Combining Ozone Visualization with Atmospheric Light Scattering

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Abstract The idea to combine atmospheric scattering with the simulation of near-surface ozone concentrations is the result of the ambition of GMD FIRST to present simulated ozone concentration on local television.
As a result of the different interests between scientists and non-scientists (here the television audience), common tools developed for scientific visualization are not useful for a presentation of graphical data on public television. All the information should be shown in a simple, descriptive, yet interesting way. One method to accomplish this is the visualization of the ozone data in a virtual environment which is a life-like copy of the polluted region. The goal here is to minimize the accomodation time of the television spectator concerning the shown data, and to facilitate its interpretation.
Due to the particular interest in the near-surface ozone, the visualization environment is limited by the ground and the sky hemisphere. Independent of a realistic visualization of the ozone data, which in fact is impossible due to its invisibility, the natural look of the viewable parts is of great importance.
To obtain a natural look, enhanced satellite images are used for the visualization of the ground. The color and brightness of the sky is calculated by using the output of an atmospheric light scattering system. It simulates the interactions between the sun light and the atmospheric molecules and embedded particles (soot, dust, water vapor). The simulation of clear blue sky, sunsets, smog polluted air or for example rainbows is in the scope of the model. Furthermore, the realistic reflection of the sky on water surfaces can be achieved with this atmospheric light scattering model.

1 Introduction

The software presented in this paper belongs to the last stage – the visualization –in the system of applications, which together form the DYMOS air pollution simulation environment. This system is used to simulate the rise and development of surface-near ozone, known as summer smog. Information about its application in several European regions can be found in Rufeger et al. [9] and details concerning the simulation models are described in Heimann [3]. The system offers the possibility to calculate detailed ozone forecasts and to study the influence of certain emission sources (traffic, industry or transboundary ozone). Besides the use in scientific research these possibilities make the system a tool for decision support for local authorities.

After a validation project with the city of Berlin[6] it was decided to use the system during the summer times for a continuous forecast and to present the calculated results to the public. The used output data of the simulation system are the near ground ozone concentrations in $\mu g/m^3$. Each volume element has a horizontal dimension of 2000 m and a height of 50 m.

The basic idea was to show this data in a virtual flight over the simulation area (the region Berlin/Brandenburg in Germany), which is intended to be shown within the weather forecast on local television. Since existing visualization tools are mainly written for scientific evaluation, new tools were needed. Furthermore the medium of representation (e.g. television, radio, newspaper, WWW) and the viewer of the information (his scientific background, his interests) have a great influence on the visualization method. Some of these will be outlined in section 2. The main focus of this paper, however, will be on on the virtual visualization environment (section 3) and its use of a light scattering model to obtain greater realism (section 3.2). The physical background is presented in section 4 and the conclusion in section 5.

2 Visualization tools

The visualization is an important part of any simulation system. It hides the underlying physical and mathematical system from the user and allows to concentrate on the relevant information. Unfortunately, there exist no all-purpose visualization method. The existing tools can be divided in four classes:

- Two dimensional diagrams, graphs, charts, plots.
- Two dimensional views.
- Pseudo three dimensional pictures or movies.
- Stereoscopic presentations.

Because the last class needs special hardware (e.g. shutter glasses, polarized spectacles or virtual reality helmets) it cannot yet used for presentations to a wider public. The methods of the first class are very useful for printed presentations because of their simple style. This makes them fast to produce and easy to interprete by the reader. But the range of information is rather limited.

A better way is shown in picture 1. It displays the ozone concentration coded in different colors over the entire simulation region of Berlin/Brandenburg. Rivers, lakes and town borders are outlined for better orientation. The picture is generated by the IDL graphics library and is used in papers, at conferences or in the WWW. Regions of high and low ozone concentration are easily recognized. Short films can be assembled from several pictures at different times of the day. In many cases, this form of presentation is adequate. For the scientific research, a different tool (VISU [7]) developed in our group is used.

But for the presentation in television these or advanced three dimensional tools (e.g. Vis5D [10]) are not suitable.

The reasons therefore are mainly:

- the resulting films are missing an eye-catcher, which makes them interesting to view besides its informational content.
- the data are mostly presented in abstract environments in which orientation is not easy.
- the poor quality of television (low resolution, low frequency and the display of 50 (Germany) or 60 (USA) half frames instead of 25 or 30 full frames) results in several visualization problems (e.g. flickering at lines of great contrast). Most tools cannot solve these problems, because, for scientific visualization on computer monitors, they are not visible or are not disturbing the viewer.

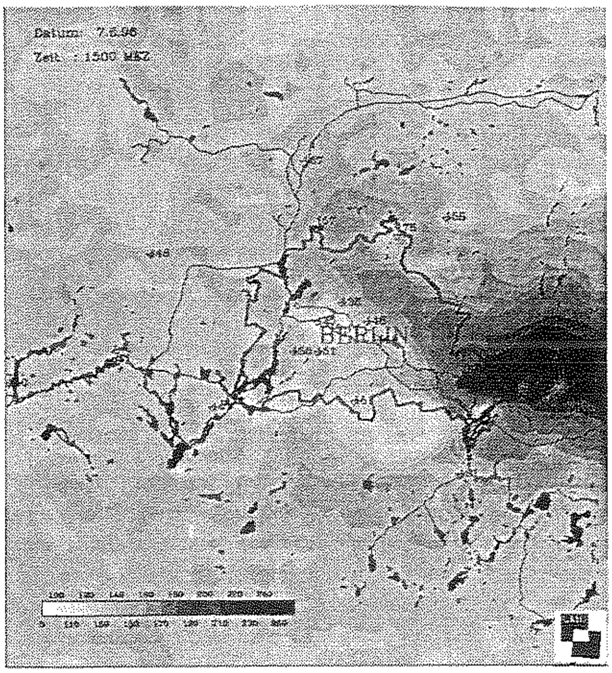

Figure 1: Ozone concentration shown with the 2D IDL library.

The last problem is solved by filtering during and after the image creation. Details can be found in standard computer graphics literature. The use of a virtual visualization environment takes care of the other disadvantages. Moreover, the questions of a potential viewer concerning the ozone demands a realistic reproduction of his living area:

- At which locations will the ozone concentration be high/low?
- Which limiting values will be exceeded?
- At what time will the limiting values be exceeded?

3 Virtual visualization environment

The above mentioned reasons seem to suggest to present the data in an environment which is familiar to the viewer. This minimizes the accomodation time and makes the areas of interest (the viewers living/working area) instantaneously recognizable.

Such an environment is made of two boundaries between which the data are visualized: The ground of the earth and the sky hemisphere.

Depending on the data to visualize (near-surface ozone or pollution clouds) and the direction of the camera (down-look in flat areas or up-look in mountain areas) different parts of these boundaries are visible. Additionally, the sky is visible in an indirect way when it is reflected in shiny objects, e.g. water surfaces.

The ground is generated from satellite images which are projected onto a height field of the simulation area. To guide the viewers eye the state and district boundaries are outlined and their names are shown. Due to the realistic colors of the image and its great detail it is easy for the viewer to find and recognize his region of interest. This could be the living area, the working area, the allotment garden, the jogging area or where the weekend is spent.

The sky is a sphere with its center in the middle of the earth and has a radius which is the sum of the earth radius plus the thickness of the atmosphere ($\approx$ 50km). The sphere consists of a large number of rectangles which are textured in the same way as the above mentioned height field. For this task real photographs could be used. A more flexible way is to calculate the color and brightness of every point in accordance to the sun height and the composition of the atmosphere. The most advanced algorithms are described in Walter [11] and Nishita et al. [8]. The basic physics are described in section 4.

3.1 Visualizing the surface-near ozone

Although ozone is a natural component in the atmosphere (stratospheric ozone) it is invisible for the human eye. Therefore, an artificial representation must be used. Since this is not familiar to the viewer there could arise a problem of understanding. On the other hand, the use of real world objects (e.g. clouds) for the visualization of ozone has the disadvantage that the viewer is induced to make certain assumptions which could be incorrect. In the case of clouds which are floating high in the air the viewer could assume the ozone to be located at the same height and not at the ground.

For these reasons the surface-near ozone is visualized by using a colored and transparent layer which is laid atop of the satellite picture. Because of this direct connection of the ozone information (layer) with the geographical information (satellite picture) the viewer can take in both informations with one view. If objects are high in the air they should cast a shadow to achieve the same grade of geographical coordination.

3.2 Achieving greater realism

One way to achieve greater realism is to adjust the satellite images to the daytime. This is done by changing their brightness according to the power of irradiance. Furthermore, the color of water is calculated, by applying Fresnels Laws to the reflected skylight and the light which leaves the water surfaces (assumed as constant). The latter can be used to change the background color of the water which is influenced e.g. by alga, mud or iron.

An example is shown picture 2. It displays the south west part of Berlin with the ozone legend in the bottom. The reflected sun image is seen right atop the small island. The image of the water changes from a dark blue in front of the picture to a light blue in the background. This is the result of the increasing reflectance in accordance with the viewing angle following Fresnels Laws.

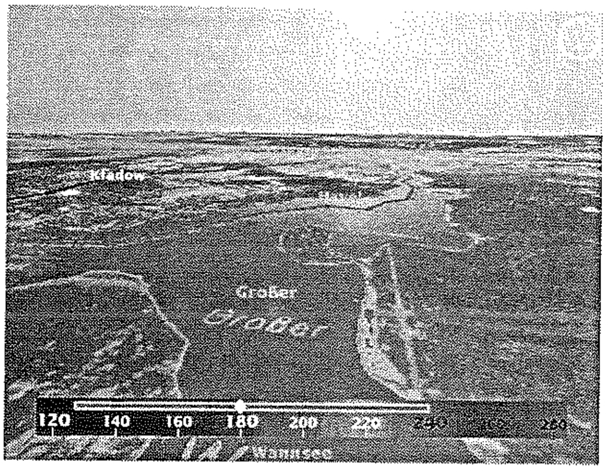

Figure 2: South west part of Berlin in the late afternoon.

The framework for these enhancements is a realistic sky boundary. Taking into account the sun position (derived from date and time) and the composition of the atmosphere (e.g. amount of water, dust or soot), a light scattering simulation gives the sky light from every direction. The result are spectral irradiances L_B for twenty wavelength evenly spaced between 380nm and 780nm. These data are converted to the RGB color space by applying the spectral and brightness perception of the human eye. Details and formulas for this conversion can be found in Walter [11].

4 Scattering and extinction

When the sun light enters the atmosphere it is scattered and absorbed by the air molecules and the particles embedded in the air (e.g. water vapor, dust). Without an atmosphere the sky would be black except for a tiny bright spot at the sun position.

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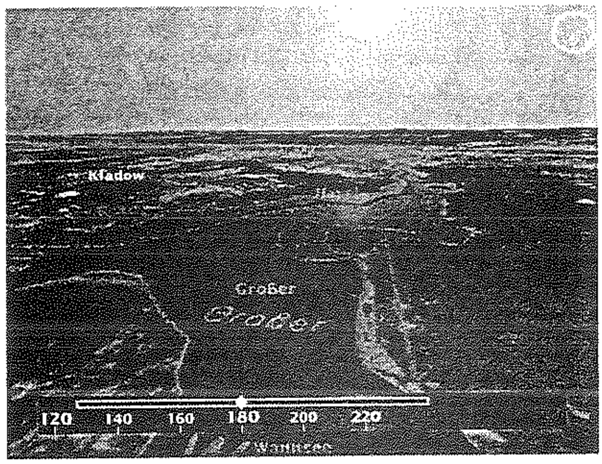

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This process of interaction (scattering plus absorption) is described by two models: Rayleigh scattering and Mie scattering. These models are only valid for homogeneous, isotropic and spherical particles. For atmospheric scattering these assumption can be regarded as fulfilled. Unfortunately, the formulas describe only what is called single scattering. Multiple scattering – the light undergoes several scattering processes alike a billiard ball that hits many other balls before it goes into the pocket – is important but rather complicated. There exist many models starting from Monte-Carlo simulations to solutions to the radiation transfer equation (RTE) which all have their own advantages and disadvantages. For the purpose of the visualization presented in this paper the methods described in Walter [11] are sufficient in accuracy and computational speed.

When a beam of light hits a particle some of the incoming energy is absorbed (transformed into heat) and scattered in arbitrary direction. This energy loss of the incoming light ist called extinction and is described by the extinction coefficient γ:

$$\gamma = \sigma_e = \sigma_s + \sigma_a. \tag{1}$$

This means that light of irradiance $I_0 = 1W/m^2$ that travels through a scattering volume of component j with thickness l, extinction coefficient γ_j and variable density $p()$ is decreased by the fraction τ:

$$\tau = \exp(-\delta(j, 0, l)) \tag{2}$$

$$\delta(j, a, b) = \gamma_j * \int_{s=a}^{b} p(s)ds \tag{3}$$

The irradiance of the light behind the volume is therefore $I = I_0 * \tau$.

4.1 Rayleigh scattering

At the end of the last century Lord Rayleigh developed his scattering theory. It describes the interaction between electromagnetic radiation and spherical particles, the diameter of which is much smaller than wavelength of the radiation ($a \ll \lambda$). Air molecules and the visible part of the sun light (380 nm ... 780 nm) fall into the valid range of the model. One common result is the blue color of the sky which is a result of the term $1/\lambda^4$ in (4): the shorter the wavelength the larger the term and therefore the scattered intensity.

The scattering formula for N_L particles is

$$I_{\lambda,\theta} = I_{\lambda,0} * \frac{9 * \pi^2}{2 * \lambda^4 * r^2 * N_L} \left(\frac{m^2 - 1}{m^2 + 2}\right)^2 (1 + \cos^2\theta). \tag{4}$$

The corresponding extinction coefficient is calculated by integrating (4) over the surface of the bounding sphere:

$$\gamma = \frac{16}{3}\pi * I_{\lambda,90} * r^2. \tag{5}$$

The scattering angle θ is the angle between the vector towards the propagation direction of the incoming light and the vector in the propagation direction of the scattered light as shown in figure 3.

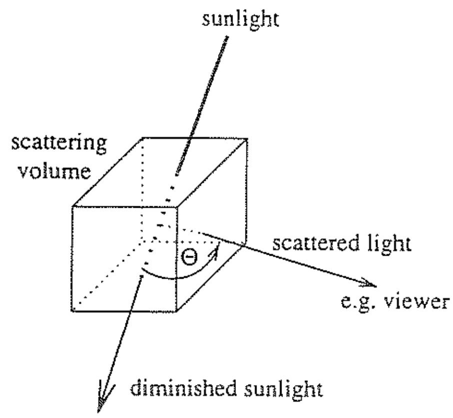

Figure 3: Scattering angle θ.

4.2 Mie scattering

The advantage of the Mie theory is that it is valid for every relation between a and λ. This is important because many particles (e.g. water, dust) in the air have diameters near or larger the wavelength of the visible portion of the sun light.

The two main equations describing the extinction and the scattering for a mixture of particles with a size distribution $n(a)$ ranging from size $S1$ to $S2$ are

$$\gamma = \int_{S1}^{S2} \pi a^2 Q_e n(a) da \tag{6}$$

$$I_{\lambda,\theta} = I_{0,\lambda} * \frac{1}{2k^2r^2} * \int_{S1}^{S2} (i_1(\theta, x) + i_2(\theta, x))n(a)da. \tag{7}$$

The terms for Q_e and the two polarization intensities i_1,i_2 are very extensive and can be found in the standard literature about scattering: van de Hulst [4], Barber [1] and Bohren [2].

Figure 4 shows the scattered intensities for light of $\lambda = 555nm$ hitting one water droplet with a size of 0.005 (top) respectively $10.0\mu m$ (bottom). The top curves fulfill the relation $a \ll \lambda$ and they are therefore identical to the ones which would be obtained by applying the Rayleigh formulas.

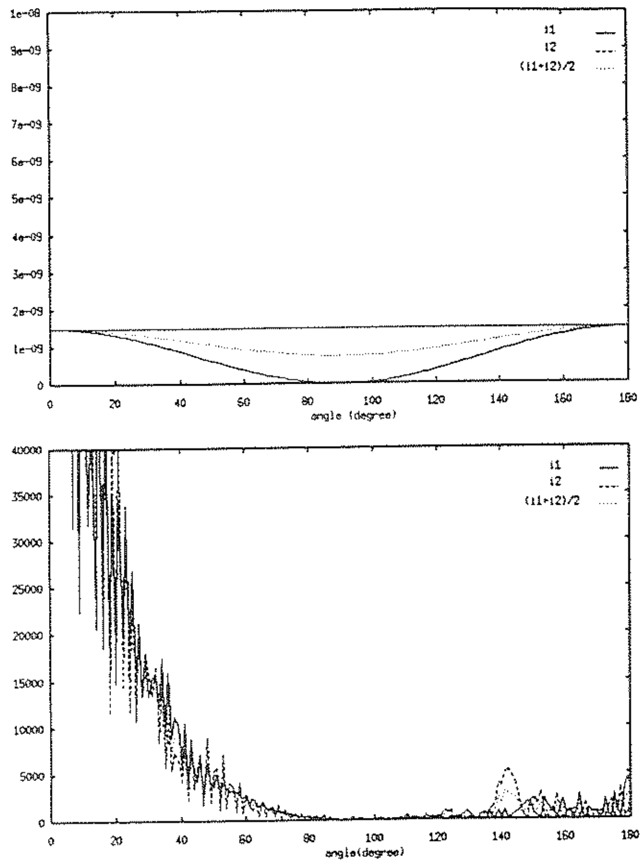

Figure 4: i_1, i_2 and $(i_1+i_2)/2$ for a water droplet of $a = 0.005\mu m$ (top) and $10.0\mu m$ (bottom).

4.3 Scattering and extinction in the atmosphere

A standard atmosphere can be seen as a superposition of three different particle components:

1. pure and dry air (only air molecules),
2. ground aerosol (water content, dust, soot etc.)
3. stratospheric ozone layer (prevents a greenish sky for low sun heights).

The number of particles per volume for the first two components changes with the height and is corrected by the relative density

$$p(h) = \exp\left(\frac{-h}{H_0}\right). \qquad (8)$$

To calculate the skylight one has to precalculate the scattering properties for the first two components. This is done by building lookup tables $L_j[\theta, \lambda]$ using (4) or (7) according to the particle sizes for every component j. Then the skylight $L_B(\lambda)$ coming from an arbitrary direction for the two scattering components (1 and 2) and the absorption component (3) is calculated by (for the integration range see figure 5):

$$L_B(\lambda) = \int_0^S \left(\sum_{j=1}^{2} p_j(s) * L_j[\lambda][\theta]\right) * \exp\left(-\sum_{j=1}^{3} \delta(j,0,s) + \delta(j,s,H)\right) ds. \qquad (9)$$

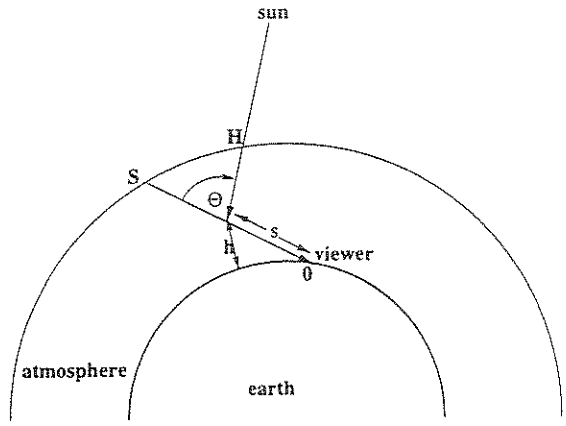

Figure 5: Scattering integration.

For non-photo-realistic visualizations it is sufficient to build a lookup table containing spectral or RGB values for the sky hemisphere with an angular resolution of one degree.

5 Conclusion

The virtual visualization environment was written to present the ozone data in a virtual mirror of the simulation area. The information provided by the detailed environment eases the spatial assignment of the simulation data (e.g ozone concentration). Furthermore the method can be used whenever the information has to be presented in an interesting or variational way (e.g. television, WWW movies). A reduced version could be used in the WWW for the interactive presentation of other atmospheric (pollution, burn times) or meteorological (air or water temperature, wind speed) data.

At the moment the visualization of clouds is not possible. One reason is that the automatic generation and movement of clouds due to meteorological quantities is very complicated. This is investigated by Limbach [5] in his dissertation. Additionally, many visualization methods for clouds do not reproduce the physical correct modeling of the important multiple scattering in clouds. This area is studied by the author.

Color pictures, movies and additional information concerning the scattering model and the visualization environment is found at http://www.first.gmd.de/persons/Walter.Bertram.html.

6 NOTATION AND UNITS

symbol	unit	description
$I_{\lambda,\theta}$	$Wm^{-2}nm^{-1}$	scattered irradiance
$I_{\lambda,0}$	$Wm^{-2}nm^{-1}$	incoming irradiance
λ	m	wavelength
a	m	radius of particle
h	m	height above NN
H_0	-	scale height: air: $\sim$ 8900m aerosol: $\sim$ 1200m
$L_B(\lambda)$	$Wm^{-2}sr^{-1}nm^{-1}$	spectral radiance
$p(h)$	-	relative density
i_1	-	scattered intensity ($\|\|$)
i_2	-	scattered intensity ($\perp$)
k	m^{-1}	wavenumber $k = 2\pi/\lambda$
r	m	distance of particle to e.g. the viewer
N	m^{-3}	number of particles per unit volume
N_L	m^{-3}	Loschmidt number
m	-	real refraction index
$n(a)$	$1/m^3$	size distribution
x	-	size parameter $x = 2\pi a/\lambda$
$\delta(j, a, b)$	-	optical depth of comp. j between points a and b
Q_e	-	extinction efficiency
γ, σ_e	m^{-1}	unit extinction coeff.
σ_s	m^{-1}	unit scattering coeff.
σ_a	m^{-1}	unit absorption coeff.
τ	-	transmission factor
θ	degree	scattering angle

Table 1: Description of used variables and constants.

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[1] http://www.zib.de/~bzblimba/index_engl.html
[2] http://www.first.gmd.de/persons/Motschke.Christian.html
[3] http://www.first.gmd.de/persons/bwalter/html/diplom.html