Physically-Based Atmosphere and Cloud Rendering

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ABSTRACT

In computer generated imagery, as in photography, the sky is very ubiquitous and important—as a source of light, as a backdrop, and as a subject in and of itself. However, realistic and aesthetically appealing skies are also very difficult to render. Models exist to approximate the appearance of the sky, but they make many assumptions and have many limitations. To create truly realistic images a full physical simulation of atmospheric scattering, including clouds, is necessary. For this project, I will simulate and produce photorealistic and aesthetically pleasing renders of atmospheres (and clouds if time permits), lit by the sun.

Project Blog: http://skyrenderer.blogspot.com/

1.INTRODUCTION

Realistic and dynamic skies are very difficult to render. Analytic sky models can be used to model the appearance of the sky, but they make assumptions and have many limitations, such as only working from the point of view of ground, not taking ground albedo into account, not working for twilight, not modeling clouds, etc. Image-based lighting in the form of HDR environment maps can also replicate real-life lighting, however they are static—only valid for a very specific time and location. Some researchers have tried simulating the atmosphere, which can be very accurate but very slow.

In real life, the sky is very ubiquitous and important. It serves as a source of light. It acts as a backdrop for everything we do. It indicates the time of day, the season, and the weather. It affects our moods. And it serves as a subject of contemplation, admiration, and artwork. The sky can also serve these same purposes in computer graphics. In particular, realistic sky light can make the difference between a flat, unrealistic image and a photorealistic image.

I will write an atmosphere simulation that balances physical accuracy, aesthetic beauty, flexibility, and performance. The simulation will work from any location and altitude (including from space), with various input parameters, and, if time permits, with clouds. I will use real-life data and physics where applicable. However, I will not necessarily directly simulate all of the complex effects of light (including polarization, diffraction, dispersion, and atmospheric refraction)—instead, I will focus on the effects that have the most visual impact, such as Rayleigh and Mie scattering from air, water vapor, dust, and pollutants.

This project makes the following contributions:

- I will develop a new sky rendering system that produces physically accurate and aesthetically pleasing images.
- I will learn about a variety of subjects that I will need to understand to do further research, and subjects that will be highly relevant and useful in the movie and game industries.
- Time permitting, I will add clouds, which are a very important visual element in the real sky, but which are ignored in most atmosphere simulation and sky models.

1.1Design Goals

The target audience for my project is anyone who wants to be able to utilize realistic, computer-generated skies and atmospheric effects. The user will be able to create realistic and pretty pictures with this technology.

1.2Projects Proposed Features and Functionality

I will implement the following features and functionality for my design project:

- Simulate atmospheric scattering using Monte Carlo path tracing, ray marching, various forms of importance sampling, and various optimizations.
- Use real-life data for the composition of the Earth's atmosphere, and real-life physics for the scattering properties of the atmosphere and clouds.
- Write a spectral rendering system, that will work for all wavelengths of visible light, as well as ultraviolet and infrared.
- Employ colorimetry to convert spectral data to images that can be displayed on computer displays.
- Save HDR images, along with deep alpha maps and other information.
- If time permits, model and render clouds.

2.RELATED WORK

People in various disciplines have been interested in characterizing the appearance of the sky for many many years. Summarized below are some of the past work that I will draw on when developing my sky renderer.

Over a period of decades in the late 1800s, Lord Rayleigh published a series of papers that explained his theories about atmospheric scattering and how it caused the color and appearance of the sky. In [Ray71] and [Ray99] he formulates and refines his theory of the scattering of light by air molecules, now known as Rayleigh scattering.

[McC76] describes turbidity, the scattering of light by haze in the atmosphere. Turbidity is an important aspect of atmospheric scattering.

In 1982, Jim Blinn developed methods for simulating light scattering in volumes in [Bli82]. He brought science from physics literature to computer graphics.

In [Kla87], Klassen simulated the color of the sky using a planar model of the atmosphere and single scattering.

Kaneda et al. simulated the color of the sky using a spherical model of the atmosphere and atmospheric density that decreases exponentially with altitude.

Later, [NDKY96] extended the previous paper to take multiple scattering into account. Learning how they approached their simulation should give me insight and techniques for creating my own.

Preetham et al. presented an analytic sky model in 1999, which has been widely used ever since. The paper contains many descriptions, data, and references that should be very useful for my project.

[LL01] is a well-reviewed book that covers a large range of light and color phenomenon. It contains both high-level, intuitive descriptions of these phenomenon, as well as technical details. It also contains many photographs and diagrams.

At SIGGRAPH 2012, Hosek and Wilkie introduced a new and improved analytic sky model [HL12] which is more accurate than the Preetham model. They derived their analytic model from a series of brute force simulations.

3.PROJECT PROPOSAL

I have written a detailed description of my project below. To summarize, I will be building a spectral renderer, modeling the Earth's atmosphere, simulating atmospheric scattering. Then if time permits, I will be adding clouds.

3.1Anticipated Approach

The atmosphere simulation will work from any location and altitude (including from space), with various input parameters.

For the simulation I will use Monte Carlo path tracing and ray marching. Ray marching will be necessary because the Earth's atmosphere varies as a function of location—altitude in particular. I will use real-life data for the composition of the Earth's atmosphere, using interpolation to create a continuous model of atmospheric composition between data points. I will keep the system as general as possible so that it can also be used for other planets.

I will use real-life physics for the scattering properties of the atmosphere and clouds (under a geometric optics approximation), including Rayleigh scattering for light scattering from air molecules, which is what gives the sky its blue color during the day under normal conditions.

I will model the Earth as a sphere. I will give let the user specify the color of the ground, and I will include diffuse reflection from the ground in the simulation because it has an effect on sky color.

I will implement a spectral rendering system, that will work for all wavelengths of visible light, as well as ultraviolet and infrared. I will also use real radiometric units and data for the simulation. I will employ colorimetry to convert this spectral data to images that can be displayed on computer displays. To enable manipulation and deep compositing, I will save HDR images, along with deep alpha maps and other information.

I will sample the sun directly, otherwise almost all rays would get lost in space and images would take forever to converge. In order to sample the sun directly, I will likely have to ignore atmosphere refraction, which is aesthetically not very significant, except when the sun is very close to the horizon. However, I will think about ways that atmospheric refraction could be simulated efficiently, and add it if I come up with a good idea. I will use the sun's actual emission spectrum for the light that the sun emits, potentially using it for importance sampling wavelengths when ray-casting from the camera.

If I have time leftover after simulating the atmosphere (which I likely will not), I will add clouds. Storing volumetric data for a sky full of clouds with sufficient detail would use a lot of memory. To avoid doing this, I will use proceduralism where applicable. To generate plausible clouds, I will investigate various techniques and technologies including metaballs, advanced data structures (non-uniform grids, frustum-aligned grids, or no grids at all), and Perlin noise. I will try to mimic the appearance of real-life clouds, however they will not be dynamic, physically-based, or the result of a simulation. They should nevertheless add to the realism of the resultant images, and seamlessly integrate with the physically-based atmosphere simulation. The structures of these clouds will be more advanced and fine-tuned than those of the volumetric renderer written in CIS 460, and the clouds will be lit much more realistically by taking into account multiple scattering and realistic phase functions.

3.2Target Platforms

I will write the simulation in C++. As a starting framework, I will use some pieces of my own 3D renderer (Photorealizer, which I wrote from scratch): a basic Qt GUI, some image processing features (including anti-aliasing, gamma correction, and writing bitmap image files to disk), and code for ray-casting from the camera, and code for generating sampling points on the sun. I will consider using GLM as a linear algebra library.

3.3Evaluation Criteria

I will render images that are generally very difficult to render, including pretty sunsets, crepuscular rays, and the shadow of the earth that is visible in the atmosphere at twilight. I will compare my sky simulation to existing simulations and to photographs. I will explain all of the science that went into creating the simulation.

4.RESEARCH TIMELINE

Below are some planned project milestones. I have also included a Gantt chart with more detail.

Alpha Review (October 19, 2012)

- Completed all background reading
- Proposed software framework is functioning with simple base case
- Built a spectral rendering system
- Collected all necessary data

Beta Review (November 20, 2012)

- Modeled the Earth's atmosphere
- Implemented atmospheric scattering and absorption

Before Final Presentation (Mid-December, 2012)

- Clouds, time permitting

Final Presentation and Final Deliverables (Mid-December, 2012)

- High quality rendered images showing various effects

- A timelapse video of a full day
- Live demo of renderer
- Completed report
- Completed renderer

Project Future Tasks

Given 6 more months to work on this project, I would do the following:

- Add clouds or improve my existing cloud implementation.
- Port the program to the GPU using CUDA. The atmosphere simulation will likely be highly parallelizable.
- Create an analytic version of my sky model using spherical harmonics and interpolation.
- Integrate my sky simulator into my 3D renderer, Photorealizer.
- Compare my results to existing analytic sky models.

5.METHOD

6.RESULTS

7.CONCLUSIONS and FUTURE WORK

APPENDIX

A. Optional Appendix

The appendix will be located here in the final document, if applicable.

REFERENCES

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[KNN91] KANEDA, K., OKAMOTO, T., NAKAME, E., NISHITA, T.:: Photorealistic image synthesis for outdoor scenery under various atmospheric conditions. *The Visual Computer 7*, 5 and 6 (1991), 247–258.

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[NDKY96] NISHITA, T., DOBASHI, Y., KANEDA, K., YAMASHITA, H.: Display method of the sky color taking into account multiple scattering. *Pacific Graphics '96* (1996), 117–132.

[PSS99] PREETHAM, A. J., SHIRLEY, P., SMITS, B.: A practical analytic model for daylight. *Proceedings of the 26th annual conference on computer graphics and interactive techniques* (1999), 91–100.

[Ray71] RAYLEIGH, L.: On the scattering of light by small particles. *Philosophical Magazine 4,* 41 (1871), 447–454.

[Ray99] RAYLEIGH, L.: On the transmission of light through an atmosphere containing small particles in suspension, and on the origin of the blue of the sky. *Philosophical Magazine 5,* 47 (1899), 375–394.

I also plan to use a number of online resources. In particular, the following Wikipedia articles should be particularly useful:

http://en.wikipedia.org/wiki/Rayleigh_scattering

http://en.wikipedia.org/wiki/Sunlight

http://en.wikipedia.org/wiki/Diffuse_sky_radiation

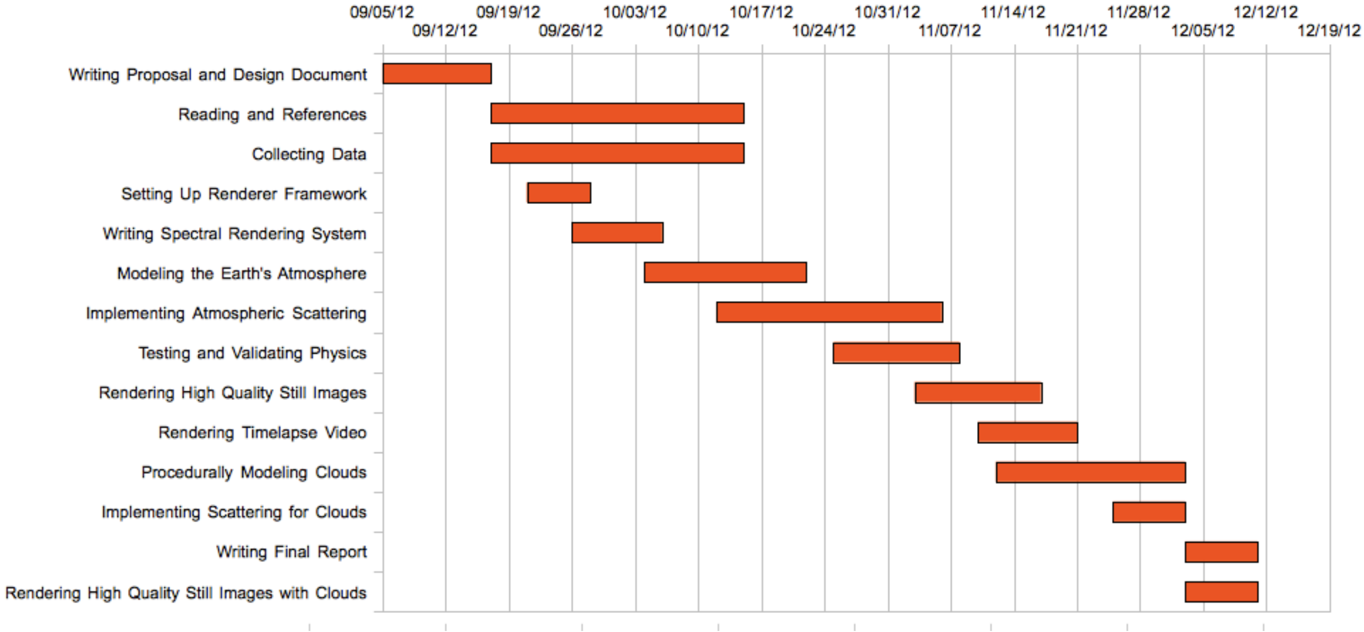

Figure 1: *Gantt chart showing planned project schedule.*