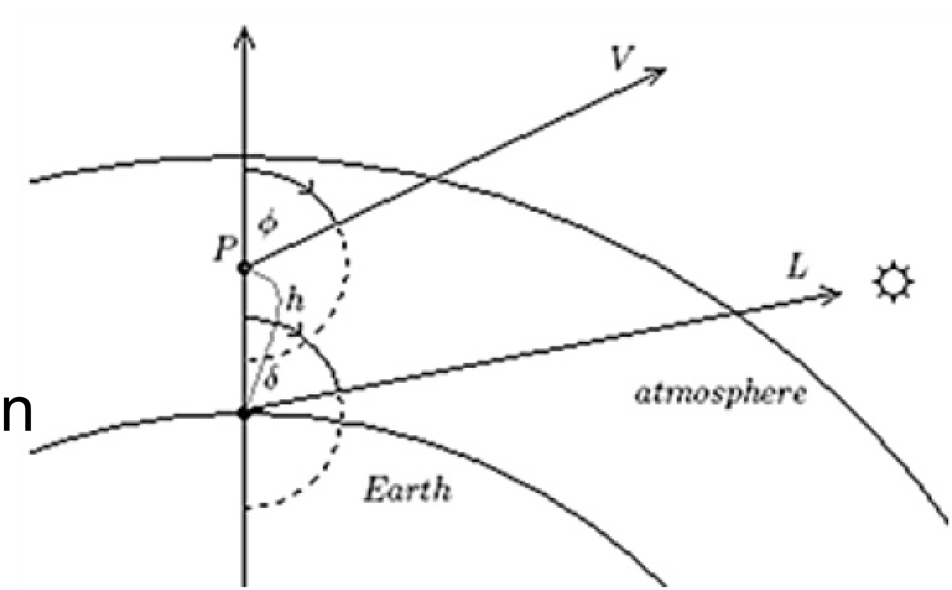
Precomputation of atmospheric light scattering

- We want light intensity for:
  - Every observer **position** ~ $P[p_x,p_y,p_z]$ … 3 DoF
  - Every observer **view direction** ~ $V[v_x,v_y,v_z]$ … 3 DoF
  - Every **daytime** (light direction) ~ $L[l_x,l_y,l_z]$ … 3 DoF
- 9 DoF is too many
- Let's assume:
  - Atmosphere is spherical with exponential density falloff, isotropic otherwise
  - Earth surface is spherical
  - Light rays from Sun are parallel (20" at most)

Precomputation of atmospheric light scattering – 1 try

- Representing
  - Observer position as **altitude** ~ h … 1 DoF
  - Observer view direction as **view-zenith angle** ~ θ … 1 DoF
  - Light direction as **light-zenith angle** ~ δ … 1 DoF

gives us only **3** DoF!



- What's the catch?
  - We neglect the **azimuth** from the Sun

Precomputation of atmospheric light scattering – 2 try

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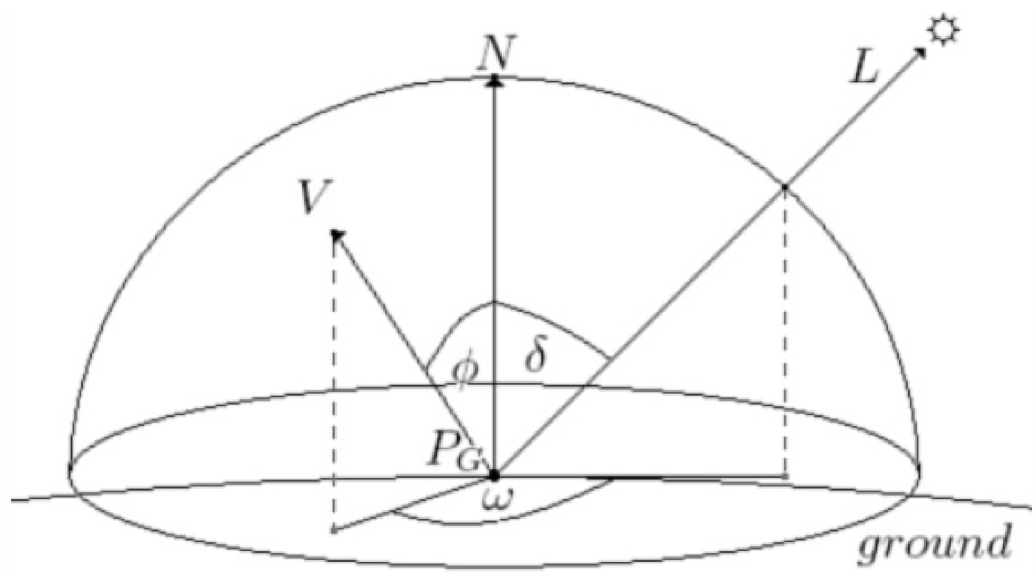
- Everything stays, but we add **azimuth** ~ ω … 1 DoF
  - Problem – graphics HW supports only 3D textures!
    - Use vertical tiling
  - Problem – data are too large!
    - Use nonlinear importance mapping for sampling texture's parameters (priorize areas with larger **gradient**)
- One more flaw – Mie phase function
  - Is too steep! (forward lobe)
    - Deferred evaluation (in fragment shader)

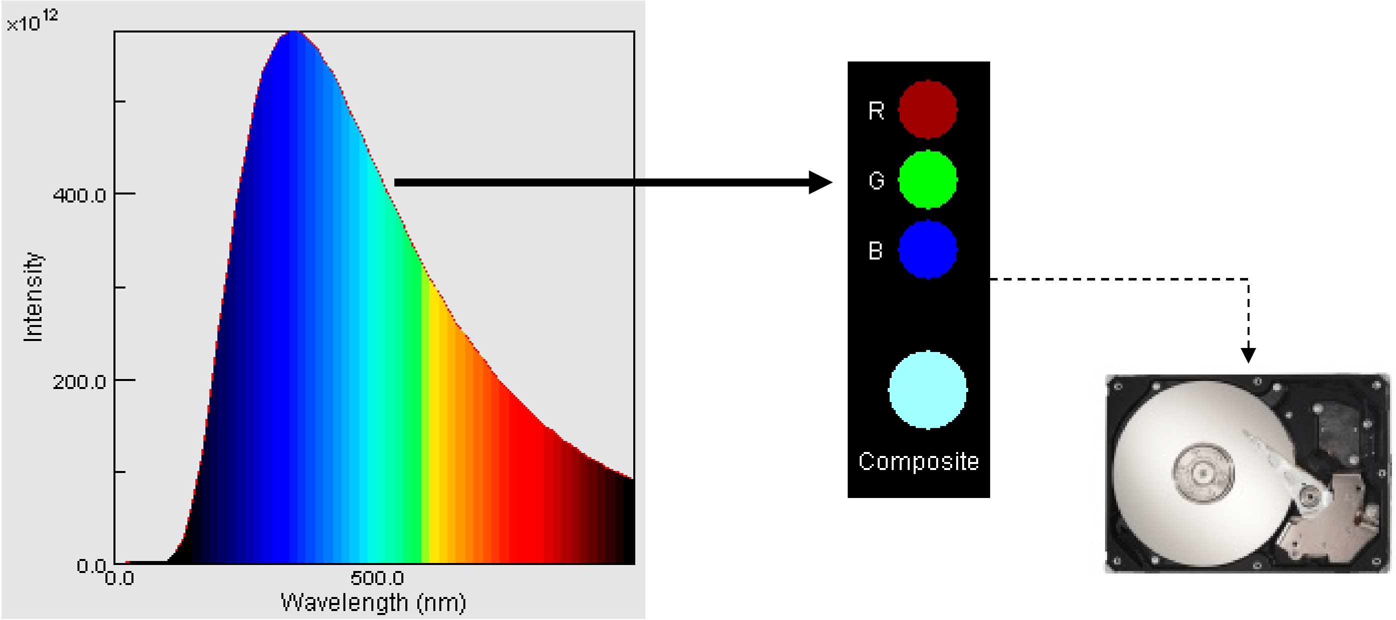


Multiple scattering

- Single scattering computation complexity is $\mathbf{C*n^2}$ for every texel (**C** not neglectable)
  - n … sampling rate
- Multiple scattering – $\mathbf{C^k*(n^2+n^3)^k}$ per texel!
  - k … number od orders
  - Brute force approach will 'never' finish
- Solution – **dynamic programming**
  - 1) Compute 1. order normally and store it
  - 2) Each k. order compute from stored (k-1). order as if computing single scattering (with a bit more complicated gathering step)
- New complexity → $\mathbf{C*n^2 + (k-1)*(C*n^2+C*n^3)}$
  - 'n^3' term now **very** fast (n*n^2 fetching op-s)
  - Result – complexity almost **linear in relation to k** (!!)

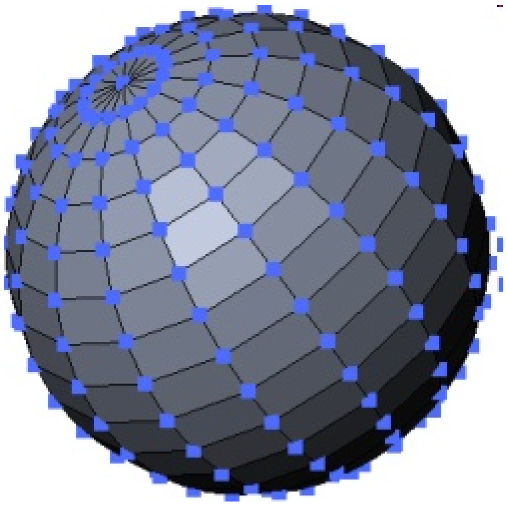
Spectral precomputation

- Tens of spectral values instead RGB triplet
- λ sampling as next DoF
  - Computational cost grows up only few %
    - λ only multiplies integrals
- Conversion spectrum→RGB before storing



Rendering I

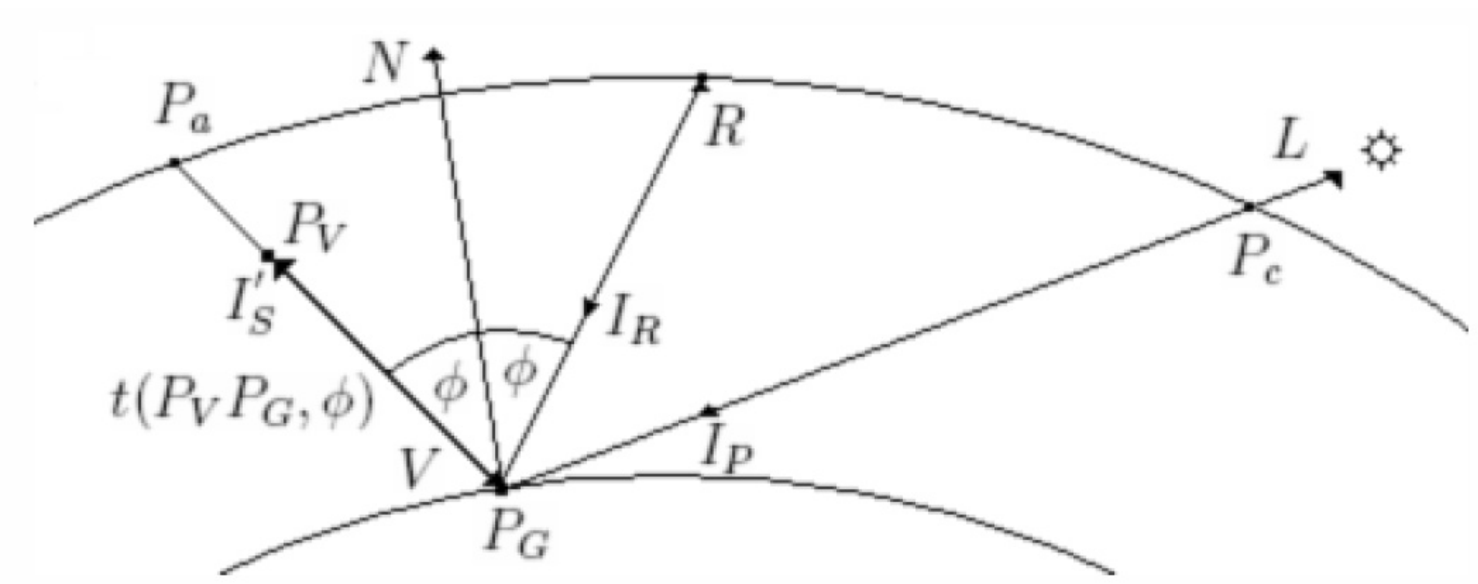
- CPU-based precomputation
- GPU-based realtime renderer
- Sky and planet represented by simple tesselated spheres



- Sky is simple
  - 1) Calculate ***h***, ***θ***, ***δ*** and ***ω*** in the fragment shader
  - 2) Fetch the sky colour

Rendering II

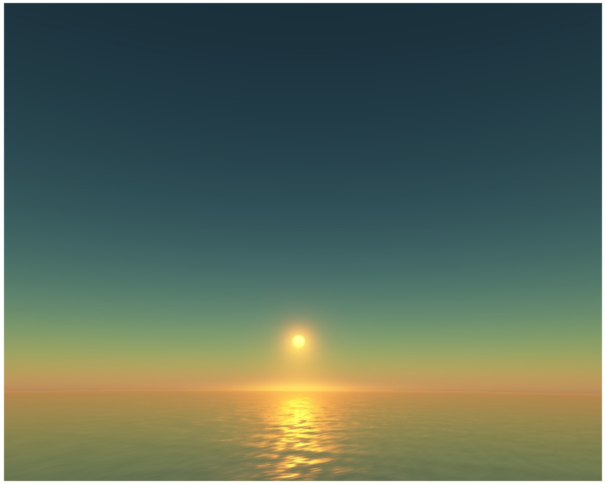
- Ground is little bit harder
  - 1) Scattering same as sky
  - 2) Add direct illumination (after attenuation)
  - 3) Add water reflections
    - Precomputed data serve as environment texture



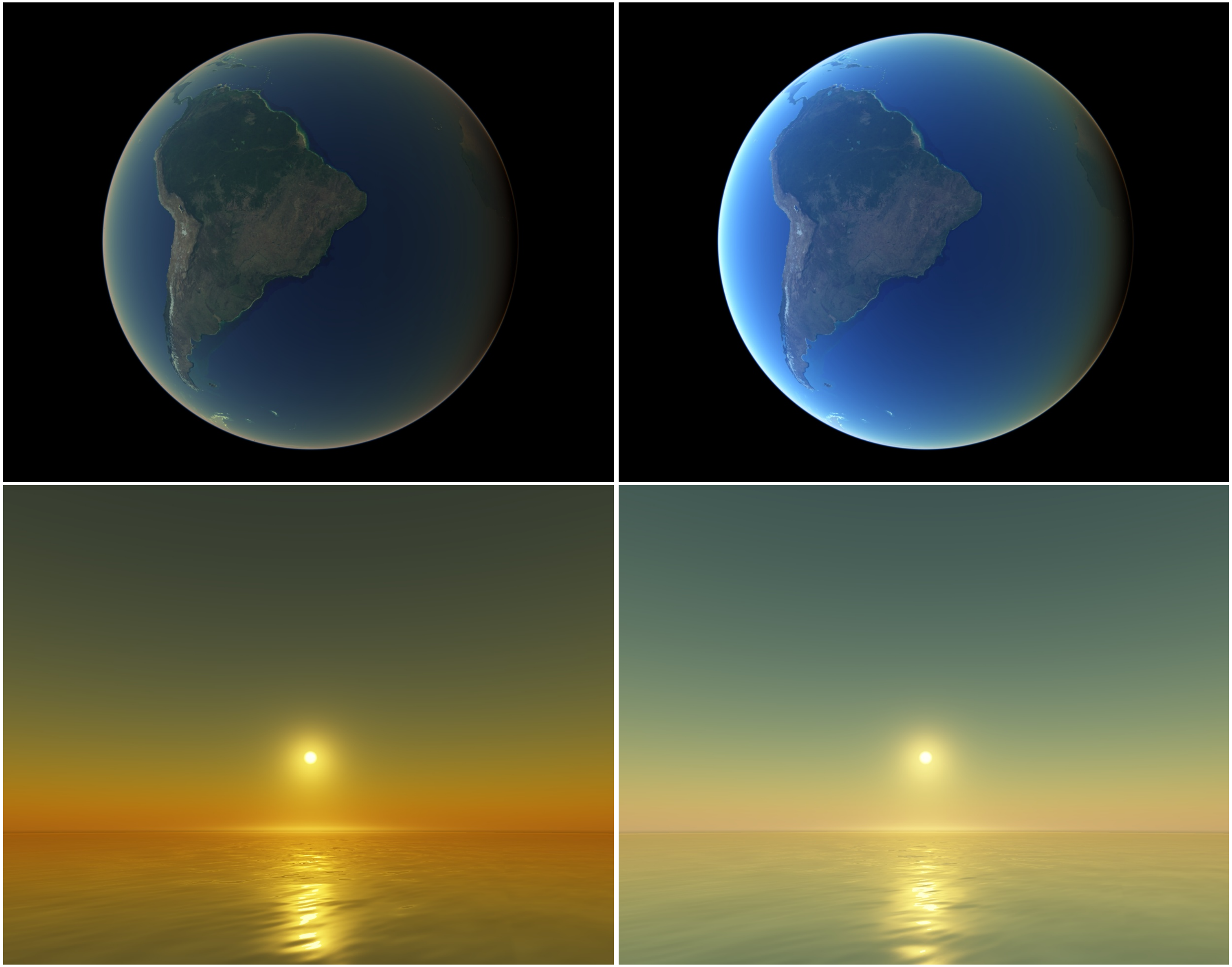
Comparation – ‘engines’

- Evening sky during sunset

- Real photo (continental sky, Prague)
- Non-realtime system (Maxwell Render)
- Realtime system (my renderer)



Comparation – single vs multiple LS



Single scattering

Multiple scattering

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Who need realtime atmosphere?

- Majority of 3D games
  - FPSs, RTSs, RPGs, racers, flight sims, ...
- Professional flight simulators (training purposes)
  - Aircraft pilots
  - Spacecraft pilots
- Animated movies
  - Much less (maybe interactive ones?)
- Scientific visualisations
  - Meteorology, climatology, …

Talk outline - conclusion

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- Visualisation
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  - comparation
- Why bother?

- **Interactive demonstration**

Thank you for your attention!

Questions?

References, further information

- **Elek Oskar:** Rendering Planetary Atmospheres in Real-Time, Bachelor Thesis, MFF UK, 2008
- **Nishita T., Sirai T., Tadamura K., Nakamae E.:** Display of The Earth Taking into Account Atmospheric Scattering, Siggraph ’93: Proceedings of the 20th annual conference on Computer graphics and interactive techniques, 175-182, 1993
- **Schafhitzel T., Falk M. and Ertl T.:** Real-Time Rendering of Planets with Atmospheres, Journal of WSCG, Vol. 15, 2007
- **Bruneton E. and Neyret F.:** Precomputed Atmospheric Scattering, 19th Eurographics Symposium on Rendering, EGSR08, Sarajevo, 2008

- **Keywords:** atmospheric light scattering, Rayleigh scattering, Mie scattering, multiple scattering, spectral rendering
- **My homepage:** http://www.oskee.wz.cz/stranka/oskee.php