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Visualization of Features in 3D Terrain

Steve Dübel * and Heidrun Schumann

Institute of Computer Science, University of Rostock, A.-Einstein-Str. 22, D-18059 Rostock, Germany; heidrun.schumann@uni-rostock.de

* Correspondence: steve.duebel@uni-rostock.de; Tel.: +49-381-498-7490

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Abstract: In 3D terrain analysis, topographical characteristics, such as mountains or valleys, and geo-spatial data characteristics, such as specific weather conditions or objects of interest, are important features. Visual representations of these features are essential in many application fields, e.g., aviation, meteorology, or geo-science. However, creating suitable representations is challenging. On the one hand, conveying the topography of terrain models is difficult, due to data complexity and computational costs. On the other hand, depicting further geo-spatial data increases the intricacy of the image and can lead to visual clutter. Moreover, perceptional issues within the 3D presentation, such as distance recognition, play a significant role as well. In this paper, we address the question of how features in the terrain can be visualized appropriately. We discuss various design options to facilitate the awareness of global and local features; that is, the coarse spatial distribution of characteristics and the fine-granular details. To improve spatial perception of the 3D environment, we propose suitable depth cues. Finally, we demonstrate the feasibility of our approach by a sophisticated framework called TEDAVIS that unifies the proposed concepts and facilitates designing visual terrain representations tailored to user requirements.

Keywords: visualization; rendering; terrain; geo-spatial data; trajectory; feature; realtime

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1. Introduction

The exploration of 3D terrain topography is important in many application areas—for instance, in geology, archeology, avionics, or oceanography [1–3]. Besides terrain data, geo-spatial data, such as climate or weather information, are often another essential part of the analysis [4,5]. Understanding terrain and geo-spatial data is a major, yet challenging task. To facilitate this process, interactive, visual representations are an important tool. They require both the terrain rendering and the geo-spatial data visualization to identify and analyze important features in the data. Features refer to subsets of data that are of particular interest, such as certain mountainous structures, specific weather conditions, or objects of interest. It is important to effectively communicate these features and, therefore, customized presentations are required. Our work addresses the question of how visualizations of terrain and geo-spatial data can be tailored to emphasize important features.

Terrain models and geo-spatial information can be considerably complex, easily exceeding gigabytes of data and consisting of several hundred thousand elements. Thus, creating appropriate visualizations is highly challenging. Firstly, interactive exploration of terrain models requires very fast image generation, and secondly showing that many data values at once would inevitably lead to visual overload. To address these issues, strategies are typically applied that reduce the amount of data for the terrain and the geo-spatial information. As a consequence, the recognizability of local features, such as small elevations or local temperature values, can be impaired. In the same way, it is difficult to communicate global features that are required to grasp fundamental characteristics at a coarser level of abstraction. We refer to global features as the spatial distribution of certain terrain characteristics. Examples are the location of large mountains or relevant geo-spatial data manifestations, e.g., hazardous weather areas. In order to enhance the communication of local and global features, we propose using customized emphasis strategies.

On top of that, the correct estimation of distances, in particular the depth, is a common issue in 3D computer graphics. This issue impedes the recognition of the spatial relationships of features. We engage this problem by employing depth cues tailored to rendering terrain models and embedded geo-spatial data.

Finally, improving feature communication and depth perception requires a careful visual design and substantial considerations regarding suitable render methods and fitting parameterization. Though there are already individual approaches for particular issues, there is not much work on how they integrate into a holistic presentation of terrain models and geo-spatial data. Therefore, we developed the comprehensive visualization framework TEDAVIS that facilitates various render strategies and configurations to design customized terrain visualizations. In this sense, our aim was to create a unified system that integrates these diverse methods rather than designing particular new visualizations.

To summarize, in this paper the following contributions are made:

- Concepts to effectively communicate local and global features of 3D terrain and geo-spatial data.
- Design and application of depth cues that are tailored to improve perception of 3D distances in terrain environments.
- A software framework that enables real-time rendering and design of sophisticated terrain visualizations.

This paper is structured as follows. Section 2 gives a brief summary of related work, including the visualization of terrain and geo-spatial data, and the representation of features. In Section 3, we describe our approach on visualizing and emphasizing features of the terrain and the geo-spatial data. Section 4 presents our software framework TEDAVIS that enables designing, parameterizing and applying complex visualizations of features in terrain environments. Finally, Section 5 concludes this paper and gives a brief outlook on future work.

2. Related Work

In this section, we refer to recent work on visualizing terrain models with geo-spatial data and on feature presentation and visual emphasis.

2.1. Terrain and Geo-Spatial Data

Rendering 3D terrain is a challenging topic, and a lot of research has been conducted on this subject in the recent years. To a certain extent, this is because of the ever-growing availability of continuously increasing terrain models, regarding size and resolution. Representing large terrain models requires efficient level-of-detail approaches, e.g., [6–8], and sophisticated render strategies, e.g., [9,10]. In general, the 3D topography can be depicted either by drawing lines [11], shading [12], or using textures [13]. For more details, we refer to Ruzinoor et al. [14], who give an overview of terrain visualization methods in GIS environments. Terrain rendering techniques can also be combined in order to improve the perception of spatial distances. For instance, Stevens [15] and Bolton et al. [16] have investigated how textures of lines, points, or grids can be used to improve surface perception. However, to our knowledge, little research has been done to improve distance perception in 3D terrain and geo-spatial data visualizations.

Regarding geo-spatial data, we distinguish between numerical data on the one hand and geometrical data on the other. Numerical data refers to measured or calculated data values that, even though spatially referenced, have no predefined geometrical form. As a consequence, numerical data values are mapped to appropriate graphical elements in the visualization process. Examples of numerical data would be climate or weather information [17,18]. In contrast, geometrical data is defined by a concrete shape that can be zero-, one-, or multidimensional. Typical geometrical data would be points of interest, roads, or buildings [19]. The visualization of both numerical data and geometrical data is a broad scientific field and lots of research is done in these areas. Thus, we will not go into detail of specific visualization techniques. Instead, we refer to the survey of presentation methods for geo-spatial data given in [20] and to the comprehensive books about visualizing spatial data by Andrienko and Andrienko [21] and Kraak and Ormeling [22].

2.2. Feature Visualization

Visualizing topographical features is an important task—for instance, in geology or archeology. In the field of 2D digital elevation model analysis, much research has been conducted on how to communicate features, such as hills and ridges. Besides the well established analytical hill shading [23,24], numerous techniques have been developed to represent terrain models in 2D, for instance contour mapping [25], Sky-View-Factor [26], Local Relief Mapping [27], and Openness [2]. However, approaches that apply these techniques in 3D, or emphasize features in 3D terrain visualizations in general, have rarely been developed. Kenelly and Steward [28] propose using single-light illumination techniques, i.e., different sky models, to reveal features of 3D terrain. Bratkova et al. [29] emphasize features to create tailored 3D landscape visualization, though they aim for artistic overview presentations. In contrast to our work, both papers focus on watching the terrain from a fixed viewing angle and do not deal with dynamic real-time rendering and navigation.

Visualizing data features is another important topic in different application areas, such as medicine [30], flow visualization [31], or meteorology [32]. In this sense, features can refer, for instance, to pathological areas in medical data, meaningful patterns in simulations, or hazardous weather conditions in meteorology. Many features can be found by directly extracting subsets from the data, e.g., through clustering or data mining. In other instances, it is difficult to find appropriate extraction methods, or features must be analyzed together with their context. In this case, it is common to present a larger portion of the data set and to highlight features by using visual means. Typical concepts would be Overview and Detail [33], Lenses [34], and Focus and Context [35,36]. When applying these concepts, visually emphasizing interesting parts of the data is particularly important. Regarding data values, a comprehensive overview of emphasis techniques is given by Hall et al. [37].

However, feature visualization and emphasis in the context of 3D terrain model visualizations combined with geo-spatial data has yet to be investigated in detail. This work is a first step in this direction. In the following section, we will discuss our approach of feature visualization in terrain environments.

3. Visualization of Features

Analyzing terrain topography and geo-spatial data requires the visual communication of features, i.e., the interesting characteristics of the data. The question regarding what part of the data is interesting, and, thus, what the data features are, can shift depending on the visualization goal. In our work, we focus on two fundamental visualization goals. The localization of certain characteristics and the detailed analysis of the characteristics. To this end, we distinguish between global and local features. The communication of global features should provide a general overview of the data, while showing the position and distribution of interesting manifestations. In contrast, presenting local features should reveal details of a defined subset of the data.

In the following, we describe the communication of features with regard to terrain data, numerical data, and geometrical data. We explain how each data type can be represented and then go into detail how local and global features can be communicated. Additionally, we discuss approaches to improve the spatial perception of the features.

3.1. Visualizing Features in Terrain Model

The aim of 3D terrain model visualization is conveying the structure and shape of the surface, that is, the spatial layout of large-scale global features, e.g., mountains or valleys, and the fine local features, such as ridges or slopes.

3.1.1. Representing Terrain Models

Terrain data is typically available as height-field functions that are generated, for instance, from satellite images. A height-field function can be considered a 2D grid, where each node represents one height value (Figure 1a). Though it is possible to render 3D scenes directly from height-fields, e.g., using raytracing [38], they are typically converted into triangular irregular networks beforehand (Figure 1b). Depending on the size and the resolution of the original height-field, triangular networks can consist of millions of triangles, making the representation computational challenging. Hence, efficient render strategies, e.g., adapted level-of-detail [6] and shading techniques [28], must be applied (see Figure 1c).

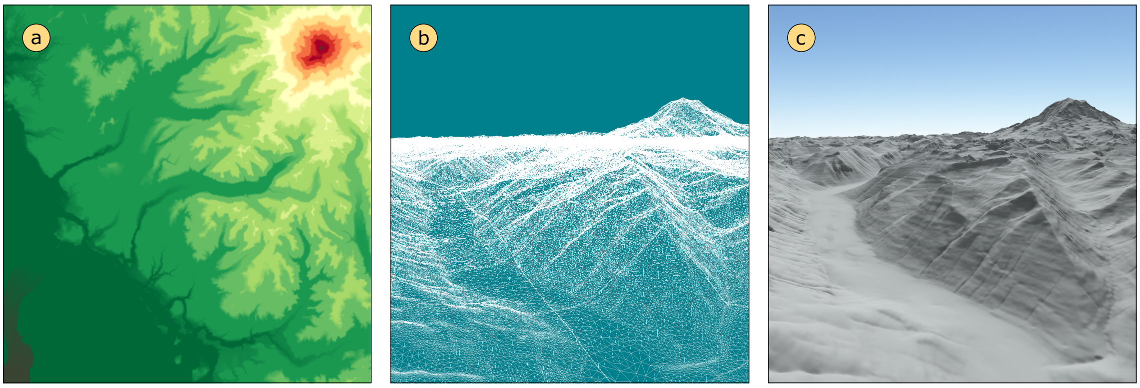

Figure 1. Visualizing 3D terrain. The terrain model is typically based on height-field data (**a**) from which triangular networks are generated (**b**) before the final model is rendered (**c**).

Within the terrain representation, large shapes are often easily observable, since they prominently protrude off the silhouette. However, perceiving small elevation below the horizon is more difficult. These local characteristics are only exposed by using appropriate shading. Alternatively, textures can be applied to communicate the characteristics of the surface. Elevation-colored textures (Figure 2a), for instance, are a common technique to convey the height of surface elements. Conversely, aerial photos or satellite images can be used as textures to give the terrain a more natural look and to convey surface compositions, such as vegetation (Figure 2b).

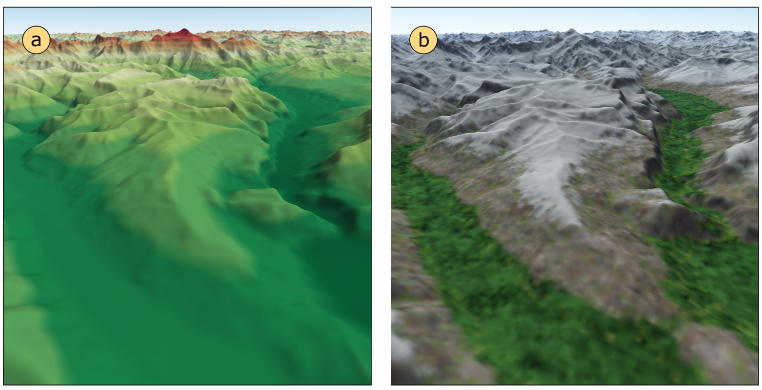

Figure 2. Visualizing terrain using textures. (**a**) uses color to encode the elevation of the terrain, while (**b**) uses a more natural coloring.

3.1.2. Emphasizing Features

The features of the terrain model are the characteristic topography of the surface, i.e., its landforms. These characteristics refer to large structures, such as mountains and cliffs, but also to small variations, such as fine relief structures, riverbeds, or ridges. Consequentially, we differentiate between global features and local features. Global Features refer to the larger geomorphological structure of the surface. They facilitate an overview on fundamental properties of the terrain, whereas local features communicate the finer granular characteristics of the relief and are essential for analyzing details of the surface.

Local Features of the terrain topography are important—for instance, when analyzing erosion along slopes, riverbeds, or coastal areas. Though shading and texturing can provide a good overview on the terrain, small variations in elevation or orientation of the surface easily go unnoticed. Since these small protrusions neither occlude nor change with different viewing angles, they are almost only perceivable by unconsciously interpreting shades on the surface. Therefore, the quality of shading determines how well these structures can be recognized. Most commonly, terrain surfaces are shaded using local illumination, e.g., by applying the phong illumination model [39]. Local illuminations can be computed quite fast because they only depend on the orientation of the surface towards the light source. In many cases, this is sufficient to convey the terrain curvature, as shown in Figure 3a. However, because brightness values are uniformly distributed along all potential surface orientations, small variations are hardly perceivable. To improve the depiction of such fine structures, an approximative global illumination model, e.g., ambient occlusion (AO) [40], can be applied on top of a local illumination. As Figure 3b shows, AO makes fine grooves and scarps more recognizable. AO can be computed in a pre-processing step, making it almost as fast as local illumination. However, the memory footprint is increased. To further improve the highlighting of fine local features, more sophisticated global illumination models can be applied, e.g., [41–43]. Global illumination enables casting shadows from elevations onto the surface, creating a more realistic representation of the terrain. Moreover, global illumination achieves higher contrast for local elements and in this way makes them more prominent. On the downside, computing global illumination is considerably more expensive. Figure 3c shows the application of global illumination on the terrain surface. In summary, local features of the terrain can be emphasized using sophisticated high-quality shading methods based on global illumination, though memory consumption and computation time are increased.

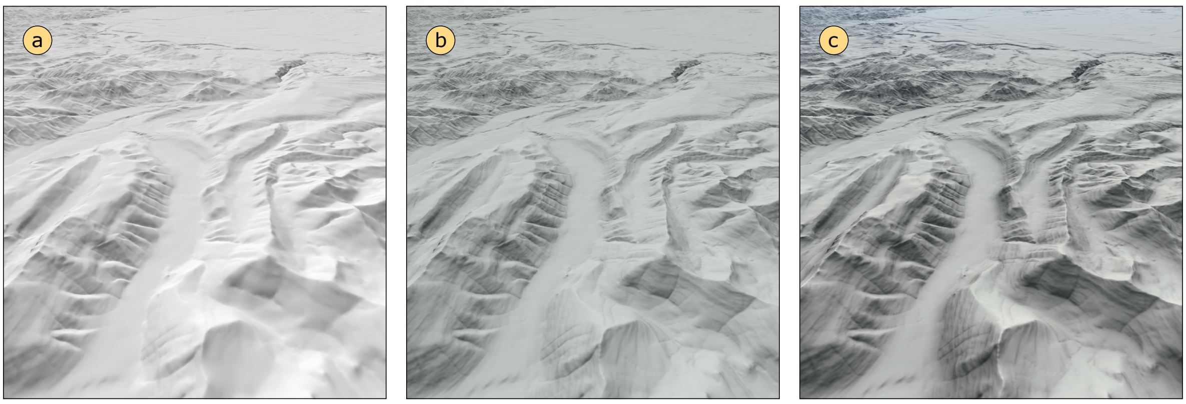

Figure 3. Conveying fine 3D structures of the terrain surface using different illumination models: (**a**) local illumination; (**b**) local illumination combined with ambient occlusion; and (**c**) global illumination.

Global Features of the terrain topography are large shapes that characterize the surface. In the case of these feature types being of particular interest, non-photo-realistic render techniques (NPR) can be applied. While shading communicates details of the entire surface, NPR techniques can be used to show only important subsets of the terrain characteristics. Among the existing NPR techniques, edge enhancement is most suitable to convey such global features. A common form is enhancing silhouettes. To determine the silhouettes, we search for discontinuities in the depth buffer. Edges are enhanced, where depth values change above a certain threshold within a 3×3 pixel matrix. Figure 4a illustrates how drawing silhouettes only can already communicate characteristics of the terrain at a very coarse level of abstraction.

To generate a more detailed presentation of the terrain, more edges, such as ridges, must be shown. We can identify ridges by using information about depth and variations of surface normals, for instance through the curvature. For this purpose, we use an algorithm based on the work of Shishkovtsov [44]. As Figure 4b shows, this technique enables adding more lines at characteristic edges. Even more details can be made identifiable by using suggestive contours [11], as illustrated in Figure 4c. Suggestive contours are a sophisticated NPR technique, with which lines are drawn on clearly visible parts of the terrain, where a true contour would first appear with a minimal change in viewpoint. As all described edge extraction techniques, suggestive contours are an image-based algorithm. Thus, the achieved visual results depend on chosen thresholds. In summary, edge enhancement focuses on the communication of coarse structural features. It can be used individually or together with surface shading (see Figure 5). This combination allows for highlighting global features while still communicating small structure variances.

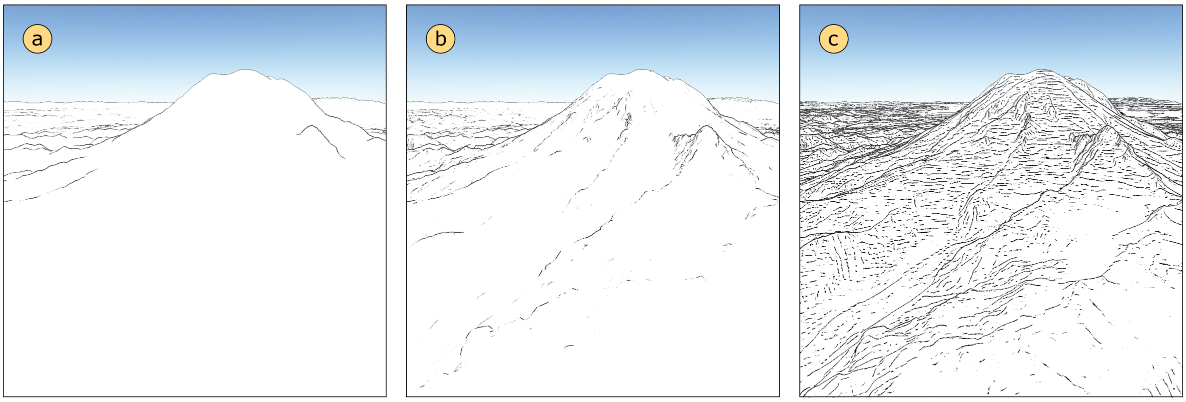

Figure 4. Enhanced edges using line drawing: (**a**) silhouettes are emphasized; (**b**) additional contours along ridges are drawn and (**c**) additional suggestive contours are drawn.

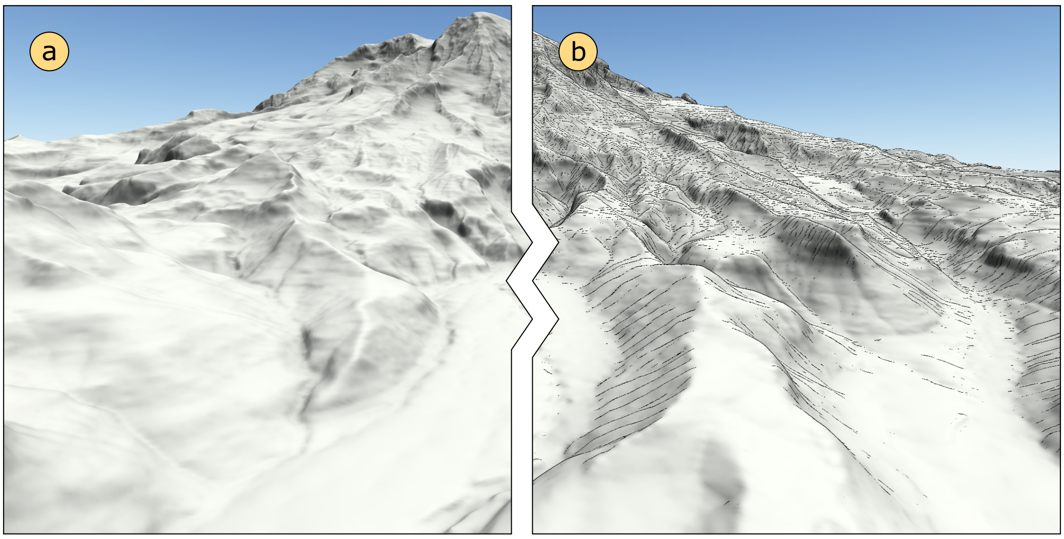

Figure 5. Shaded surfaces (**a**) can be extended with enhanced edges (**b**) to emphasize contour-based features of the terrain.

Distance Awareness is important to comprehend the spatial layout and the size of characteristics. However, as a typical computer graphics issue, cognition of depth is very difficult in 3D scenes. This is particularly true in case of the terrain being watched from a flat viewing angle (Figure 6a). For one part, this issue can be engaged using stereoscopic images. However, this is not always applicable. Hence, we deploy tailored depth cues to improve distance perception. One reason for the difficulties in depth perception in terrain environments is the fact that the viewer does not know about the size of terrain components. Hence, the perspective distortion, an important depth cue, does not provide many hints on distances. One approach would be placing new elements into the scene, to which size the viewer can relate. For instance, a regular grid can be laid above the terrain surface. Figure 6b illustrates this method. Since the perspective distortion of the grid cells is easily interpretable, the viewer gets a better sense of the scene's depth. Distances between surface structures, e.g., mountains, can also be better estimated if the cell size is known. As a side-effect, the application of grids can further improve the communication of the terrain curvature. However, on the downside, this technique might clutter parts of the image.

When watching natural landscapes without additional elements, however, the viewer can still interpret distances in the terrain. This is mainly due to atmospheric effects that are subtle but effective depth cues. Since the atmosphere absorbs and scatters the light while it travels to the viewer's eye, contrast and saturation decreases with increasing distance. A fast and simple render method to simulate such an effect is fogging. Fogging fades the color of the scene to the color of the background with increasing distance, creating the impression of thick mist. In contrast, outdoor light scattering, also called aerial perspective [45], is way more sophisticated with regard to both image quality and computational cost. Aerial perspective simulates the interrelation of light and atmosphere more realistically, taking scattering on water and oxygen molecules into account. Figure 6c illustrates that aerial perspective blends nicely with terrain rendering, making the representation look more realistic and natural while giving the viewer a hint on object distances.

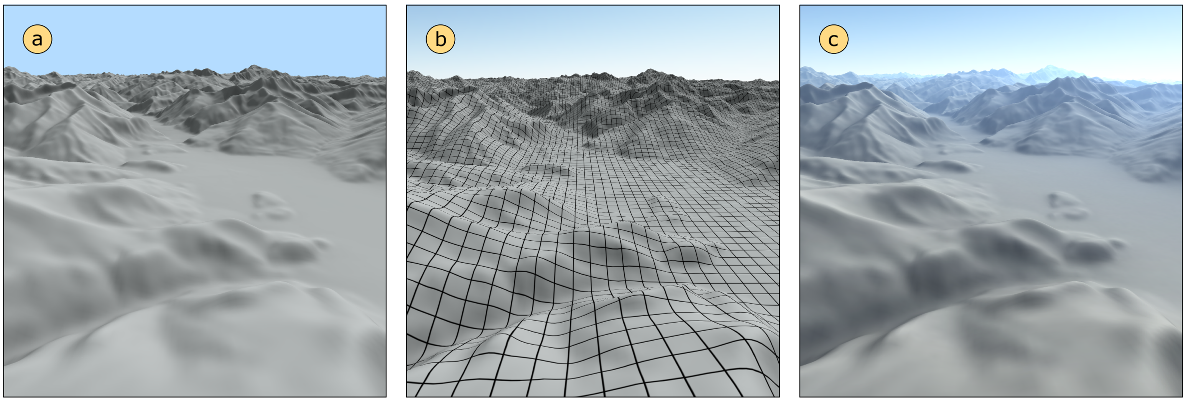

Figure 6. Enhancing distance awareness within terrain model. In (**a**) the terrain is represented without depth cues; (**b**) uses a regular grid; and, in (**c**), aerial perspective is applied.

To conclude, the usage of tailored render techniques can improve terrain visualizations with emphasis on the communication of local and global features as well as depth perception. At the same time, different render techniques have different effects with regard to quality and intensity of the enhancement. Moreover, an appropriate parameterization, for instance by properly adjusting the light source or atmosphere characteristics, is important to achieve the desired effects.

3.2. Visualizing Features in Numerical Data

Most commonly, terrain models are not analyzed in isolation, but together with numerical data. For instance, analyzing information about agriculture, pollution or weather requires the terrain as context and hence, both numerical data and terrain are often visualized together. In this section, the representation of numerical data and the emphasis of data features is discussed. Due to the huge diversity of visualization methods for numerical data, we will not go into detail of individual techniques, but consider fundamental approaches instead.

3.2.1. Representing Numerical Data

There are two general approaches to visualize data values along with the terrain: intrinsic and extrinsic techniques [46]. Intrinsic techniques modify the appearance of the terrain surface. For instance, data values are encoded into the color of the surface. Figure 7a shows, for example, relative humidity values encoded into color. However, the shading of the surface (cf. Section 3.1.2) and the color gained by encoded data values must be blended and might affect each other. Extrinsic techniques, on the other hand, place additional graphical primitives, e.g., data glyphs, into the scene. Figure 7b shows an example of wind glyphs to visualize wind speed and direction above the terrain surface. Extrinsic techniques are typically more prominent and easy to read. On the downside, the additional elements might occlude the surface and can lead to visual clutter. Hence, both techniques, intrinsic as well as extrinsic, must be applied with care.

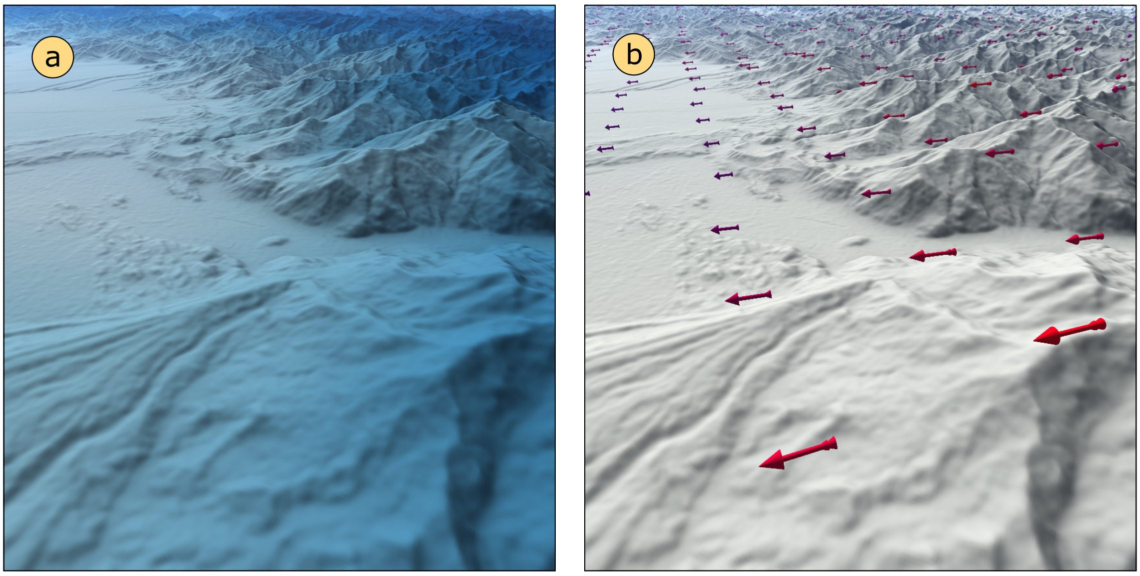

Figure 7. Visualizing data together with terrain. (**a**) shows relative humidity encoded into the color of the surface (light blue means low humidity, dark blue means high humidity); (**b**) shows wind glyphs, encoding wind direction and strength. The direction is given by the arrow head and the strength is encoded by the length of the arrow and a continuous color scale, ranging from blue (light wind) to red (high wind).

3.2.2. Emphasizing Features

There are different types of feature descriptions for numerical data [47]. We focus on the more general distinction—global and local features as well as distances. In the following, we describe visualization techniques to emphasize these types of features.

Global Features of numerical data are the spatial distribution of certain data values within terrain. Typically, not all data values are relevant, but those bearing specific characteristics. For instance, when visualizing wind, the location of areas with hazardous wind conditions might be of interest. Hence, emphasizing such characteristics means highlighting the location of respective data points. To expose subsets of the data, various techniques exist, such as coloring, blurring or resizing [37,46]. Figure 8 shows examples for extrinsic and intrinsic visualization, respectively. In the intrinsic visualization of thunderstorm cells (a), hazardous areas that are growing and have threatening potential are highlighted, using red color. Analogously, in (b), wind speed above terrain is extrinsically visualized by using wind glyphs and those data points that exceed a certain value are highlighted in red.

Local Features are related to the actual data values of a data subset. For instance, if visualizing global features exposes the location of relevant data, the user might get interested into the concrete manifestation of this data. At the same time, typically not all data values are represented due to data complexity and limitation in the number of perceivable elements per image. Instead, data values are aggregated and filtered to reduce information. Thus, the representation must be adapted to facilitate access to details on demand. To this end, concepts such as Overview and Detail, Focus and Context, and Lenses are particularly suited. As an illustrative example, Figure 8c shows the deployment of a distortion lens that emphasizes an area of interest by enlargement to expose the data values in detail.

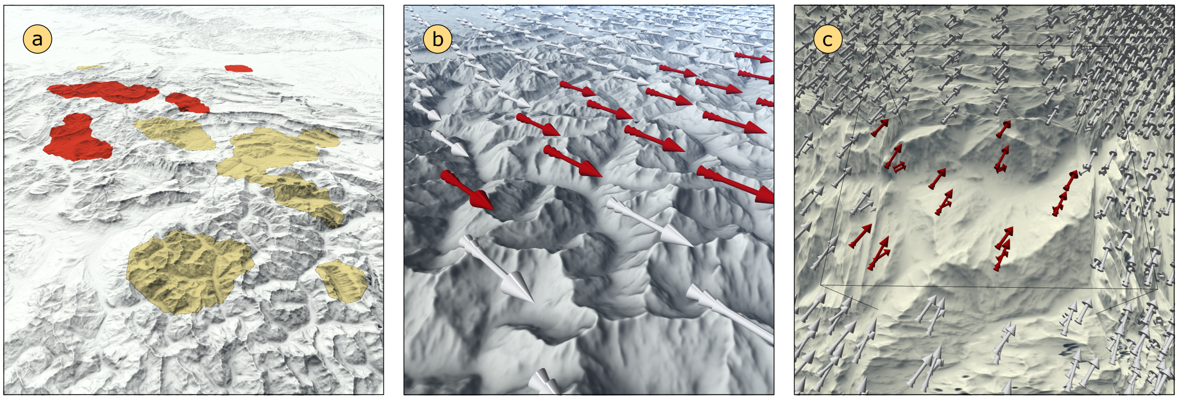

Figure 8. Emphasizing data features. (**a**) shows a visualization of thunderstorm cells. Emerging thunderstorm cells with hazardous potential are highlighted using red color. (**b**) and (**c**) show wind glyphs that encode wind direction (arrow head) and strength (length of the arrow). In (**b**), strong wind conditions are highlighted using a prominent color for corresponding wind glyphs. In (**c**), local features are emphasized by distortion: the framed area is magnified to better observe details of the wind data.

Distance Awareness is particularly challenging when using extrinsic data visualizations. Besides the usual insufficient depth perception in 3D scenes, the spacing between the data elements and their reference space, i.e., the terrain, further impedes the assessment of their spatial distribution. One approach to address this issue is the usage of atmospheric effects, as mentioned earlier in Section 3.1.2. Alternatively, the application of shadows is well suited to indicate the 3D position. However, if elements are wide apart, they cannot cast shadows onto each other. Thus, we use volumetric lighting that allows for casting shadows into the air, as shown in Figure 9a. This technique originates from photo-realistic rendering and is commonly used to achieve a sense of atmospheric density. We apply it to data visualization to improve depth perception, though this is on a subtle level. Volumetric lighting depends on various parameters, such as density of the atmosphere and light source position. These parameters control the unobtrusiveness of this effect and must be adjusted with care. Otherwise, too strong shadows, for instance, could confuse or distract the user.

Volumetric lighting improves depth recognition, especially for data elements close to the viewer. To improve depth recognition for elements in the distance, we utilize depth of field. This technique uses a defined focus area in which everything is rendered sharply. Outside of the focus area, however, elements are blurred, depending on the distance to this area. Figure 9b shows the application of this technique on a visualization of wind glyphs. Elements far away (or very near) to the viewer are blurred, highlighting only data glyphs at a specified distance. Besides the achieved depth sense, this technique also relieves the visual budget because elements far away are intuitively considered less relevant. To this end, the size and position of the focus area can be adapted either with regard to the camera position or to the data location.

To conclude, global features of numerical data can be emphasized using highlighting techniques to better communicate the spatial distribution of certain data values. Local features can be emphasized by exposing details on demand using tailored concepts, such as lenses. In addition, appropriate render effects, such as depth of field, can enhance distance recognition.

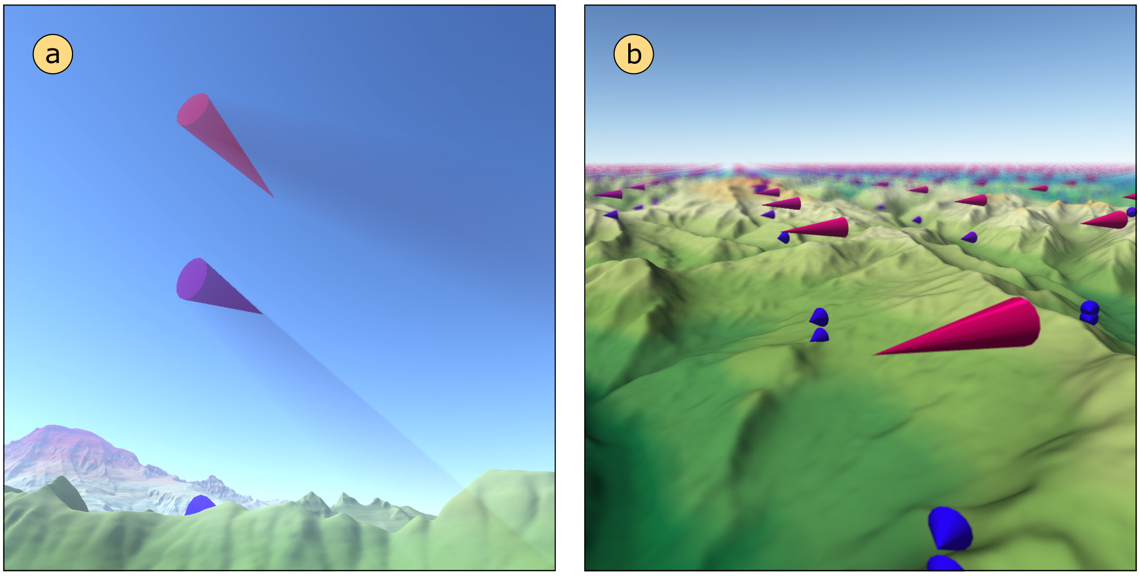

Figure 9. Enhancing the perception of the spatial distribution of objects within terrain. The images show wind glyphs that encode wind direction (arrow head) and strength using length and a continuous color scale, ranging from blue (light wind) to red (high wind). (**a**) shows the application of volumetric light. In this case, the shadowing effect is stressed for illustrative purpose. In (**b**), depth of field is applied to improve depth perception.

3.3. Visualizing Features of Geometrical Data

As terrain visualization commonly shows the earth's surface, in many instances, prominent geometrical objects are embedded. These can be real world objects, such as buildings, trees, and roads, but also synthetic objects, e.g., representations of radar measured obstacles or trajectories. Geometrical objects are defined by their concrete shape. However, such entities can also exhibit additional attributes, such as height, density or speed.

3.3.1. Representing Geometrical Data

Geometrical data can be placed in the terrain using geo-coordinates, e.g., latitude and longitude. In most cases, rendering this data is straightforward. Compared to the terrain data, the objects typically consist of few graphical primitives, at least if level-of-detail is applied. However, the terrain and the geometric object usually originate from different data sources. This is why inaccuracies in the representation due to imprecise geo-references, or due to a poor resolution of the terrain or the object respectively, are a common problem. Consequently, manual adaption or approximation are often necessary. On the other hand, some object types, such as line-based objects, e.g., roads or trajectories, often lack information of the size or the width. To be still able to represent such objects prominently within terrain, a certain extent must be presumed. Figure 10 illustrates this by the example of a trajectory visualization above terrain. The original trajectory data set consists of temporally ordered positions only. This, however, would define just a 1D path. To create a suitable visualization, a 3D bounding tube is defined. Concerning the size of this tube, it is important to balance out the perceptibility and the occlusion induced by the trajectory. In the following, we address the issue of trajectory visualization in more detail.

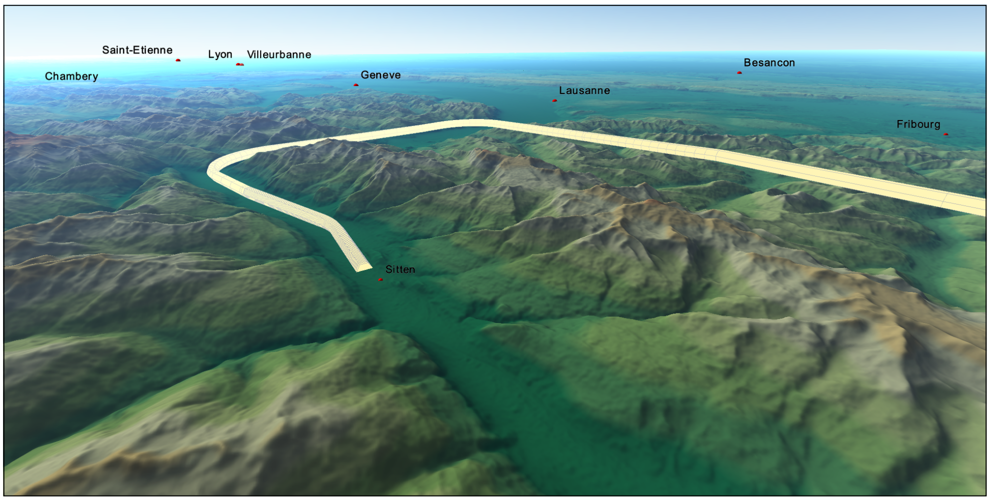

Figure 10. Visualization of an approach trajectory to the airport of Sion, Switzerland. The trajectory is depicted as a hexagonal tube.

3.3.2. Emphasizing Features

In conformity with the previous sections, we discuss the emphasis on global and local features by the example of trajectory visualization.

Global Features are defined by the location and the characteristic shape of the terrain-embedded trajectory. Both are often difficult to observe. Due to their small size, trajectories are easily occluded by elevations of the terrain surface. One approach would be to enlarge the trajectory. However, when viewed from close up, the trajectory would in turn occlude much of the terrain. Instead, we are using semi-transparent halos [48]. In contrast to an enlargement, the halo is less obtrusive and does not fully occlude the terrain. Moreover, the halo can be adjusted, so that it increases the size when far away and is less prominent, when viewed from a close-up position. Figure 11a shows how the trajectory is visually highlighted and how the path is coarsely recognizable, even when occluded by terrain. However, occlusion through the terrain can still occur. As a second approach to engage this issue, we apply ghosted views. Ghosted views are a common NPR render technique that lets the geometry shine through occluders. Figure 11b illustrates a ghosted view of the trajectory shining through the terrain surface.

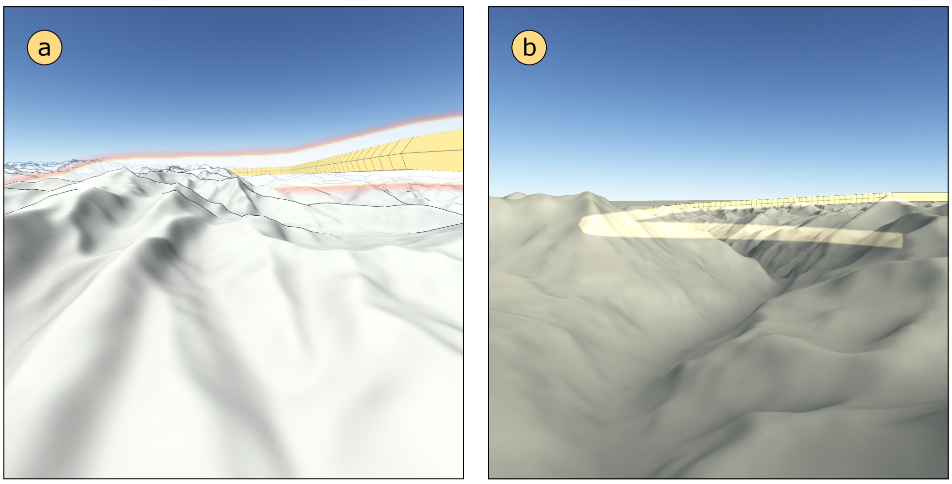

Figure 11. Improving communication of the position and path of the trajectory. (**a**) depicts a halo around the trajectory to increase its prominence; in (**b**), the geometry of the trajectory shines through the terrain if it is occluded.

Local Features of the trajectory comprise additional details. Typically, a trajectory is not only defined by its path, but also exhibits measured or calculated attributes for each position. Common attributes are, for instance, height, speed, or surrounding wind conditions. To communicate these features, we can utilize color, texture, and, to a certain extent, size of the trajectory. Color, for instance, is particularly suited to encode quantitative attributes [49]. Figure 12a illustrates this by showing a trajectory that is colored with two color scales. One color (yellow to red) represents wind speed that affects the aircraft along the path, the other color (light blue to dark blue) shows the amount of cross wind during airport approach. Both attributes together sum up to dangerous wind conditions along the path. Figure 12b shows another example, where the attribute is encoded by size. While quantification of size in a 3D presentation is quite difficult, side-by-side comparison is still facilitated. Thus, size can be used to expose outliers, as they would result into an abrupt change of extent. In our example, the disproportional fuel consumption shortly before landing is emphasized.

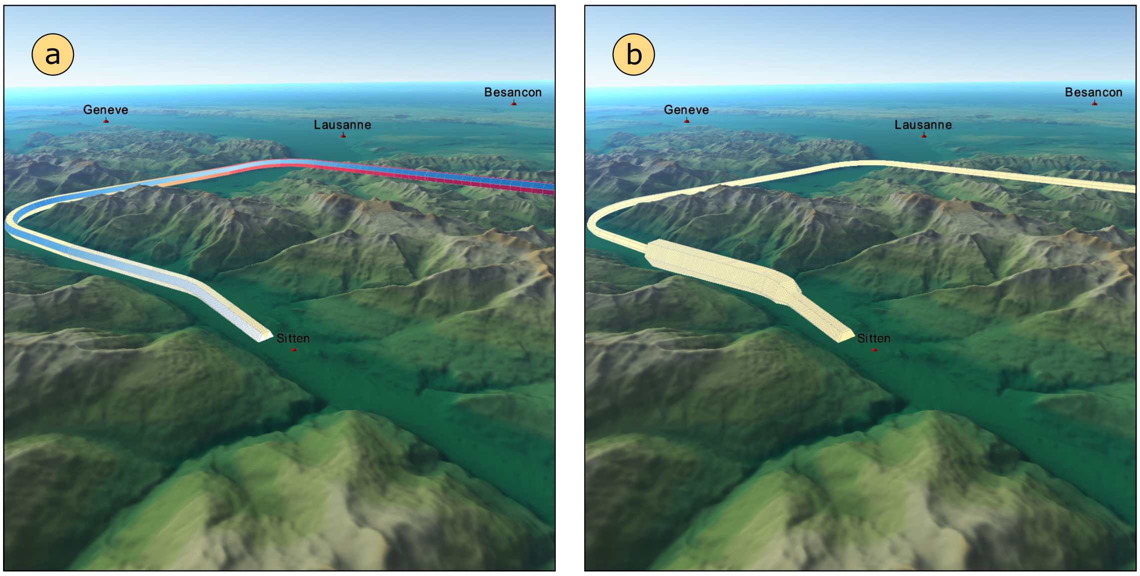

Figure 12. Communicating further details of the trajectory. The image on the left (**a**) depicts two parameters encoded into color: wind speed (yellow to red) and the amount of cross wind (light blue to dark blue). The image on the right (**b**) shows outliers in fuel consumption along the path by the width of the trajectory (greater width means larger fuel consumption).

Distance Awareness for geometrical data is similar to numerical data. Thus, techniques such as depth of field are also suitable. For trajectories, however, distances along the path might also be relevant. To emphasize such distances, an extension of the previously described grid technique (cf. Section 3.1.2) can be applied. Instead of a grid, we place vertical lines onto the terrain surface as well as on the object. Figure 13 shows that lines can ease the association between parts of the terrain and the corresponding parts of the trajectory regarding distance to the viewer. To further improve this technique, these lines can be animated, so that they travel away from the viewer.

In conclusion, the communication of features in terrain and geo-spatial data visualizations can be facilitated by means of emphasis. While emphasis on global features can provide an adequate overview of spatial attributes on a coarse level of abstraction, local features can communicate in-depth characteristics with more detail. Moreover, depth perception is always difficult in a 3D presentation. The application of depth cues can alleviate this issue, though they must be used with care since they heavily affect the overall visualization.

The different render strategies for terrain, data, and trajectories are based on various options for refining and adapting the visualization process to given scenarios. This allows creating customized visualizations that meet the user's requirements. However, the large amount of possibilities also complicates the overall design process. This is because it is not clear what impact the different methods and parameters have and how they affect each other. In order to support the user in the design process, we developed a comprehensive visualization tool. It enables testing different render strategies and configurations to create suitable visualizations.

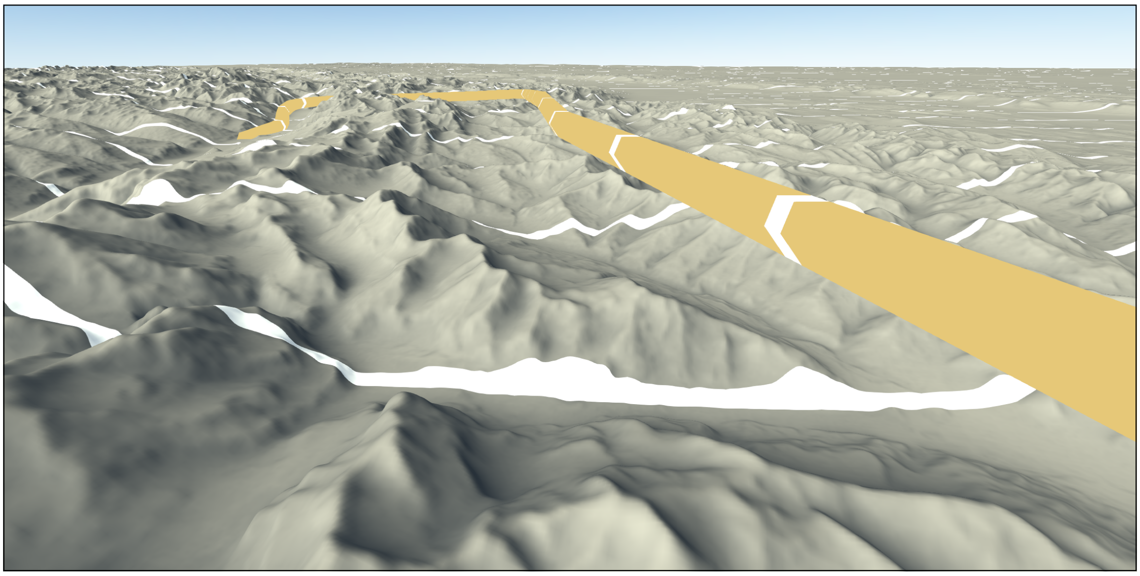

Figure 13. Using horizontal lines along the scene to emphasize distances. The white lines on the terrain and on the trajectory have the same distance to the viewer.

4. Visualization Tool TEDAVIS

To design 3D terrain visualizations that communicate features of the surface's topography and geo-spatial data, many different options must be considered. First, a suitable fundamental render method for the terrain model and the data must be selected and carefully blended to minimize interferences. Second, the render process must be parameterized and fine-tuned to emphasize particular features of interest.

In order to support this task, we developed a comprehensive visualization framework, called TEDAVIS (short for Terrain and Data Visualizer). Figure 14 shows an overview of our framework. The software enables presenting large terrain models along with different types of geo-spatial data. It allows for high-quality rendering of 2D, 3D, and stereoscopic images in real time. With our tool, visualizations can be configured interactively. Adjustments are incorporated into the render process immediately. Thus, the software supports experimenting with different setups to adapt the visualization to given requirements, in particular to emphasize features. To this end, TEDAVIS supports all render methods and parameterizations for feature visualization, which we discussed in the previous sections. In fact, all images in this paper were rendered, using our framework.

The following section describes the fundamental architecture of TEDAVIS, after which we illustrate how the framework can be used to design terrain visualizations.

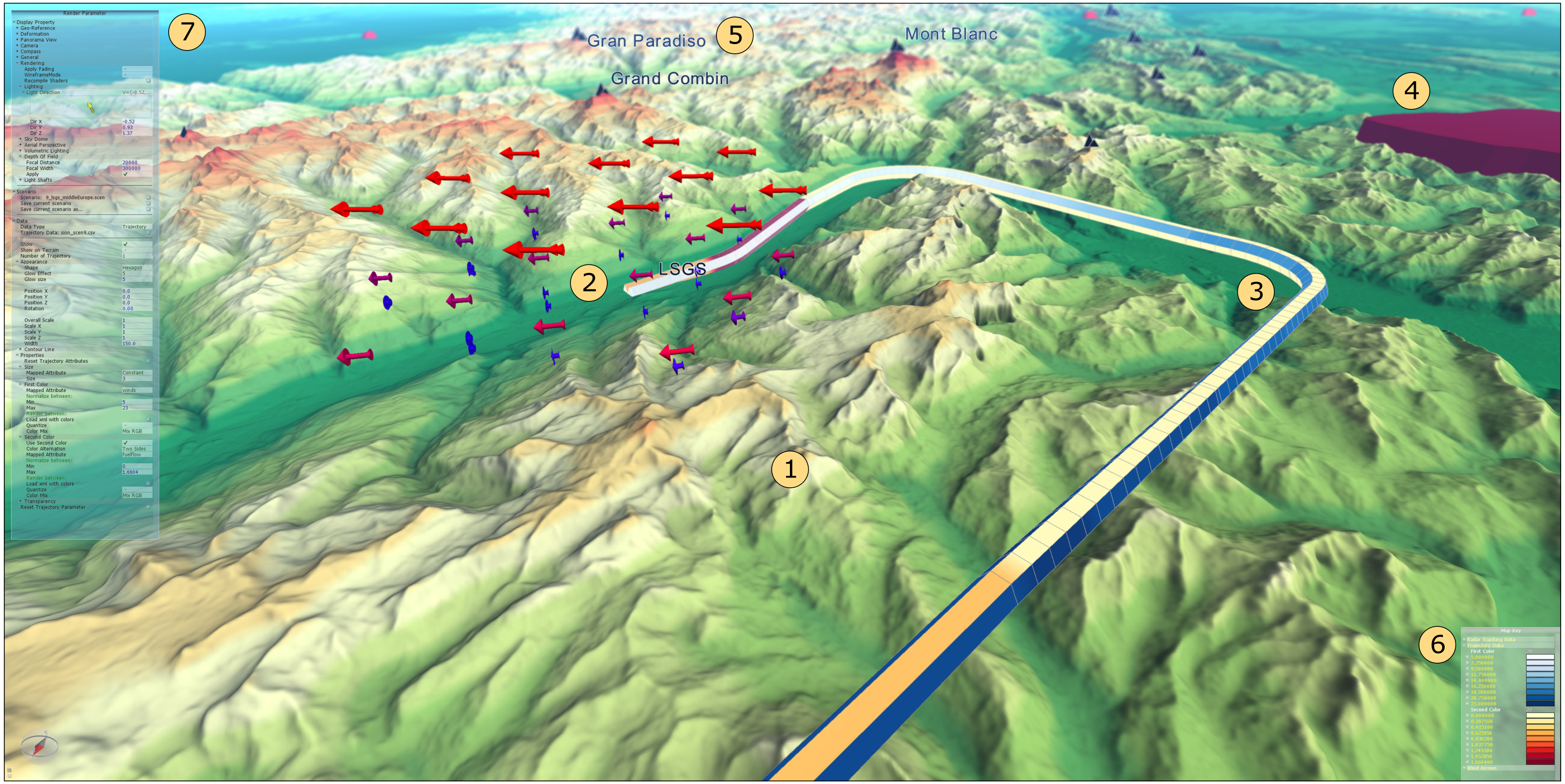

Figure 14. Overview screenshot of TEDAVIS that shows an elevation-colored terrain model of Central Europe ①, embedded wind data around the Sion airport ②, an approach trajectory of an aircraft ③, no-go-areas ④, and labels for points of interest ⑤. The applied color scales are specified in a legend shown in the lower right ⑥. The visualization can be interactively parameterized using the graphical user interface ⑦.

4.1. Architecture

Our framework is designed to support an interactive design process, even when handling large and complex data. To this end, TEDAVIS is developed as an efficient, modular framework. Figure 15 shows the fundamental architecture. In the back-end, the Data Interface creates and utilizes efficient data structures and loading strategies. The User Interface in the front-end allows for interactive exploration and configuration of the visualization. The Rendering component finally applies sophisticated render techniques to create suitable outputs.

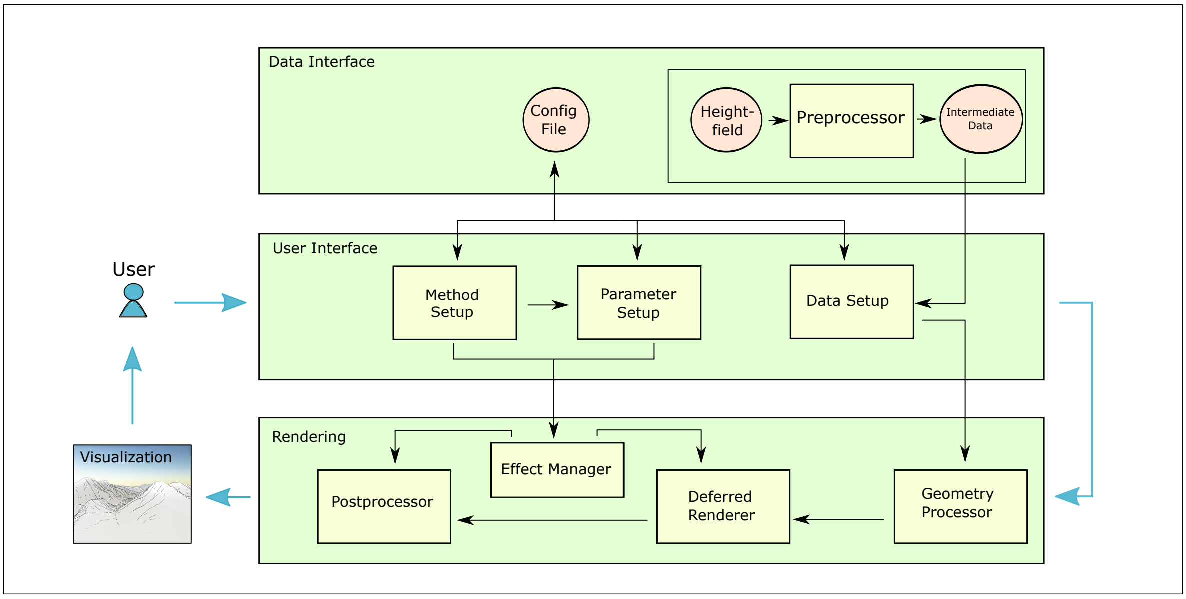

Figure 15. Overview of the architecture of TEDAVIS.

4.1.1. Data Interface

The data source of our tool is managed by the Data Interface (top of Figure 15). It supports loading various common height-field-formats (e.g., hf2, ter, bt, and mmf) and can process very large terrain models. For example, the terrain model shown in Figure 14 has a resolution of 1.5 asec and spans over a virtual area of 600 km^2, comprising approximately 12 GB of data. These massive data can only be rendered by using sophisticated level of detail concepts. TEDAVIS utilizes a quadtree-based data structure similar to Chunked LOD [6]. Additionally, we use a refined error metric that allows pixel accurate model representation. This means that, even though level of detail is used, no perceivable geometrical errors occur. Generating this data structure from the Height-field can take considerable time. Therefore, a Preprocessor carries out this task beforehand, allowing TEDAVIS to resort to prepared Intermediate Data. During the preprocess, various attribute maps, e.g., curvature or light maps, are computed as well, which further speed up the render process. As for numerical data, TEDAVIS supports common data types for scalar fields, for example, weather data values given on a 3D grid. Regarding geometrical data, the framework facilitates loading radar measured objects, e.g., polygonal shapes, or attributed trajectories. In addition, the tool can load and depict point-based, geo-referenced information, such as cities, airports, and mountain names. Eventually, the preprocessed terrain model as well as the data is loaded and managed by the Data Interface.

Another functionality of the Data Interface is loading and serializing a snapshot of the application's configuration, i.e., selected render techniques, parameterization, and used data sources. This information is combined into a single Config File. This file is written in a human readable text format, making the configuration adjustable by external tools, and, hence, allows for duplicating and scripting multiple scenarios outside of our software.

4.1.2. User Interface

The framework is operated by using a straightforward graphical User Interface (middle of Figure 15). Basically, it supports a three-step procedure to design terrain visualizations. The first step is the Data Setup, which means choosing the desired data. This might also imply loading only parts of the data, for instance through filtering. Having specified the data that should be presented, the next step involves the Method Setup, where an appropriate render method is selected for each data type. For example, when a terrain model is loaded, the user can decide to use shading by means of a specific global illumination model, or regarding numerical data, the user can choose between intrinsic or extrinsic techniques. Finally, the Parameter Setup enables configuring the selected render method. The user might parameterize the lighting situation, choose appropriate color scales, or apply specific depth cues. Alternatively, the User Interface can read in the previously mentioned Config File, which automatically loads data and applies methods and parameters according to a predefined setup. The configuration can be adjusted afterwards and then be saved again. Whenever the configuration is changed, data, methods, or parameters are immediately updated in the Rendering component, which is described next.

4.1.3. Rendering

The Rendering component of our tool (bottom of Figure 15) has direct access to the configuration set of the User Interface. Thus, changes are incorporated immediately. For instance, the Geometry Processor is checking for modifications in the data each render cycle. If the data have been changed, the associated objects are faded out and the geometry is constructed anew. From the data, the Geometry Processor builds up graphical primitives, processes them to efficient rendering resources and stores them on the graphics hardware. Subsequently, the Deferred Renderer renders the graphical primitives, using appropriate render methods and effects. Effects are multi-pass shader programs maintained by the Effect Manager. The Effect Manager, in turn, is using the configuration from the User Interface to adjust each shader pass and render method, resulting in the desired rendering outcome. The Deferred Renderer creates multiple image layers (k-Buffers), each containing different types of information about the rendered object, such as color, normal, or depth. Moreover, each data type is rendered into a separate render target. Lastly, the Postprocessor creates the final image. Using the k-Buffers, it computes the final color of each object, taking into account the environment information, such as lighting. Since all data types are rendered into separate render targets, otherwise global effects, such as aerial perspective or depth of field, can also be applied locally only on a subset of objects. To this end, the Postprocessor also utilizes effects from the Effect Manager, and is thus parameterizable by the User Interface. The multiple render targets are finally blended and post-edited to ensure a proper image quality. If stereoscopic vision is applied, the render process is traversed a second time to create an image for the left and the right eye, using slightly different camera positions.

4.1.4. Performance

TEDAVIS is a state-of-the-art terrain visualizer implemented using OpenGL, GLSL, OpenCL and C++. For performance benchmarks, we tested our framework with different visualization scenarios to render Full HD images (1920 × 1080 px) and listed the resulting minimum and maximum frame rates and render times in Table 1. We tested our tool using a standard PC with an Intel Core i7-3770K CPU and 32 GB RAM as well as an NVIDIA Geforce GTX 780 graphics card with 6 GB RAM. We inspected the performance of our tool under different scenarios, also listed in Table 1. The tested terrain data sets were a mid-sized model of Kauai (≈0.5 GB) and a large model of Central Europe (≈12 GB). All scenarios, except the first one, use Central Europe as a terrain model. For numerical data, we used a wind data set consisting of approximately 100,000 wind glyphs and regarding geometrical data, we embedded ten larger trajectories into the terrain. In summary, our framework always sustained real-time frame rates, even when sophisticated effects, such as aerial perspective or volumetric lighting were applied.

Table 1. Benchmark tests of TEDAVIS under different visualization scenarios. The table shows the minimum and maximum render frame-rates per second (FPS) and the resulting average render time for 1080p images as well as the number of rendered triangles.

Scenario	Max. # Triangles	FPS	∅ Render Time
Kauai (≈0.5 GB)	≈3.2 Mio	342∼563	2.2 ms
Central Europe (≈12 GB)	≈6.0 Mio	267∼488	2.6 ms
+numerical data	≈7.5 Mio	168∼254	4.7 ms
+geometrical data	≈7.6 Mio	128∼199	6.1 ms
+atmospheric effects	≈7.6 Mio	64∼78	14.1 ms
+volumetric lighting	≈7.6 Mio	58∼72	15.4 ms

4.2. Feature Visualization Using TEDAVIS

Our tool particularly supports the design of tailored visualizations. To create a presentation, firstly, the data is selected, secondly, an appropriate render method is chosen for each data type, and, thirdly, the representation is parameterized to fit the visualization task at hand. Accordingly, a typical workflow would start with loading a terrain model for the desired area. Initially, the data is displayed by a default render method. For instance, the terrain is initially shown by using edge enhancement combined with elevation-coloring, as shown in Figure 16a. The user can then choose another render method to expose local features, such as shading. Lastly, the selected render method can be further parameterized to create a fitting visualization. For one thing, the user can choose an appropriate illumination model, such as global illumination (Figure 16b) or apply additional volumetric lighting effects (Figure 16c). If the user is satisfied with the terrain presentation, another data source can be added and the depiction of this data type can be configured. For instance, either intrinsic or extrinsic visualization techniques can be chosen for any numerical data type. By using appropriate color scales or other highlighting techniques, emphasis on data features is facilitated. To ease the interpretability of data values, a legend can be shown in the visualization. Finally, the user might want to improve distance recognition in the scene by using atmospheric effects. The user is able to apply such effects either to all data types or only to individual ones. This can be useful, for instance, if data values are encoded by color and should not be affected by the distance emphasis placed on the terrain or vice versa.

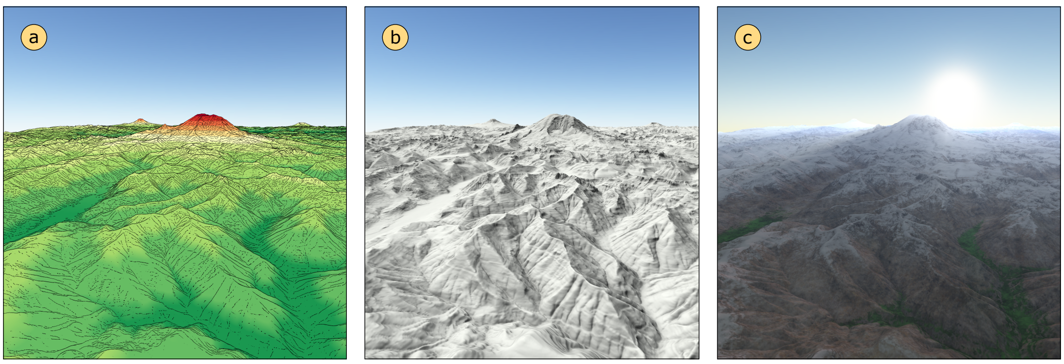

Figure 16. Visualizing terrain using different render methods and parameters: In (**a**), edge enhancement combined with elevation-coloring is used; in (**b**), a global illumination model is applied, and, in (**c**), volumetric lighting is added.

During this procedure, the user can explore the representation either by interactive means, using mouse and keyboard, or by being toured automatically, for instance along a predefined path.

The presentation can be adjusted by reviewing any step of the configuration in arbitrary order, thus, permitting the user to view the changes at once. After all parameters are adjusted, the entire configuration can be saved along with the data. This allows for continuing the work at a later date or storing finished scenarios.

5. Conclusions

In this paper, we addressed the question of how features in 3D terrain can be communicated effectively. We argued that emphasizing local and global features with regard to terrain topography, geo-spatial numerical data as well as geometrical data is an important requirement for appropriate visualizations. Moreover, we identified distance recognition as a key factor in 3D presentation design.

Our approach utilizes customized render methods that emphasize features of interest and improve distance recognition by appropriate depth cues. To this end, we provide refined render techniques as well as different options for configuration. Many of these techniques have already been used in other contexts, for instance in photo-realistic rendering. Nonetheless, they have rarely been applied for feature emphasis in terrain environments. Moreover, the combination of all these methods and their integration into one unified system, TEDAVIS, is a novel contribution. All implemented emphasis techniques can be interactively selected and parameterized by our tool. This allows for generating tailored presentations of large terrain and geo-spatial data sets on demand.

In summary, with TEDAVIS, the visualization designer has a potentially powerful tool at hand, which can be used to create individual visualization designs. As a consequence, the designer is responsible to choose adequate configurations to minimize interferences, which inevitably occur between the different effects. For instance, visualizing geo-spatial data by intrinsic techniques on top of the terrain surface impedes the analysis of local features of the terrain topography and vice versa. Previous research [46] suggests that prioritization can help to decrease such interdependencies. However, comprehensive evaluations are still required. To this end, TEDAVIS can be used to create different versions of a visualization in order to test them with end-users or domain experts.

Due to its modular design, TEDAVIS is well suited for further upgrades and rapid prototyping. Apart from additional render techniques, we are also interested in improving the user experience. Currently, the user must select and adjust all render techniques and configurations manually. Thus, the original aim of emphasizing features is only achieved indirectly. Therefore, we plan to guide the user according to his requirements through the user interface. We will also adjust certain parameters semi-automatically, if the user can state what features are of particular interest.

Another direction for future work would be investigating how global and local features can be visualized together. Currently, we consider local and global features separately. This is because we currently do not know how distinct render techniques affect each other. Using TEDAVIS, we are be able to design and evaluate specific visualizations. We are confident that the results of such evaluations can improve prospective terrain visualizations.

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Author Contributions: Steve Dübel conceived, designed, and implemented the approach; Steve Dübel and Heidrun Schumann wrote the paper; Heidrun Schumann finally approved the published work.

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