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Visualizing 3D Terrain, Geo-Spatial Data, and Uncertainty

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Academic Editor: Paul Parsons
Received: 1 December 2016; Accepted: 31 January 2017; Published: 8 February 2017

Abstract: Visualizing geo-spatial data embedded into a three-dimensional terrain is challenging. The problem becomes even more complex when uncertainty information needs to be presented as well. This paper addresses the question of how to visually communicate all three aspects: the 3D terrain, the geo-spatial data, and the data-associated uncertainty. We argue that visualizing all aspects with a high degree of detail will likely exceed the visual budget. Therefore, we propose a visualization strategy based on prioritizing a selected aspect and presenting the remaining two with less detail. We discuss various design options that allow us to obtain differently prioritized visual representations. Our approach has been implemented as a tool for rapid visualization prototyping in the context of avionics applications. Practical solutions are described for a use case related to the visualization of 3D terrain and uncertain weather data.

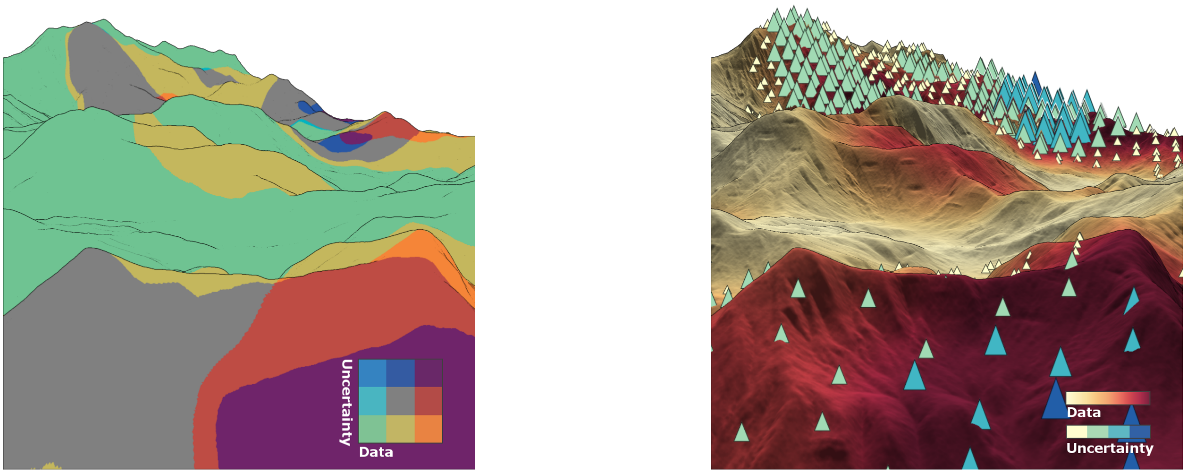
Keywords: visualization; terrain rendering; geo-spatial data; uncertainty; prioritization

1. Introduction

The analysis of geo-spatial data requires visualizing both the data and their spatial frame of reference [1]. The frame of reference is typically depicted as a 2D map, but for many applications, including applied geology, oceanography, or avionics, a 3D presentation of the terrain is needed [2–4]. Besides the spatial context, the interpretation of data strongly depends on knowledge about the data quality. Hence, visualizing the data's associated uncertainty is another important objective [5–7]. Existing approaches usually consider only two out of the three aspects: either data in their frame of reference or data together with their uncertainty. Visualizing all three aspects, the 3D terrain, the data, as well as uncertainty information in a single comprehensible image remains an open question. Our work aims to fill this gap.

Terrain rendering alone is challenging with regard to both real-time processing and image complexity [8]. Showing data along with the terrain aggravates the problem. To visualize data and the terrain, generally two different strategies can be applied: (i) The appearance of the terrain surface is modified to communicate data values, e.g., by colors, isolines or textures; or (ii) the presentation of the terrain is enriched with additional objects, such as data glyphs or visual cues. The same strategies can be applied to visualize uncertainty information along with the data: (i) The data presentation is modified by adjusting e.g., color, saturation or transparency; or (ii) uncertainty is encoded by additional graphical elements. If data plus terrain plus uncertainty are depicted together, the resulting visual representations can be quite complex. This is particularly true, if all three aspects are communicated with a high degree of detail. A simple example shall illustrate this problem.

Figure 1 shows a 3D terrain with color-coded weather forecast data and associated uncertainty information. In Figure 1a, all three aspects are presented at low detail. The structure of the terrain is communicated by drawing just silhouettes. This provides a general overview, but local features of the terrain are neglected. Data and uncertainty are encoded by a discrete bivariate color scale. Its few different colors support a simultaneous identification of data and uncertainty values, but only coarsely. In contrast, Figure 1b shows 3D terrain, data, and uncertainty at high fidelity. Shading is added to show more details of the terrain, and a continuous color scale is applied to encode data values more precisely. While theoretically being superior, this detailed visual representation actually has some drawbacks. Comprehending data values accurately involves additional mental effort, as it requires frequent lookups of continuous colors in the color legend. Moreover, shading the terrain leads to different levels of brightness, which in turn distorts the perception of colors. Parts of the terrain that are less illuminated (e.g., in shadows) might not show any color at all. This could lead to wrong interpretations of data and uncertainty, and eventually to false conclusions. On top of this, uncertainty is encoded using additional graphical primitives, which theoretically better expose the degree of uncertainty. However, there is a considerable amount of occlusion of these graphical primitives with the terrain and color-coded data.



(**a**) (**b**)

Figure 1. Visualization of 3D terrain, wind speed forecast data, and forecast uncertainty. (**a**) The terrain is depicted abstractly using contour lines, and a bivariate color scale with few discrete colors is used to encode the data (green to red) and the uncertainty (green to blue); (**b**) The terrain is depicted faithfully by shading its surface, a continuous color scale (yellow to red) is used for the data, and uncertainty is represented by color-coded (yellow to blue) triangular glyphs.

This simple example demonstrates that representing 3D terrain, data, and uncertainty at a sufficiently high level of detail is challenging. Apparently, it is not possible to simply show each individual aspect with full detail. It is rather necessary to balance the interdependencies of the involved visual encodings.

We address this issue by an elementary approach: prioritization. We prioritize a selected aspect of particular interest (terrain, data, or uncertainty). The aspect of interest is shown as detailed as possible, while the remaining two aspects are represented at a lower level of detail.

In this paper, we present basic strategies for prioritizing the visualization of terrain, data, and uncertainty. A number of visualization designs will be discussed and demonstrated. All were generated with a comprehensive visualization tool that facilitates rapid experimentation with different design options and levels of detail. In summary, the following contributions are made:

- Concept of prioritizing the visualization of 3D terrain, data, and uncertainty
- Visual representations for depicting all three aspects simultaneously
- Visualization tool for rapidly prototyping differently prioritized visualizations

This paper is structured as follows. Section 2 gives a brief overview of the related work. Section 3 describes our concept. We explain fundamental visualization strategies and combine them into differently prioritized visualization designs. Practical applications are illustrated in the context of flight-related scenarios. Section 4 introduces our prototypical visualization tool for designing and parametrizing such visualizations. Section 6 concludes the paper and discusses future work.

2. Related Work

There is much work on rendering 3D terrains, visualizing geo-spatial data, and considering uncertainty. It is beyond the scope of this paper to review the existing approaches. Instead, we are interested in combinations of these aspects. Approaches that pursue such a combination typically focus on only two aspects: either terrain plus data or data plus uncertainty. There are only very few works that actually address all three aspects.

2.1. Presenting Geo-spatial Data in Terrain

The three-dimensional geometry of terrain can be rendered in various ways, including line drawings [9], shading [10], or textures [11]. Terrain rendering techniques can also be combined to improve the perception of spatial features and depth cues [12,13].

In order to visualize geo-spatial data along with terrains, data values can either be mapped onto the terrain surface or be represented by additional graphical elements. While both strategies allow understanding data in their spatial context, there are also problems. If data is mapped directly onto the terrain surface, the presentations of data and terrain features are blended. This can produce mixed colors, which might be hard to interpret. We have already seen this in Figure 1b. If, on the other hand, graphical elements are added to the terrain rendering, occlusions will occur inevitably [2,14]. To improve the readability of data values, it makes sense to take perceptual issues into account, such as the adjustment of size and orientation of data-encoding objects [15].

2.2. Presenting Uncertainty of Geo-Referenced Data

Already in the early 1990s, MacEachren [16] and Goodchild et al. [17] pointed out the significance of uncertainty visualization in geographic information science. They emphasized the complexity of the concept of uncertainty, and the many different facets it covers. Some of the facets are objective, such as error, accuracy, and completeness, while others are more subjective, such as validity, variability, lineage, and confidence [18]. Although these facets may partially differ significantly, they all have in common that they represent a certain degree of data quality.

Several surveys provide excellent overviews and taxonomies for the visualization of data and uncertainty [5,7,19–21]. The survey by MacEachren et al. [6] is of particular relevance with regard to geo-spatial data. It considers the different types of uncertainty with respect to the three conceptual dimensions of space, time, and data attributes.

In general, uncertainty visualization can be categorized into intrinsic or extrinsic techniques [22]. Intrinsic techniques visualize uncertainty by altering existing graphical representations of the data, for example, by modifying visual variables, such as hue, saturation, and transparency, or by applying noise [23,24]. In contrast, extrinsic techniques integrate additional graphical primitives into the presentation, such as contours or glyphs [25,26]. Studies have found that extrinsic techniques perform either as good as intrinsic techniques or even better in terms of accuracy and effectiveness [27–29]. Yet, the effectiveness of intrinsic or extrinsic techniques may vary depending on the given task, the type of uncertainty, and the preferences of users [30].

The majority of research has addressed the representation of uncertain geo-spatial data in a 2D context, that is, on maps [31–33]. 3D representations are only rarely considered in the literature. An example is the work by Johnson and Sanderson [34]. However, they do not investigate geo-spatial data. In general, presenting uncertainty in a 3D geo-spatial frame of reference is a concern of ongoing research.

2.3. Presenting Uncertainty and Data in 3D Terrain

As already mentioned, only few works visualize terrain, data, and uncertainty together. Wittenbrink et al. [35] visualize uncertainty in wind data sets embedded into a coarse 3D terrain presentation. They focus on designing wind glyphs for the uncertainty information. Davis and Keller [36] propose a 3D presentation of slope stability. In their work, uncertainty is visualized via animation. While this is a viable approach, in some cases animation might introduce problems such as change blindness. Our work therefore focuses on static representations. Static representations are also used by Schmidt et al. [4] for underwater scenarios and by Kunz et al. [37] for natural hazards over terrain. They propose solutions for presenting data and uncertainty, but no specific techniques for terrain. The visualization is fixed and cannot be adjusted depending on the application context.

In summary, several techniques have been proposed for presenting data in 3D terrain. Much research has studied the visualization of data and associated uncertainty. However, only few works have considered the problem of visualizing all three aspects simultaneously. What we need are general design strategies that can help solving this problem. Our approach of prioritizing one particular aspect and adapting the presentation accordingly is a first step in this direction.

3. Prioritizing Terrain, Data, and Uncertainty

The concept of prioritization is a widely applied strategy—in general and in the context of visualization in particular. For a long time, the concept of focus + context has been used to accentuate regions of interest and to dim less-relevant ones [38].

Recently, Beecham et al. [39] investigated the idea of creating different levels of detail to prioritize the visualization of spatial, temporal, and descriptive aspects of spatio-temporal data. Their study suggests that prioritization is a feasible approach to deal with complex and potentially conflicting visualization requirements.

Our approach is conceptually similar to Beecham et al.'s work. We pursue a prioritization by considering different levels of detail that are to be combined into a single holistic visualization. However, instead of using a 2D map, we consider 3D terrain to visualize the spatial frame of reference, and instead of the temporal aspect, we consider the uncertainty of data. What this means concretely will become clear in the next paragraphs.

First, we briefly describe three scenarios that require prioritizing either the 3D terrain (T), the geo-spatial data (D), or the uncertainty (U). For each aspect (i.e., T, D, U), we introduce two fundamental strategies. One generates a detailed representation, the other a more abstract depiction with less detail. Finally, we explain how these individual strategies can be combined to create visual representations that include T, D, and U.

3.1. Scenarios

As a starting point for our research, we collaborated with domain experts from the aviation industry to pinpoint three flight scenarios, which include visualizations for pilots and air traffic controllers. In these scenarios, spatial awareness is relevant, and thus the geometry of T. For D, we consider weather data, including hazardous weather zones and weather forecasts. The forecasts are naturally associated with some uncertainty U. In summary, T, D, and U have to be considered in flight scenarios, yet their importance varies with the different scenarios. Typically, a selected aspect is of specific interest (denoted as $^+$), while the others communicate context information (denoted as $^-$).

- **Take-off and approach** $T^+D^-U^-$: During take-off and approach the flight altitude is low and natural obstacles in the terrain (e.g., mountains) constitute a principal threat to an aircraft. Therefore, the topography of T should be communicated accurately and as detailed as possible. Weather conditions and forecast reliability have to be considered as well, but they are not as relevant as the terrain. Therefore, it is sufficient to provide a qualitative representation of D and U, rather than full quantitative details.

- **Overflight** $T^{-}D^{+}U^{-}$: In overflight scenarios, the flight altitude is quite high (>10 km). Hence, fine-grained features of the terrain are not essential. The visual representation of T merely serves as an overview to facilitate orientation. Weather forecast data, on the other hand, can be of primary interest, in particular, the spatial distribution and characteristics of hazardous weather zones. Therefore, D should be represented at high detail. Information about potential uncertainty are needed as well. But providing a coarse overview of U to estimate the forecast quality is usually sufficient.
- **Re-planning** $T^{-}D^{-}U^{+}$: Hazardous weather zones can make it necessary to adapt flight routes. Before planning a new route, the reliability of the corresponding forecast has to be verified. Hence, the presentation of U is important and should be prioritized. Weather forecast data are needed as well, yet arguably, individual quantitative data values are not needed. A qualitative distinction of safe zones and hazardous zones is sufficient. Similarly, local terrain features are not as relevant. Therefore, D and T can be shown at less detail.

Next, we will illustrate basic rendering strategies to account for the different degrees of relevance of T, D, and U.

3.2. Rendering Strategies

As a first step, we define two rendering strategies for each aspect. Depending on whether an aspect is categorized as $^{+}$ or $^{-}$, the strategies will aim for a higher or lower amount of detail. This allows us to adjust the visual representation on a fundamental level. Fine-tuning the individual strategies will be considered later on.

Representing Terrain T

Terrain rendering is a field of research with many different techniques. For our work, we make a rather abstract distinction between representing 3D geometry of terrain either by line drawings or by shaded surfaces.

- **Line drawing for** T^{-}: Our fundamental strategy for less-detailed representations of the terrain is to use line drawings. Silhouettes, contours, or characteristic curves communicate significant geometric features [11]. Various edge styles can emphasize object boundaries or provide shape details [9]. Line drawings have been applied successfully to technical 3D models [40] as well as to terrain surfaces [41]. Figure 2a illustrates that the global topography of a terrain is communicated quite well, whereas fine-grained features are suppressed.
- **Shading for** T^{+}: We define shading, including texturing, as the fundamental strategy to visualize terrain at high fidelity. Different illumination methods can be applied to shade a terrain surface, ranging from simple local to highly sophisticated global techniques. By applying shading, local terrain features become visible and texturing can improve spatial details. For example, grid textures are useful to emphasize 3D structures [12,42]. This rendering style is demonstrated in Figure 2b. It can be seen that shading shows more and finer details of the terrain, compared to what can be discerned when using line drawings.

Representing Data D

Similar to terrain rendering, there exists a large variety of methods to visualize data. Again, we do not want to delve into the very details of all of these methods, but instead want to make a fundamental decision depending on whether a more or less detailed visual representation is needed. To this end, we propose to distinguish between showing aggregated data and individual data values.

- **Aggregation for** D^{-}: Representing aggregations, rather than individual values is a common approach. Different aggregation methods can be applied, including clustering, classification, or segmentation. As a result, individual data values are composed into larger units or groups. These units capture basic characteristics of the data and provide a good overview, yet they lack

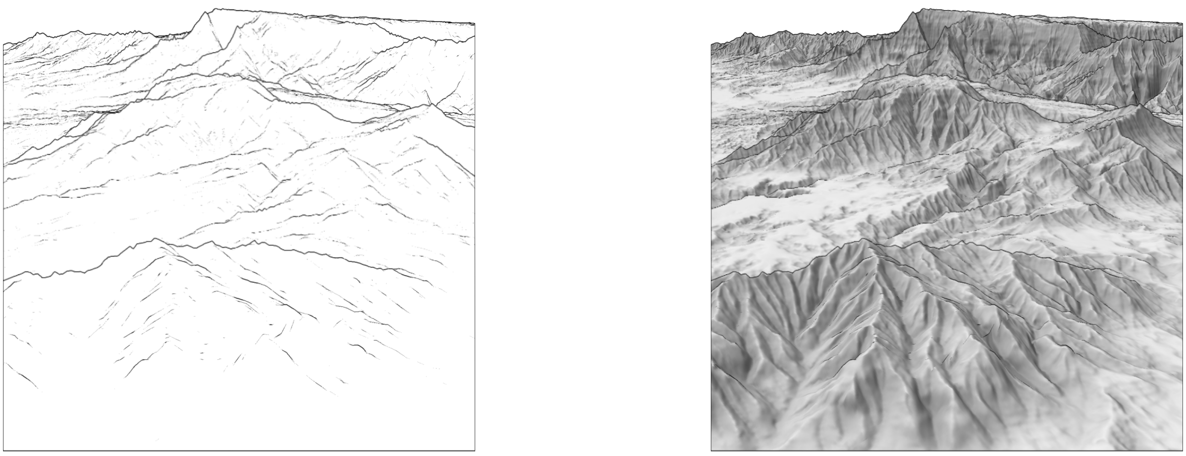
details. Figure 3a shows an example where aggregation is achieved by using a segmented color scale. The figure shows the severity of thunderstorm cells mapped onto the terrain surface. Four different colors classify regions into safe zones (white), potentially safe zones (light orange), hazardous zones (orange), and no-go zones (red). The four categories of zones can be distinguished easily, where as the underlying data values are abstracted away.
- **Individual data values for** D^+: If there is a need to grasp more details, a trace back to the individual data values can be necessary. For example, detailed data could be required to figure out whether a hazardous weather zone rather tends to be a no-go zone. To continue our previous example, individual data values can be communicated using a continuous color scale, where each data value is associated with an individual color. Figure 3b shows the individual values of radar reflectivity (dBZ), which is the quantitative measure behind the previous qualitative categorization of the intensity of thunderstorm cells.

Representing Uncertainty U

As mentioned in Section 2.2, two basic approaches exist for visualizing uncertainty: intrinsic and extrinsic techniques. Each provides a different degree of detail.

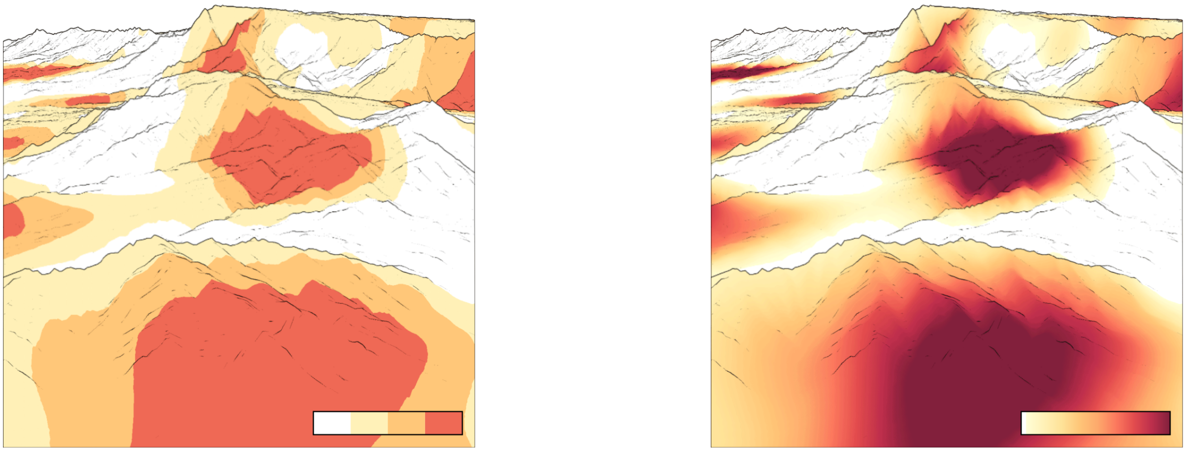
- **Intrinsic encoding for** U^-: The idea of intrinsic techniques is to modify the existing visual elements. Common techniques are to use bivariate color maps, transparency, noise, or blur. Intrinsic encodings support qualitative assessments with about three or four distinguishable levels [30,43,44]. In Figure 4a, uncertainty is intrinsically encoded by modifying transparency. Higher transparency modulates the perception of color for uncertain data values, whereas colors in certain regions remain unchanged. This allows users to quickly grasp the existence of uncertainty, but not the precise degree of it.
- **Extrinsic encoding for** U^+: Extrinsic techniques incorporate additional graphical elements. This offers a greater flexibility, better visual emphasis, and the potential to encode more details. Figure 4b illustrates an extrinsic encoding via color-coded dots embedded into the scene. In contrast to the intrinsic example, the dot's color coding can communicate several degrees of uncertainty. Moreover, the dots clearly outline the areas that are afflicted with uncertainty.

We now have two fundamental rendering strategies for each aspect: line drawing and shading for the terrain T, aggregation and individual data values for the data D, as well as intrinsic and extrinsic encoding for the uncertainty U. In the next section, we will combine these strategies to generate differently prioritized visual representations of T, D, and U.



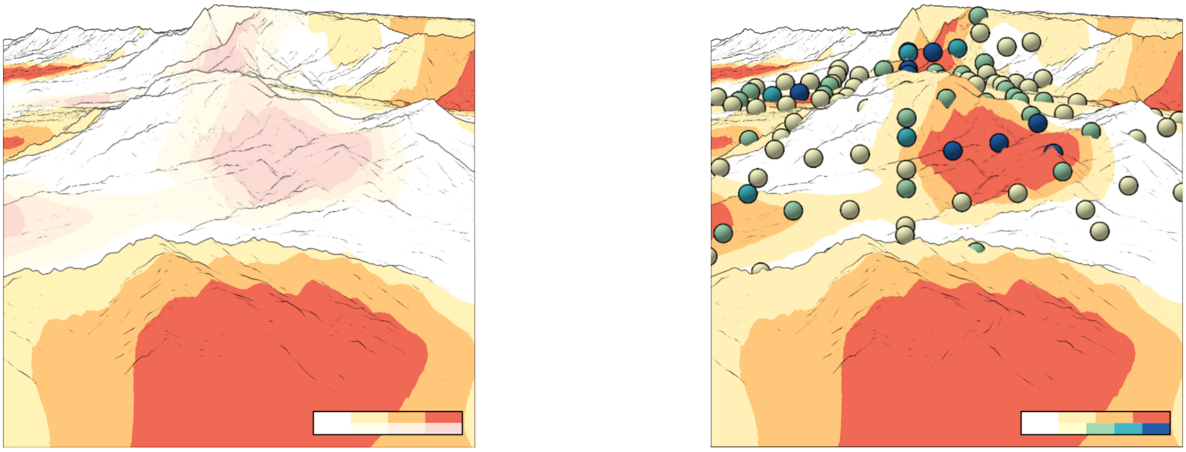
(**a**)Line drawings (**b**)Shading

Figure 2. Strategies for terrain. (**a**) Line drawing provides an overview of basic terrain features; (**b**) Shading represents the terrain at high fidelity.



(**a**)Aggregation (**b**)Individual data values

Figure 3. Strategies for data. (**a**) Aggregation via a segmented color scale shows basic qualitative characteristics of the data; (**b**) More detail can be discerned when individual data values are visualized using a continuous color scale.



(**a**)Intrinsic encoding (**b**)Extrinsic encoding

Figure 4. Strategies for uncertainty. (**a**) Uncertainty is encoded intrinsically by mapping it to transparency; (**b**) Uncertainty is encoded extrinsically by mapping it to the color of additional circles embedded into the terrain.

3.3. Prioritized Combinations

Table 1 collects the combinations of rendering strategies when prioritizing one aspect. The prioritized aspect ($^+$) is visualized by the strategy that provides details. The respective other two aspects ($^-$) are presented with the strategies that satisfy the need for contextual overviews. The resulting visualization designs will be explained by means of examples in the following.

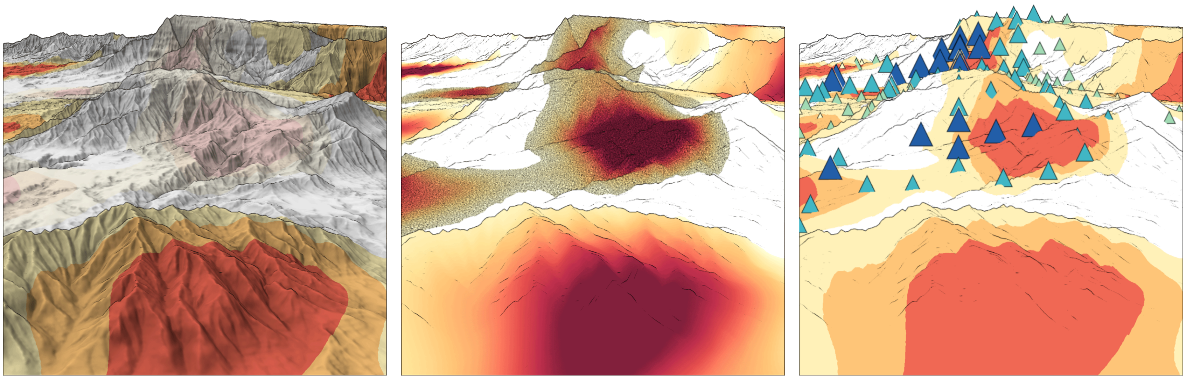
Table 1. Prioritized combination of terrain, data, and uncertainty.

Prioritization	Strategy for Terrain	Strategy for Data	Strategy for Uncertainty
$T^+D^-U^-$	**Shading**	Aggregation	Intrinsic
$T^-D^+U^-$	Line drawing	**Individual values**	Intrinsic
$T^-D^-U^+$	Line drawing	Aggregation	**Extrinsic**

Prioritizing Terrain

Figure 5a shows a combined visualization with terrain, data, and uncertainty, where the terrain is prioritized. As previously described, take-off and approach scenarios require a detailed representation of the terrain. Therefore, the terrain is visualized by shading its surface. Ideally a sophisticated illumination model is applied to expose as many detailed features as possible. Moreover, interference with or over-plotting of the terrain features should be reduced to a minimum. Hence, data and uncertainty are presented with less detail.

According to our render strategies, this means showing aggregations instead of individual data values. By using a segmented color scale with only a few distinct colors, an overview of the data is warranted without too much impact on the shading of the terrain surface. For uncertainty, intrinsic techniques should be used, because they work without additional graphical elements, and thus introduce no occlusion. A typical intrinsic approach is to vary the transparency of the data-encoding colors. The degree of transparency should be within reasonable limits to ensure that colors, and hence, data values are still identifiable, even if they are affected by high uncertainty.



(**a**)Prioritizing terrain (**b**)Prioritizing data (**c**)Prioritizing uncertainty

Figure 5. Differently prioritized visual representations of the same terrain, data, and uncertainty. (**a**) The terrain is prioritized and rendered as a detailed shaded surface. The data are visualized in an aggregated fashion by a segmented color scale, and uncertainty is depicted intrinsically by using transparency; (**b**) The data are prioritized and individual values are visualized with a continuous color scale. The terrain is rendered at less detail by drawing only lines, and uncertainty is depicted intrinsically by using noise; (**c**) Uncertainty is prioritized and depicted extrinsically via colored triangular glyphs. The terrain is rendered at less detail as in (**b**), and the data are visualized in an aggregated fashion as in (**a**).

Prioritizing Data

Figure 5b show a combined visualization where the data are prioritized. We mentioned that prioritizing data can be useful in overflight scenarios. As the focus lies on the data, individual data values are visualized. In our case, this is done by using a continuous color scale.

To prevent that the data presentation gets impaired, terrain and uncertainty are shown with less detail. A shaded terrain surface would considerably distort the perception of the color-coded data. Therefore, the fidelity of the terrain rendering is reduced to line drawings of significant edges. Uncertainties are presented by intrinsic techniques to avoid occlusions. For another intrinsic example, we now superimpose the data presentation with noise. Similar to what has been said before, a certain maximum density of the noise should not be exceeded to maintain the legibility of data values.

Prioritizing Uncertainty

Finally, Figure 5c illustrates a design where the focus is set on the data's uncertainty. Uncertainty can play a significant role when air traffic operators plan alternative flight routes. As uncertainty is the most relevant aspect now, it is visualized using an extrinsic technique. Glyphs are embedded into the terrain to prominently represent uncertainty. The locations of the glyphs encode where uncertainty occurs, and the corresponding degree of uncertainty can be mapped to properties of the glyph. In the figure, we use triangular glyphs whose color and height vary depending on the underlying uncertainty.

As terrain and data are deemed less important in this case, the occlusion caused by the glyphs is acceptable, and terrain and data can be depicted at lower detail. Again, the terrain is represented by contours and silhouettes, and the data is shown in an aggregated fashion using a segmented color scale.

In summary, the concept of prioritization allows us to adapt the visualization of terrain, data, and uncertainty to the task at hand. Already the simple combination of our fundamental rendering strategies (as collected in Table 1 and shown in Figure 5) leads to quite different visual representations suited for different scenarios.

Moreover, within each of the fundamental strategies, there are numerous design options to fine-tune the visualization. For example, which shading technique should be applied and how should it be parameterized? How many segments and which hues should a color scale have? What shapes should be used for encoding uncertainty extrinsically? The design space is considerably large. On the one hand, this allows us to better attune the visualization to application-dependent requirements. Yet, on the other hand, it is not clear beforehand how certain design decisions will affect the overall visualization outcome. Therefore, we implemented a software prototype that enables us to flexibly experiment with different design options and test potentially useful visualization variants.

4. Prototyping Prioritized Visualizations

Designing a concrete visualization that addresses a certain use case requires application-specific adaptations. In the first place, it is necessary to choose from the fundamental rendering strategies and to blend them into a suitable combination. Second, the visual encoding has to be fine-tuned to minimize interference and to tailor the design to fit the given scenario. In order to satisfy both requirements, we developed a tool PRIOVIS that supports a flexible steering of the visualization design process. PRIOVIS enables rapid prototyping and seamlessly switching between different visualization designs with only a few clicks. Figure 6 shows an overview of the software.

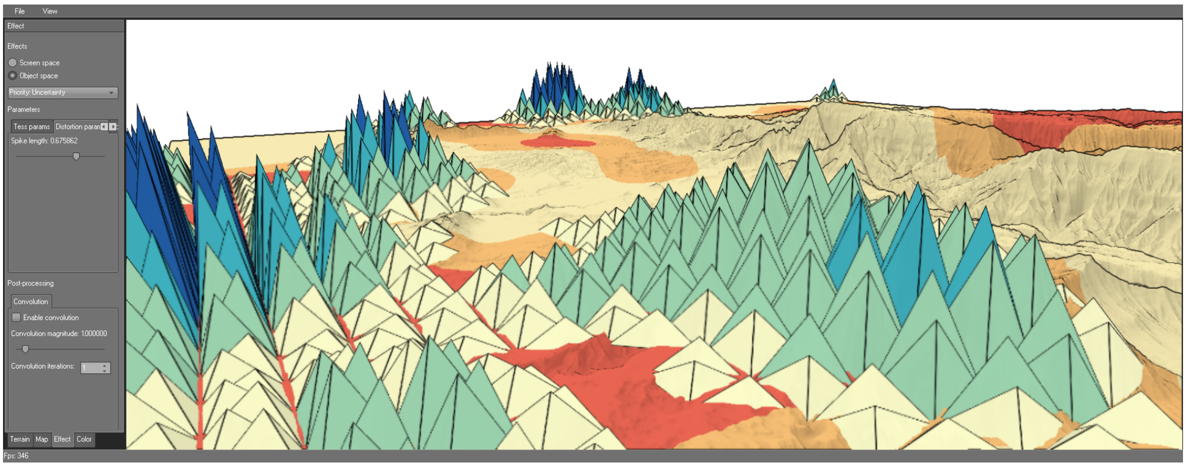


Figure 6. Visualizing hazardous weather regions and associated uncertainty information in 3D terrain. The image shows a schematic overview of PRIOVIS. The user interface supports flexibly steering the visual encoding and seamlessly switching between various visualization techniques.

4.1. Parametrization

PRIOVIS provides predefined setups to assist in generating visualizations that are prioritized for either terrain, data, or uncertainty. For each setup, the rendering strategies and combinations described in Sections 3.2 and 3.3 can be instantiated by selections of different rendering algorithms. The algorithms can be further parametrized to adapt the overall design to application-specific constraints.

Terrain Visualization

The two fundamental strategies for terrain rendering are line drawing and shading. Both strategies allow for customization as illustrated in Figure 7. When using line drawing, the user can choose between displaying silhouettes or enhanced edges. Enhanced edges can either be derived from the curvature of the terrain or from the variation of depth in image space. By selecting and parametrizing different algorithms, the quantity and quality of contours can be adjusted. This directly effects the final degree of detail. Examples are illustrated in (a) to (c).

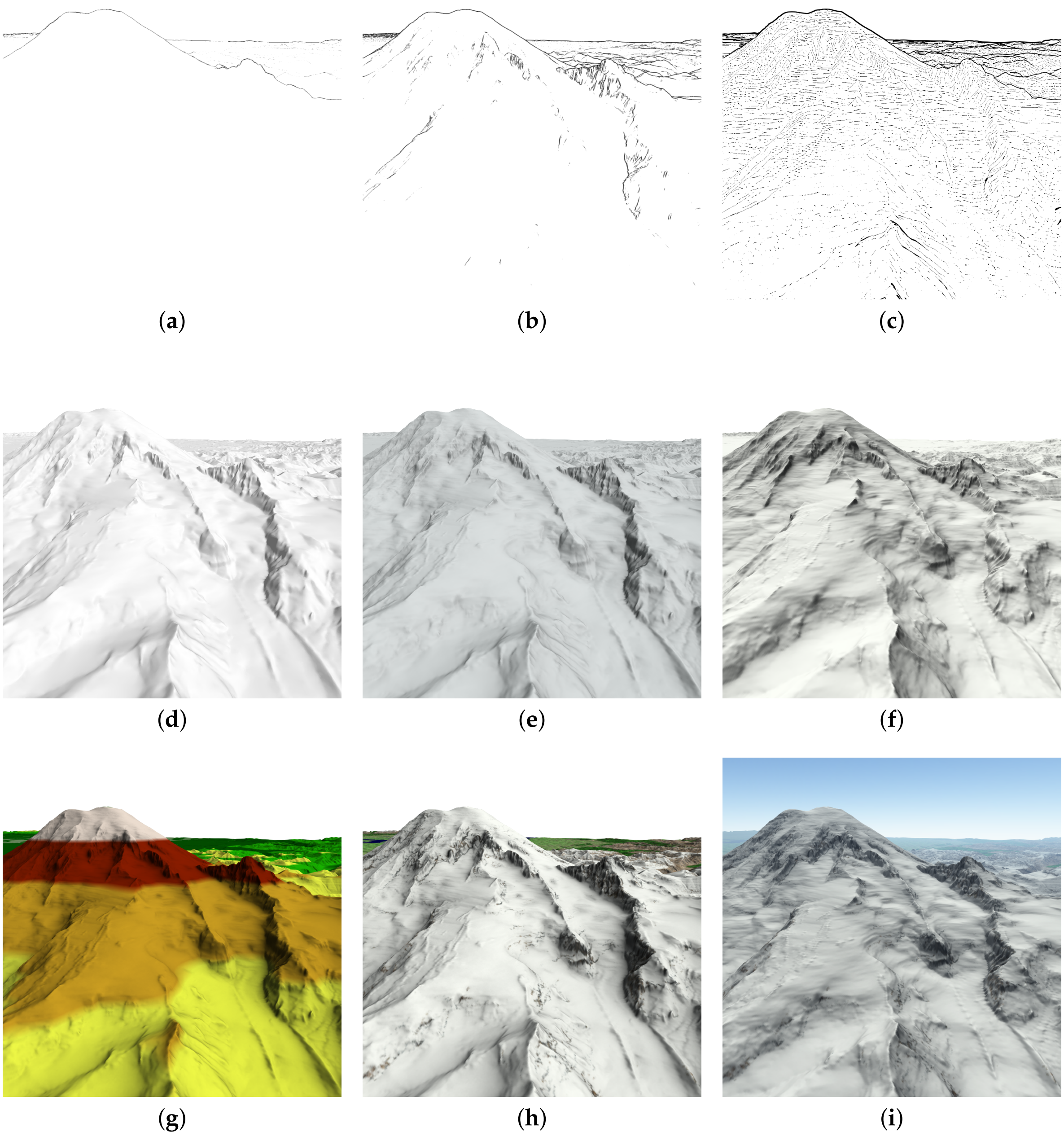


Figure 7. Parametrizing the terrain visualization. (**a**–**c**) Line drawings: (**a**) silhouettes; (**b**) enhanced edges derived from terrain curvature; (**c**) enhanced edges derived from depth variation. (**d**–**i**) Shading: (**d**) Phong illumination; (**e**) ambient occlusion; (**f**) ambient aperture lighting; (**g**) elevation-colored texture; (**h**) realistic surface texture; (**i**) atmospheric effects.

The shading strategy can be fine-tuned by choosing from a diverse set of illumination models. Currently, PRIOVIS supports Phong illumination, ambient occlusion, and ambient aperture lighting [45]. As illustrated in (d) to (f), each model achieves a different level of quality. Local illumination via the Phong model (d) already provides more details than line drawings. Global illumination via ambient occlusion (e) and ambient aperture lighting (f) enhances local surface features and improves the overall image quality. To expose even more details of the terrain, additional textures can be used. (g) shows an elevation-colored texture and (h) depicts a realistic surface texture. Additional atmospheric effects (i) can be used to improve both depth perception and image quality. Finally, line drawings and shading techniques can be combined to further customize the output image.

Data Visualization

To adjust the depicted degree of detail of the data, we visualize either individual data values or aggregations. A selection of the available encodings is shown in Figure 8. Data values can be mapped on different visual variables, such as color (a, d), size (b, e), or direction (c, f). Color scales can be freely adjusted, depending on the task at hand [46]. For our design, we used standard color scales from Color Brewer [47].

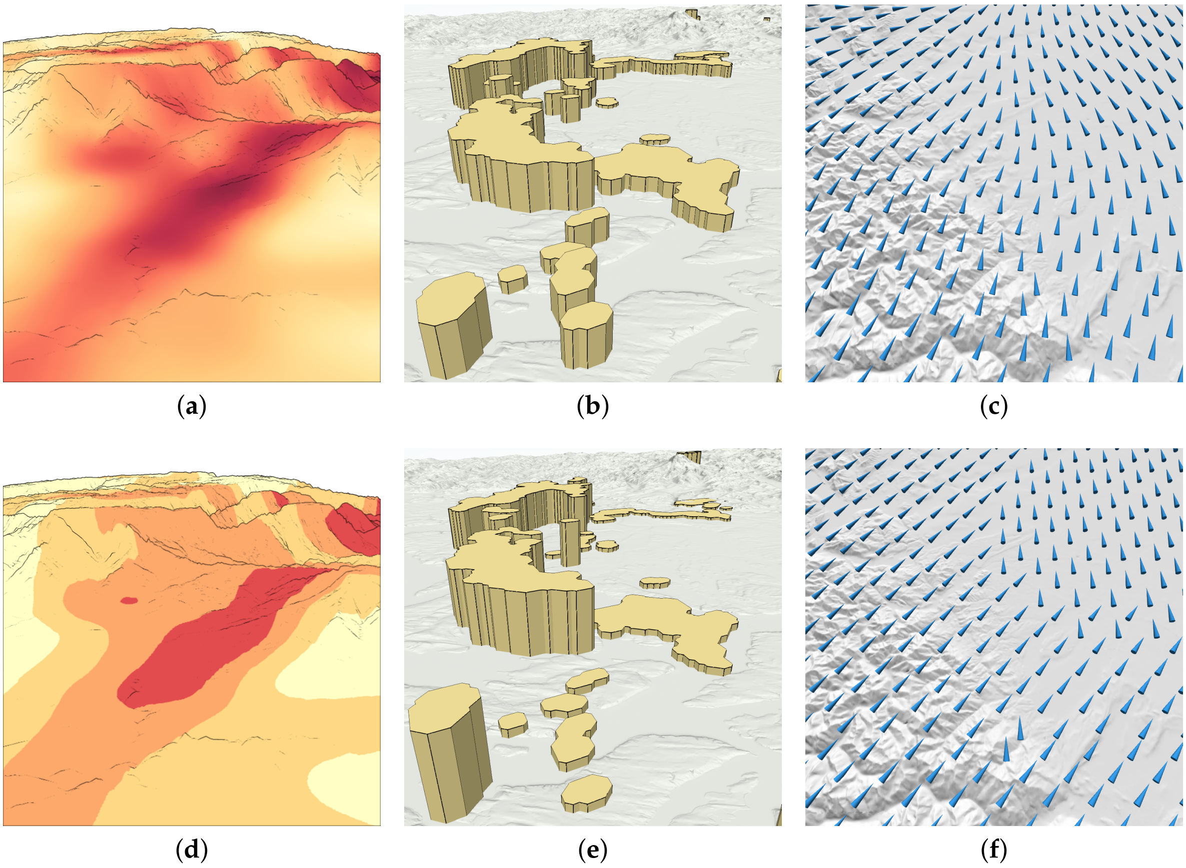


Figure 8. Showing either individual data values (**a**–**c**) or aggregations (**d**–**f**) by visual encodings based on color (**a**,**d**), size (**b**,**e**), and direction (**c**,**f**).

For full details, a continuous mapping of data values to visual variables is used. That is, each individual data value has a unique representation (e.g., a specific color). For aggregated views, the visual variables are grouped into discrete classes (e.g., segmented color scale), each representing an entire subset of the data. The number classes can be chosen freely to adjust the level of detail.

Uncertainty Visualization

For presenting uncertainty, PRIOVIS provides intrinsic and extrinsic techniques as indicated in Figure 9. Intrinsic techniques modulate existing encodings in various ways. The user can choose to vary transparency, saturation, noise, strokes, or bump mapping to modify the data representation. A suitable balance of data and uncertainty visualization can be found by adjusting the strength of the modulation. For example, (a) to (c) illustrate the modulation of transparency, where uncertain data is represented by high transparency. From (a) to (c), the modulation increases in strength. Using moderate transparency (b) allows the user to identify where uncertainty is located and which data values are affected. In contrast, when increasing the strength of the modulation (c), the actual data values in uncertain areas become barely visible. This can be useful to draw the attention to data that are certain.

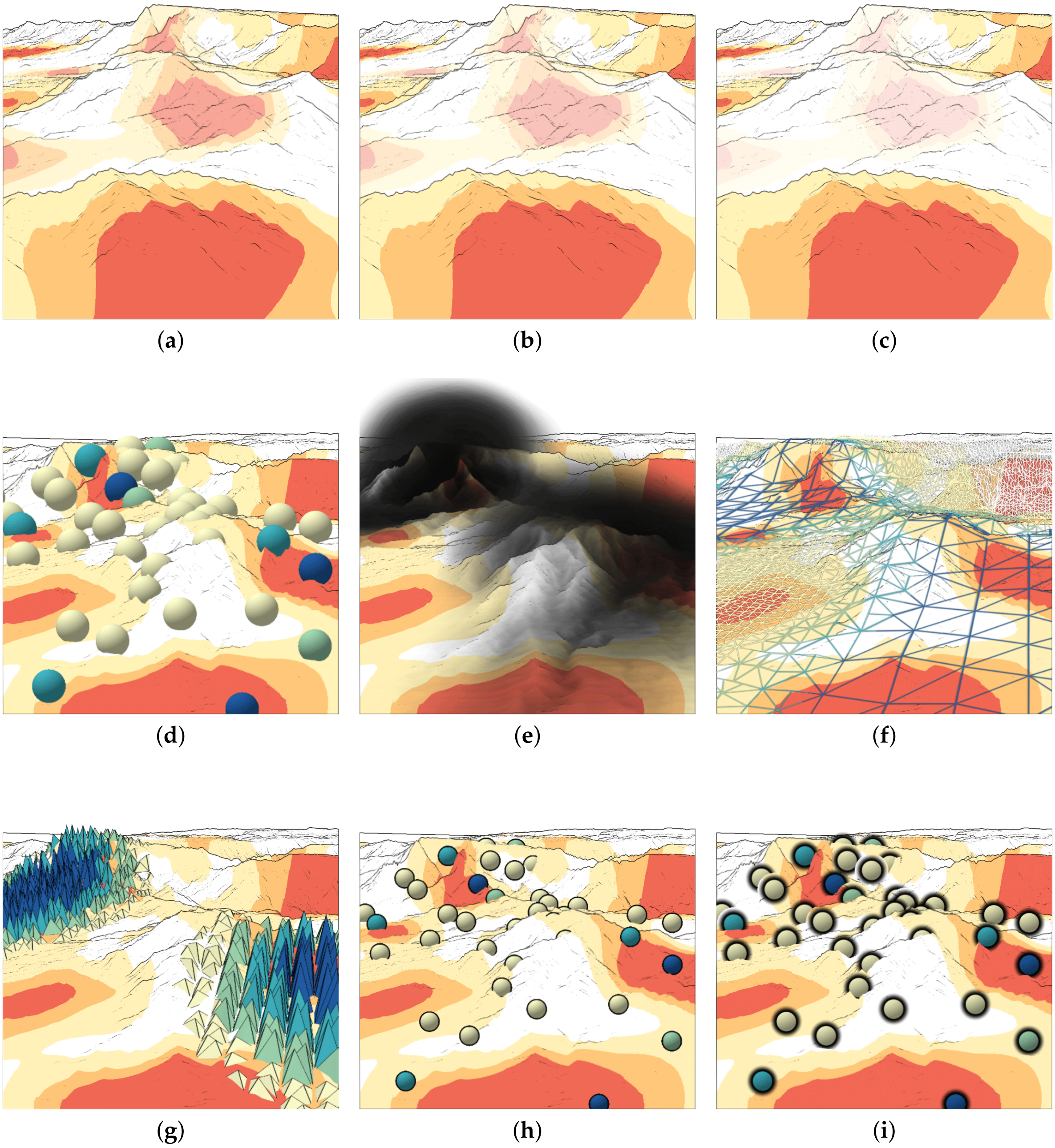


Figure 9. Options for visualizing uncertainty. (**a**) 45% transparency; (**b**) 65% transparency; (**c**) 85% transparency; (**d**) circular glyphs; (**e**) fog; (**f**) grid overlay; (**g**) tetrahedral glyphs with redundant encoding by height and color; (**h**) outline stylization; (**i**) halo stylization.

Extrinsic techniques are less dependent on the data representation and thus allow for a wide variety visual encodings. PrioVis integrates several generic 2D and 3D glyphs, such as circles, triangles, or tetrahedrons. The former are illustrated in (d). Yet, new glyphs can be added on demand, for example, to conform with domain conventions (e.g., standard symbols in aviation). Also the way how uncertainty is encoded can be altered. The standard way is to map uncertainty to a selected glyph property such as color. Redundant encodings are possible as well. For example, uncertainty can be mapped to both glyph size and color. When applied with care, this can increase the visual prominence of highly uncertain parts of the data.

In addition, our tool supports extrinsic encoding via fog (e) and grid overlays (f). For grid overlays, we depict a triangular mesh whose resolution varies with the underlying uncertainty. The mesh is subdivided coarsely for uncertain areas to indicate vagueness. A finely subdivided mesh indicates crispness in parts where the data are certain. The visual appearance of the extrinsic techniques is again subject to fine-tuning, for example, by adjusting size, density, and color. Extrinsic techniques also lend themselves to redundant encoding. (g) shows tetrahedral glyphs with varying height and color. Additional stylization via outlines (h) or halos (i) can be applied to better separate glyphs and terrain.

All the aforementioned options for parametrization allow the user to tailor the visualization design to application-dependent requirements. Figure 10 shows three additional examples of combined, prioritized, and fine-tune visualizations of terrain, data, and uncertainty. In order to enable rapid prototyping of such examples, the parametrization has to run in real-time. This requires a sophisticated software architecture.

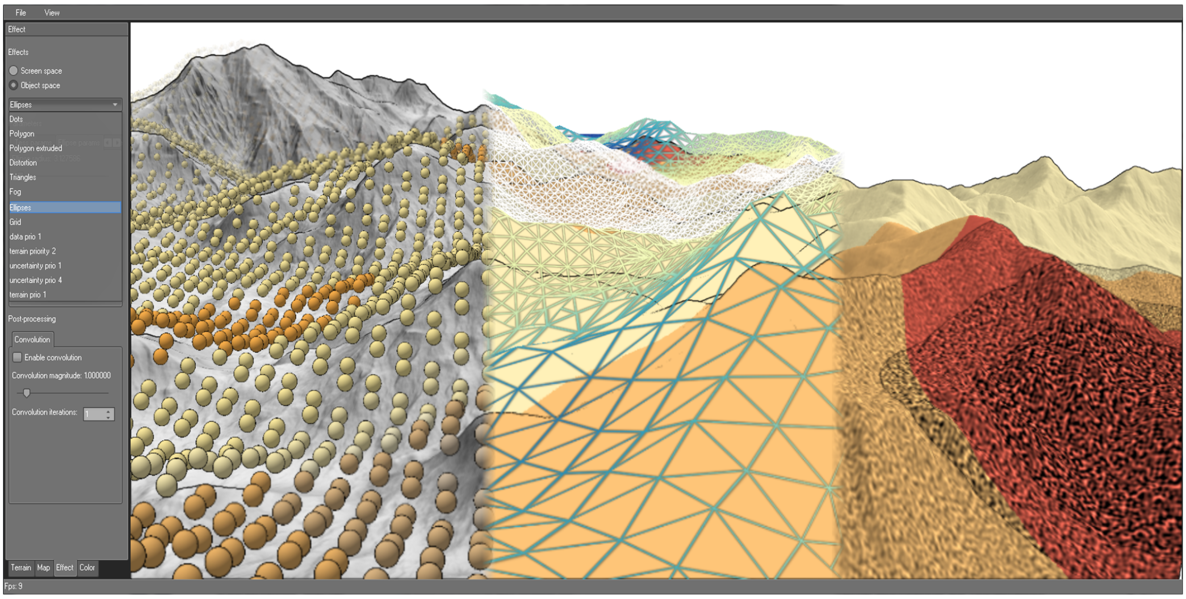


Figure 10. Interactively selecting different visual encodings for uncertainty. The graphical user interface of PrioVis allows for choosing from different visualization techniques, e.g., circular glyphs (left), grid overlays (middle) and noise (right), and tuning their parameters via GUI control elements.

4.2. Architecture

PrioVis has been implemented with the requirements of real-time experimentation in mind. At the back-end, a dedicated resource management ensures efficient data processing and rendering. The front-end supports interactive parametrization and exploration of the final visualization results.

Resource Management

The resource management comprises three components for handling the data, the visual encoding, and the configuration. The data component handles different formats of terrain, weather data, and associated uncertainty. PrioVis supports high resolution height maps of very large spatial regions. For instance, we used an 800 km^2 terrain of central Europe with a resolution of 1.5 asec as a testing data set. Regarding weather data and uncertainty, we support two common types of data: scalar fields (i.e., weather data given on a 2D grid) and weather objects (i.e., regions given as polygonal shapes). On top of that, PrioVis can visualize other data such as trajectories of moving objects.

The encoding component is based on a scripting engine. Scripting enables us to include various visualization techniques and maintain their associated parameters. Each technique is specified by one or multiple scripts, each defines how a resource from the data component is to be displayed visually. To ensure real-time rendering, the backing algorithms are implemented as a mix of OpenGL shaders and OpenCL kernels for hardware-accelerated execution on the GPU or the CPU. Particularly, rendering the terrain geometry can be computational expensive. Therefore, PrioVis integrates sophisticated level-of-detail techniques that achieve real-time frame rates even at sub-pixel precision.

The configuration component defines how to integrate data and visual encoding to form a 3D visualization of terrain, data, and uncertainty. To this end, a configuration instantiates data and encoding resources and considers a concrete prioritization and specific parameter settings.

Encapsulating and managing the memory, computational, and visual resources as described before has two main advantages. First, it enables versioning each resource's state. This allows users to interactively switch between different visualization techniques or tune associated parameters to adapt the overall visual design. Second, it facilitates handling resource updates automatically. For example, if new data is available at an external source, the visualization is refreshed automatically to reflect the incoming changes.

Interactive Parametrization and Exploration

Thanks to the flexible resource management, the user can interactively switch between alternative prioritizations, different weather attributes, and different types of uncertainty. The encoding component allows for adapting the visual design on the fly either by changing parameters exposed in the graphical interface or by modifying the visualization scripts directly in the scripting engine. It is even possible to create new visualization techniques without restarting the prototype. A sensible restriction though is that the basic design of a 3D scene be maintained. This is necessary to be compatible with the fundamental interactions for exploring the final visualization, including free 3D fly-through and moving along pre-defined trajectories.

5. Design Process and Feedback

The strategies and designs presented so far have been developed in collaboration with domain experts from the aviation industry. They have to deal with multi-faceted, uncertain data and 3D terrains on a daily basis. In this section, we briefly summarize the design process that yielded the results presented in this work.

In a first phase, we discussed the general and specific requirements in the domain context. There was agreement that visualizing multiple types of information is a necessity. However, the domain experts requested that the complexity of the visual representations be kept at a reasonable level. They identified three aspects to be of primary interest: 3D terrain, uni-variate weather data, and uncertainty. Additional aspects, such as changes over time or multi-variate data, were deemed secondary and left for future work.

In the light of the data to be visualized, we concluded that plainly showing all information regardless of their relevance would lead to visual clutter, which implies high mental load when interpreting the visual representations. Therefore, together with the domain experts, we looked into different scenarios that cover typical real-world settings. We discussed the requirements and tasks that are relevant in these scenarios. For our study, we narrowed down the scenarios to the three given in Section 3.1.

In a second phase, our first task was to develop generic strategies for prioritized visualization that can be refined later on according to particular application requirements. As a result, we obtained the strategies described in Section 3.2. Based on these strategies, we developed the principal visualization designs for each scenario as discussed in Section 3.3. The necessary visualization techniques and rendering algorithms have been integrated into the PRIOVIS prototype.

We followed an iterative process so that feedback from our partners could be incorporated to improve the designs. For example, initially, we proposed to use local illumination when the 3D terrain is less relevant. However, the domain experts expressed concerns that even such a low-fidelity representation could be too realistic in some situations. They suggested to go for more abstract representations based on silhouettes only. As a good compromise in terms of abstractness, we finally settled with a combination of silhouettes and contours.

A necessary next step is to conduct a formal evaluation of our approach. However, given the rich set of options for parametrizing the visualization, designing a controlled study poses a considerable challenge. Therefore, we first have to narrow down the scope of the study to promising candidates. This will be done in close collaboration with the domain experts and based on our principal visualization designs. Our PRIOVIS tool will be used for further prototyping and fine-tuning.

6. Conclusions

In this paper, we addressed the problem of visualizing data and associated uncertainty, embedded into a 3D terrain representation. Since all aspects can hardly be shown with the same degree of detail at once, we suggested prioritizing a selected aspect based on scenario-dependent requirements. The prioritized aspect is visually emphasized by showing more detail, whereas the other two aspects are shown with less detail.

For each aspect, we proposed two fundamental rendering strategies to be employed depending on whether an aspect is prioritized or not: line drawings vs. shading for the terrain, aggregation vs. individual values for the data, and intrinsic vs. extrinsic encoding of uncertainty. While these strategies offer basic control for steering the visual budget, a subsequent adjustment of the visual representation is still required. To this end, we developed visualization tool for rapidly prototyping prioritized visualizations. The tool provides various options for rendering terrain, data, and uncertainty, and it allows for a seamless switch between different prioritizations, visualizations, and parametrizations.

Practical relevance of our work has been indicated by means of aviation-related scenarios. We illustrated differently prioritized visual designs that can be useful during take-off and approach, during overflight, or for re-planning of flight routes. While feedback from domain experts suggests that our solution has much potential, there are still several research questions to be addressed.

So far, we have considered 3D terrain, data, and uncertainty. We are confident that the idea of prioritization can also help us integrate other information. For example, the temporal aspect of the data is relevant in many applications [48,49]. Prioritized rendering strategies could be developed in analogy to the ones we described in this work. Time could then be visualized as a third aspect in combination with two others. Alternatively, entirely new designs could incorporate time as a fourth aspect, though this would obviously further increase complexity.

Another direction for future work is to proceed from fully manual prioritization and parametrization to a semi-automatic procedure. That is, given a certain prioritization and a set of visual abstractions for each aspect, a user will be guided whilst adapting the design of the final visualization. For instance, starting by selecting a certain presentation strategy for one aspect, either terrain, data, or uncertainty, only appropriate visual encodings for the other two aspects would be suggested by the system. Likewise, inappropriate parameter settings of the selected visualization techniques could be made unavailable. For example, giving terrain the highest priority could imply that color is reserved for encoding elevation and that the size of additional objects for representing data or uncertainty is limited to a sensible maximum. Providing such guidance would reduce the complexity of designing suitable visualizations for specific scenarios.

Acknowledgments: We gratefully acknowledge additional conceptual input and contributions to the implementation by Falko Löffler.

Author Contributions: S.D. and M.R. conceived, designed, and implemented the approach; S.D., M.R., C.T. and H.S. wrote the paper; C.T. and H.S. finally approved the published work.

Conflicts of Interest: The authors declare no conflict of interest.

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