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Conveying a Sense of Scale in 3D Planetary Environments

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Conveying a Sense of Scale in 3D Planetary Environments

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at the TU Wien

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Vienna, 5th May, 2019

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Erklärung zur Verfassung der Arbeit

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Kurzfassung

3D-Visualisierungen des Mars ermöglichen die detaillierte Erkundung seiner Oberfläche und spielen eine wichtige Rolle in der Planetenforschung, der Missionsplanung und der Kommunikation wissenschaftlicher Erkenntnisse. Aufgrund der ungewohnten Umgebung, die in solchen Visualisierungen dargestellt wird, ist die Vermittlung von Größe unterschiedlicher Art erforderlich. In dieser Arbeit charakterisieren wir den Problemraum der Größenvermittlung in 3D-Visualisierungen der Marsoberfläche, die auf einen 2D-Bildschirm projiziert werden, und entwerfen Repräsentationen, die den Anforderungen bestimmter Anwendungsfälle entsprechen. Wir diskutieren Herausforderungen, die sich aus verschiedenen Größentypen, Größenordnungen, Anwendungsfällen, und der unterschiedlichen Expertise der Nutzerinnen und Nutzer ergeben. Die entworfenen Größenrepräsentationen umfassen Maßstabsleisten, Maßstabsboxen, Objektvergleich, Schichtdicken, Konturlinien, vertikale Überhöhung, Distanzschattierung und Landeellipsen. Wir erhielten informelles Feedback von einem Planetenwissenschaftler für jede unserer Darstellungen und führten ein Experiment zum Objektvergleich mit 20 Personen ohne Expertenwissen durch. Die Resultate deuten darauf hin, dass unsere Repräsentationen in der Lage sind, Größe in 3D-Visualisierungen des Mars effektiv zu vermitteln.

Abstract

3D visualizations of Mars enable scientists to explore the Martian surface in great detail and play an essential role in planetary science, mission planning, and the communication of scientific findings. Due to the unfamiliar environment depicted in these visualizations, conveying a sense of scale is necessary. In this thesis, we characterize the problem space of conveying scale in 3D visualizations of Mars projected onto a 2D screen and design representations that satisfy the requirements of specific use cases. We discuss challenges posed by different types of scale, magnitudes of scale, use cases, and levels of expertise. The designed representations include scale-bars, scale-boxes, known-object comparison, true-layer-thickness, contour-lines, vertical exaggeration, distance shading, and landing ellipses. We received informal feedback for each representation from a planetary scientist and conducted an experiment for known-object comparison with 20 non-experts. The feedback suggests that our representations are capable of conveying a sense of scale in 3D visualizations of Mars for their specific use cases.

Contents

CHAPTER 1

Introduction

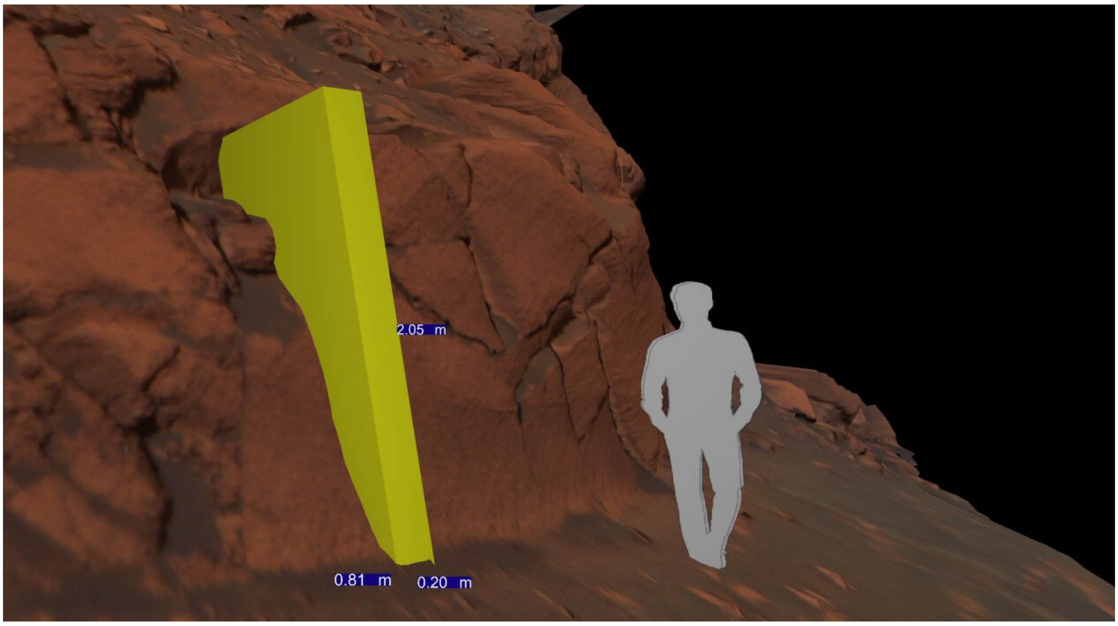

Figure 1.1: 3D visualization of a Martian outcrop with two representations to convey scale (scale-box and silhouette of a person).

A large number of missions to Mars have been launched in the last decades studying its geology, climate, and potential for human exploration [Nas19] and searching for evidence whether the planet ever supported habitable environments at some point in its history. Orbiters and rovers collect detailed image data, which is processed to compute 3D reconstructions of the Martian surface. These reconstructions are the basis for 3D visualizations that serve scientific use cases and are essential for planetary scientists, mission planning as well as communication. Specialized tools are necessary to facilitate the quantitative analysis of the Martian surface [BGT+18].

Outcrops are visible exposures of bedrock or ancient deposits on the surface of a planet [Jac97]. They are a primary source for understanding geological principles [RvLH+13] and offer a glimpse into the history of Mars. High quality reconstructions enable the geological analysis of Martian outcrops at a similar level of detail as in field studies on Earth [HGE+11]. 3D outcrop visualizations offer a number of advantages over 2D representations, which can not fully portray the 3D nature of geological features [RvLH+13]. Measurements in 2D representations can be impaired by varying pixel dimensions throughout the image, while 3D reconstructions allow scientists to take accurate measurements directly on the surface. In 3D visualizations, the scientists can roam freely, allowing them to observe the scene from different viewpoints and angles. This leads to a better understanding of spatial relationships between geological features [BGT+18].

1.1 Problem Statement

The Martian surface is an unfamiliar environment. Studies have shown that familiarity greatly influences human size judgements [Pre92]. Familiar objects establish a scale context in everyday terrestrial scenes, allowing observers to estimate the size and distance of unfamiliar objects. Geologists often place hammers and other known items in the image frame as a scale reference as it can be seen in Figure 1.2. The lack of a scale context in Martian scenes potentially confuses viewers and may lead to wrong judgements of scale. Therefore, conveying scale in 3D visualizations of Mars is necessary to aid scientists in fully characterizing the geology of paleoenvironments [BGT+18], support mission planning, and facilitate the communication of scientific findings within the scientific community and to the public. It is important to consider various aspects of scale, such as type, magnitude as well as the requirements of different user groups and use cases. Figure 1.1 shows two of our scale representations, a scale-box for assessing the 3D extent of objects and the silhouette of a person as an intuitive scale-clue.

In the workshop on 3D visualization for planetary surface science held at 'VRVis' on April 6/7 2018 [Wor19], the need for conveying scale in Martian scenes was apparent. Whenever images of Martian surface features were shown, immediate questions about their scale were asked from the audience. In this thesis we discuss aspects of conveying scale in 3D visualizations of Mars projected onto a 2D screen. We characterize the problem space and design eight scale representations for a number of use cases and user groups, based on feedback gathered through discussions with domain experts on several occasions. Some of our designs may be generalizable to other types of visualizations, which would benefit from conveying scale, however, this is not in the scope of this thesis.


Figure 1.2: Geologists place familiar objects in the image frame as scale reference [HGS+11].

1.2 Current Challenges

The unfamiliar environment of Mars as well as the diversity of user groups and use cases pose the greatest challenges to effectively convey scale. Each scale representation has to balance intuitivity against precision. Accurate measurements provide detailed information for experts but can be overwhelming for non-experts. On the other hand, intuitive representations can quickly establish a scale context but are typically not precise.

Various types of scale such as distance, length, height, area, or volume are perceived in different ways [WGK10] and require specifically designed representations. Features with a scale magnitude ranging from 10^{-3} m to 10^{6} m are observed in 3D planetary visualizations and can be viewed at various zoom levels. Some of our methods cover the entire range of magnitudes, while other techniques only work in a specific interval. We also present methods to establish dynamic scale contexts for seamless zooming that continuously adapt to the given zoom level.

Additional challenges arise through the nature of image data used as input for the reconstruction algorithms. The reconstructions consist of ordered point clouds with fine details solely provided by textures containing the color, lighting, and shadows during exposure. Texture quality plays an important role in scale perception [Pel18]. Rover image data is very detailed in close proximity to the camera but loses accuracy farther away, which can lead to a varying scale perception within a scene.

1.3 Goal

We discuss a set of representations to alleviate the aforementioned challenges. Our tools are designed to be used by planetary scientists, mission planning as well as for the communication of findings in scientific publications and to the public. They are capable of conveying scale for a range of use cases and users with different levels of expertise. We designed each tool to be integrated into PRo3D, an interactive 3D visualization platform for planetary scientists [Pro19].

1.4 Contributions

- Our main contribution is the characterization of a problem space derived from discussions with domain experts and the design of representations to establish scale contexts in various scenarios.
- Our secondary contribution is the prototypical implementation of a tool suite to convey scale in 3D visualizations of Mars.
- Our tertiary contribution is a pilot experiment of known-object comparison in 3D Martian scenes.

CHAPTER 2

Related Work

In this section we examine related work from different domains. Scale and its representation is discussed in the visualization and computer graphics domains, while scale perception is discussed in publications from psychology. Furthermore, we present existing software applications that offer specific tools to convey scale.

2.1 Visualization and Computer Graphics

Glueck et al. [GCA+09] propose multiscale reference grids and position pegs to convey the scale and position of objects in 3D scenes. Position pegs extend the grid to objects located above or below the grid plane. Their result solves several depth cue problems and is independent of the viewing projection.

Plumlee et al. [PW03] introduce methods for frame of reference interactions. The reference frame may be lost by zooming across orders of scale magnitude, so they suggest to place vertical and horizontal scales in the center of the frame. They also offer multiple zoomport proxies to link different reference frames.

Pelosi [Pel18] discusses 3D visualizations in architecture. He notes that textures, physics, lighting, and shadows can impact the spatial cognition within a virtual 3D environment. First-person views increase the immersion of the viewer, which can lead to a better spatial understanding. Complicated navigation on the other hand, can have negative effects on conveying scale and spatial relationships between objects.

Bladin et al. [BAB+18] discuss communicating planetary research to the public and propose methods to visualize celestial bodies in order to make scientific data understandable to non-experts.

2.2 Psychology

Scale perception is the topic of several publications in psychology. Predebon [Pre92] [Pre79a] [Pre79b] evaluates the effects of familiarity on absolute and relative judgments of size and distance under various viewing conditions.

Wagner [Wag12] discusses size constancy. He exposes factors that affect size perception, including age, cue conditions, and instructions. Furthermore, he provides a mathematical model for size constancy based on the visual angle.

2.3 Software Applications

A number of software solutions provide tools to convey scale. PRo3D [Pro19] allows planetary scientists to work with high-resolution 3D reconstructions from Mars and offers tools for precise geological measurements. Petrel [Pet19] is a software platform for geoscientists working in the oil and mining industries. It is equipped with a comprehensive set of scale representations, including scale-bars, scale-boxes, and contour-lines, as well as precise measuring tools. Geologists use software products such as ArcGIS [Arc19a], VRGS [VRG19], and Virtual Outcrop [Vir19] extensively. All of them offer basic tools to convey scale, such as scale-bars and contour-lines. CloudCompare [Clo19] allows users to process point clouds and to draw them inside a scale-box. It provides scale-bars and a form of distance shading.

Some software products targeted at non-experts are also equipped with tools to convey scale. Google Earth [Goo19] allows users to measure surface features of Earth, Mars, and the Moon. It contains tools to measure distances and areas as well as a horizontal scale-bar that dynamically adjusts its size depending on the zoom-level. Finally, SketchUp [Ske19] is a 3D modeling application that displays the model of a person to establish a scale reference.

CHAPTER 3

Problem Space

Conveying scale in 3D visualizations of Mars supports scientists in their work and is essential for the meaningful communication of scientific findings. It can be achieved by establishing a scale context, a reference frame, which allows viewers to judge the sizes of objects. In terrestrial scenes, a scale context is often established by the presence of familiar objects. Sizes of unfamiliar objects are judged by comparing them to these known objects [Pre92]. Estimating the scale of surface features on Mars is challenging even for experts, because the unfamiliar environment prevents the creation of a scale context, which can lead to confusion and misinterpretation. Figure 3.1 shows a photograph (left) and a rendering (right) of the Martian surface. Scale estimation is difficult in both images without support.

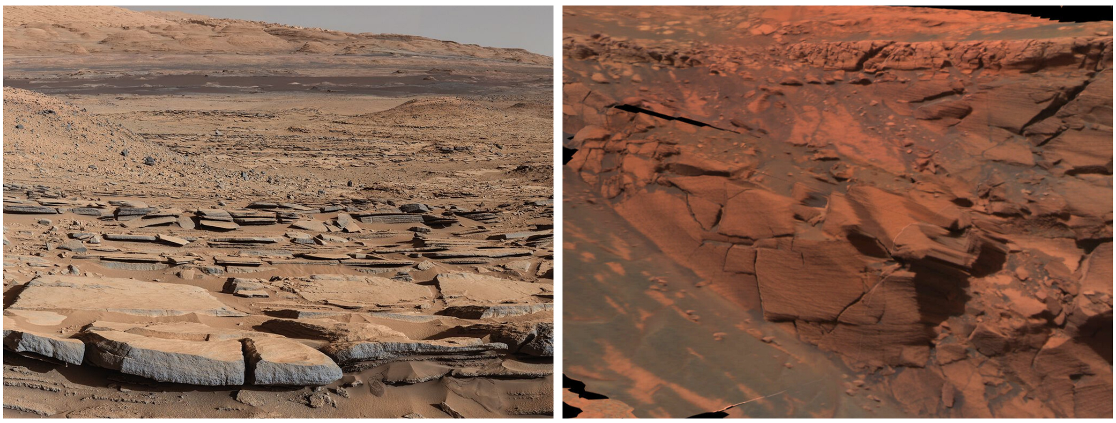

Figure 3.1: Difficult estimation of scale and distance in Martian scenes. Left: Photograph acquired by a Mars rover [GGM+15]. Right: 3D visualization of a Martian outcrop.

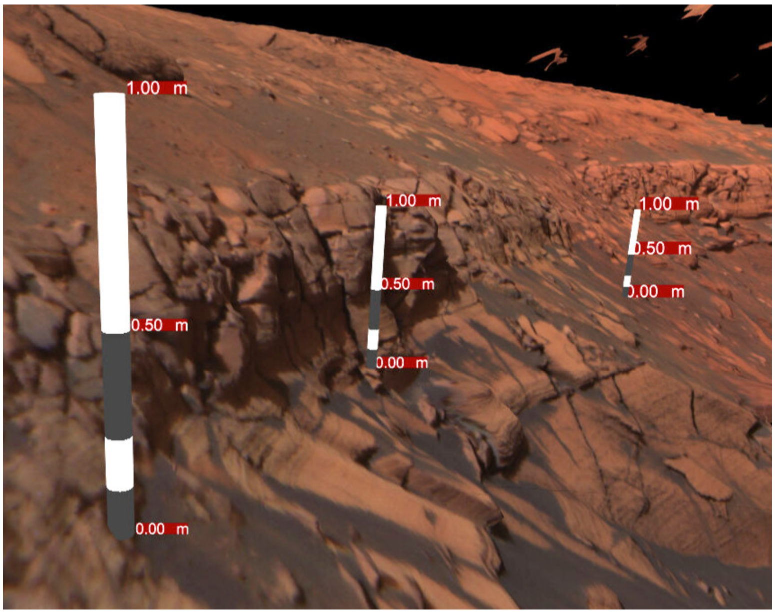

Figure 3.2: Effects of perspective projection. Scale-bars can make perspective distortion explicit.

3.1 Aspects of Type and Magnitude of Scale

Scale includes a number of aspects such as length, width, height, distance, area, and volume. According to Ward et al. [WGK10], these types of scale are perceived in different ways, therefore it is necessary to treat each type individually. A representation conveying height is, for example usually not suitable to convey the size of an area. In addition, certain characteristics of Martian features, such as steepness or sedimentary layer thickness, require specific representations as well.

Visualizations of Mars are viewed at various zoom levels, with surface features ranging from 10^{-3} m to over 10^{6} m in size, therefore representations for different magnitudes of scale are required. Some representations must be specifically designed for a distinct magnitude, while others need to adapt dynamically to changes in magnitude to provide a scale context for different zoom-levels. Plumlee et al. [PW03] show that representations at a human scale are most intuitive, because they can be related to scale experiences in real life. Differences in magnitude of scale have to be considered. Small indentations may appear flat when observing a large area, which could potentially lead to overlooking important features.

Texture quality has an impact on spatial cognition and scale perception [Pel18] [Leh02]. In Martian reconstructions, texture quality decreases with increasing distance from the rover's camera. This can lead to a varying scale perception within a scene.

Martian 3D visualizations lack many depth cues due to their rendering characteristics.

Most of the surface detail is provided by textures and the scenes are rendered with perspective projection, which causes perspective distortion as can be seen in Figure 3.2. Parallel projections are not appropriate because they explicitly remove all depth cues [GCA+09]. Static visualizations can not fully convey spatial relationships within a scene. In interactive visualizations, spatial relationships and some depth cues can be restored by viewing the scene from different angles and viewpoints.

Navigation in 3D typically requires training and can affect scale perception. According to Pelosi [Pel18], first-person views are most effective for conveying scale. Fast zooming on the other hand, can cause a loss of the scale context. Also, camera orientation and transition speed affect scale perception. Slow transitions, just as looking up at a feature, suggest a larger scale.

Representations conveying scale have to balance accuracy against intuitiveness. Generally, precise representations are informative for experts, yet difficult to interpret for non-experts, while intuitive representations quickly establish a scale context but can not provide accurate measurements. Composition of representations could lead to a better spatial understanding of a scene as multiple types of scale at various levels of accuracy could be conveyed at the same time.

3.2 User Groups and Use Cases

A number of user groups with different requirements and levels of expertise benefit from 3D visualizations of Mars in a variety of scenarios. *Planetary scientists* have expert knowledge and want to take accurate and repeatable measurements for features across all magnitudes of scale [BGT+18]. In their work, they require representations conveying height, length, distance, area, volume, thickness, and steepness, because they examine a broad spectrum of diverse features. Even though they rely on accurate measurements, they still benefit from intuitive representations to gain a quick overview of new datasets. *Mission planning* is concerned with finding feasible *landing sites* on the Martian surface, as well as investigating probable *rover traverses*, and has to expose hazards to ensure the safety of the spacecraft. Another important use case is the *communication of scientific findings*, both within the scientific community and to the public. Visualizations for communication purposes are often limited to static renderings without interaction. Conveying scale in these images is important to allow scientists who are unfamiliar with a particular dataset to follow a discussion. *Communication to the public* is challenging, because non-experts could struggle to grasp the context of the raw data [BAB+18]. Expert knowledge can not be assumed, necessitating intuitive representations to convey scale effectively.

CHAPTER 4

Scale Representations

We designed eight representations to convey scale, including scale-bars, scale-boxes, known-object comparison, true-layer-thickness, contour-lines, vertical exaggeration, distance shading, and landing ellipses. In this section we present the design decisions of our eight scale representations in detail. For each representation we also discuss use cases, intended user groups, and potential limitations.

4.1 Scale-Bars

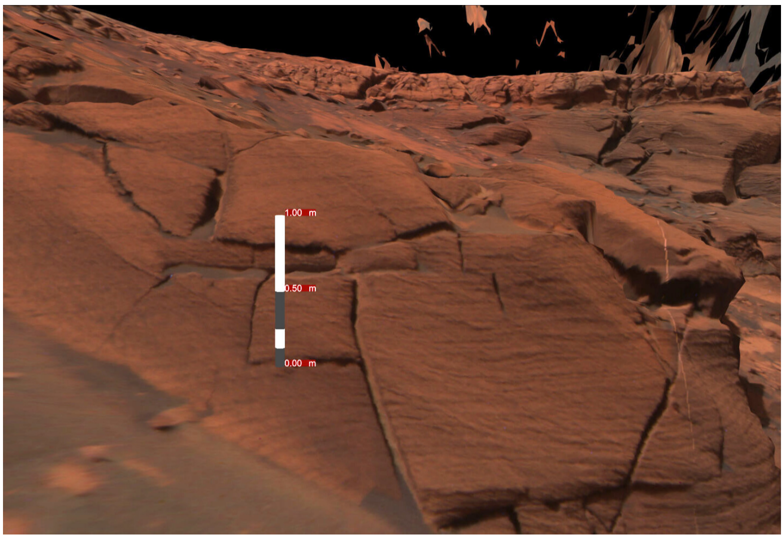

Figure 4.1: Vertical scale-bar.

Scale-bars are a standard tool in geological visualizations. They are simple to interpret, versatile, and work at every magnitude of scale. Vertical scale-bars convey height.

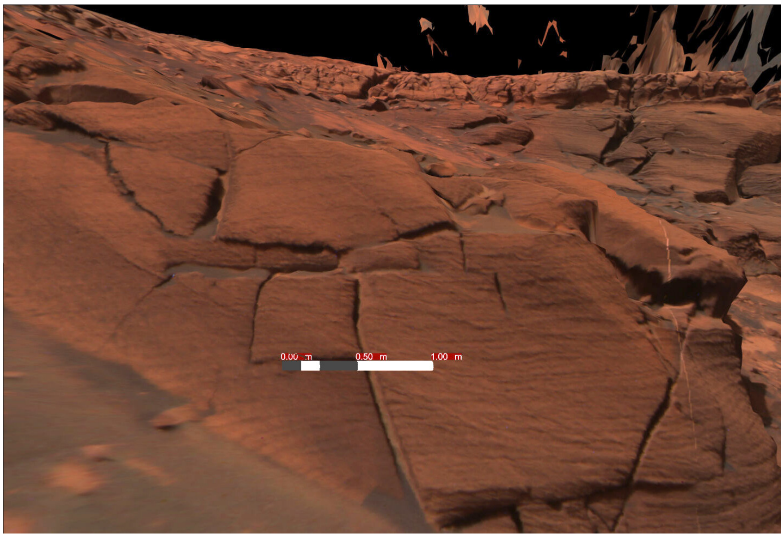

Figure 4.2: Horizontal scale-bar.

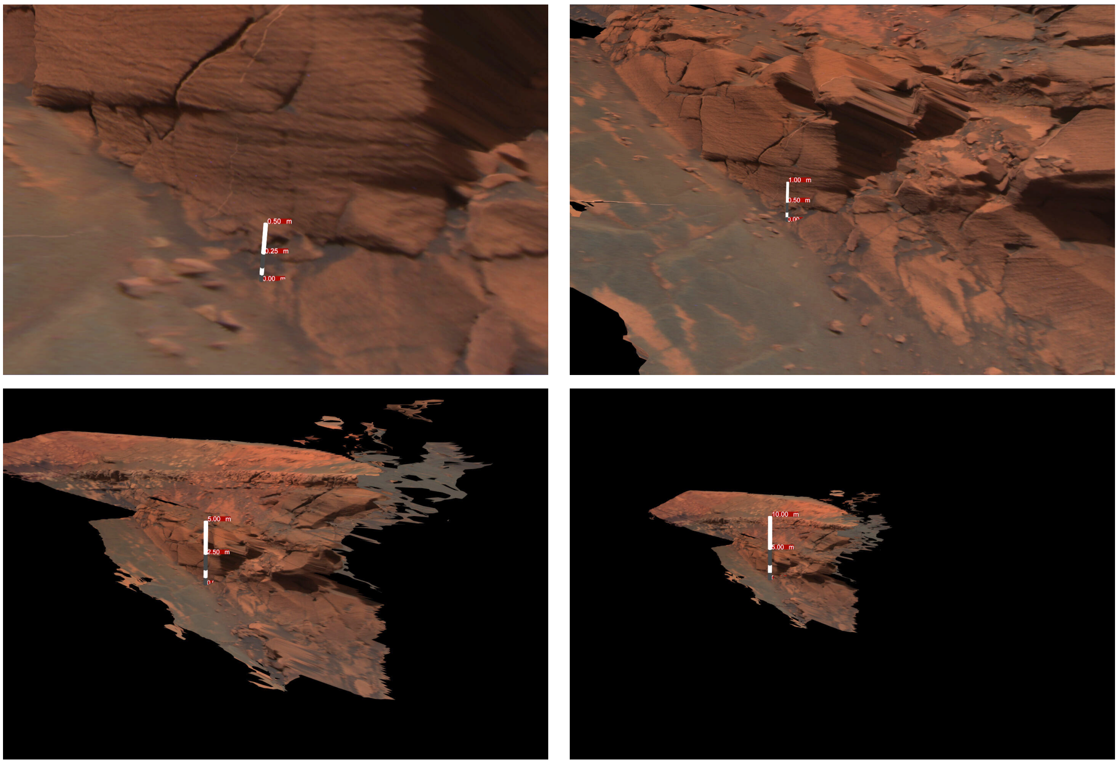

Figure 4.3: Dynamic scale-bars: the world space size of the scale-bar is dynamically adjusted depending on the distance while its size in screen space remains constant.

We align them with the sky-vector at their location to assert a vertical orientation. Horizontal scale-bars convey width or length. We align them with the view-plane to overcome the effects of perspective distortion. Vertical and horizontal scale-bars can be seen in Figure 4.1 and Figure 4.2.

Our scale-bars are cylindrical, so that their shape remains constant from different viewing angles. Stripes at $\frac{1}{8}$, $\frac{1}{4}$, and $\frac{1}{2}$ the length of the scale-bar help with size estimations of objects smaller than the scale-bar itself. Labels in the middle and at the top of the scale-bar provide clear feedback about the bar's length. The labels always face the camera for readability.

Scale-bars can be placed and moved by double-clicking a point on the surface. Our scale-bars always touch the surface at the selected location to avoid floating issues, since the visualization is rendered without shadowing. Users can grasp the severity of perspective distortion by placing multiple scale-bars of identical length at various distances.

The length of a scale-bar is set by the user in a GUI. Fixed length scale-bars are, however, not ideal when zooming, which causes the scale context to change. Dynamic length scale-bars adjust their world-space sizes depending on their distance to the viewpoint, so that their screen-space sizes remain constant. We propose dynamic length scale-bars that adjust their sizes in discrete steps to provide the users with feedback while zooming, as can be seen in Figure 4.3. The steps ensure that scale context changes are not overlooked and are computed as follows:

$$\begin{aligned}
[h!]s &= \frac{d}{f} \\
l &= 10^{\lfloor \log_{10} s \rfloor} \\
length &= l \cdot \lfloor \frac{s}{l} \rfloor
\end{aligned}$$

where, d is the distance between the viewpoint and the scale-bar, and f is a scale factor ($f = 5$ in our implementation).

4.2 Scale-Boxes

Scale-boxes represent the 3D extent of objects and convey area or volume at every magnitude of scale with an accuracy ranging from rough estimations to precise measurements. They are intended to be used by experts, but can also be meaningful to non-experts.

Scale-boxes are placed next to or around objects of interest. Our scale-boxes offer four draw modes including solid, transparent, wirebox, and front-face-culling, as can be seen in Figure 4.4. Solid drawing suggests, that the box is placed next to the object of interest, while transparent, wirebox, and front-face-culling drawing indicate that the object is enclosed by the box. Labels display the dimensions of the box in meters. Their positions

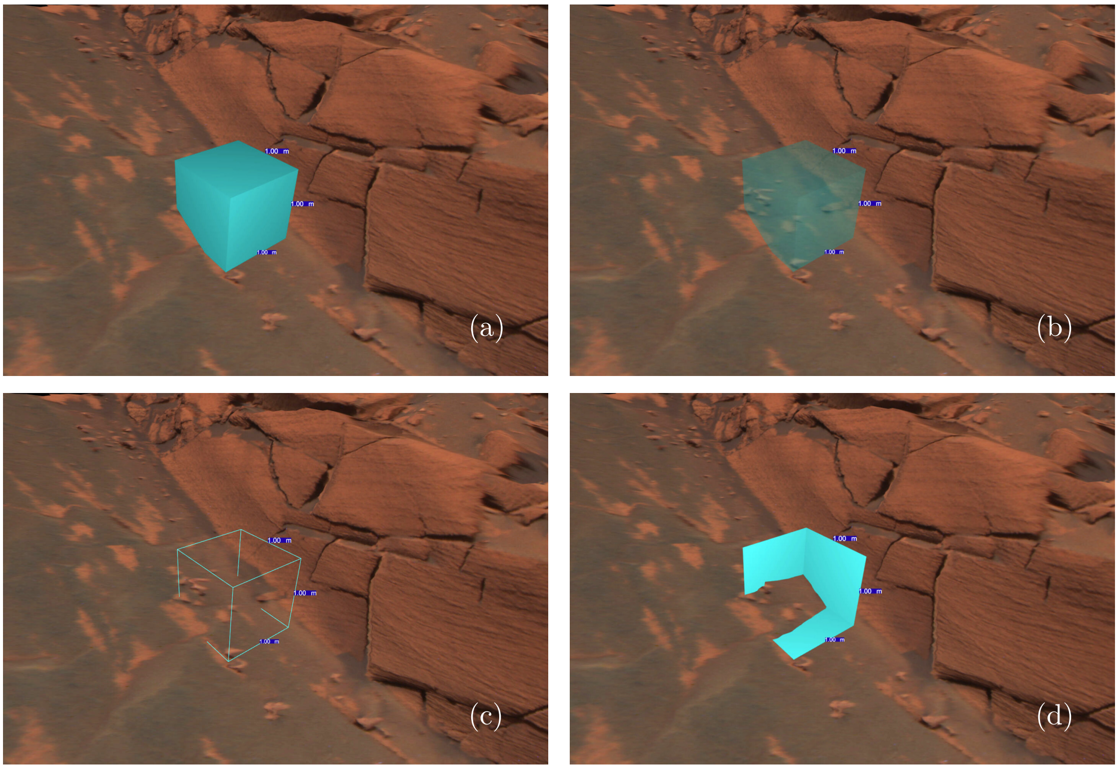

Figure 4.4: Four draw modes for scale-boxes: (a) solid, (b) transparent, (c) wirebox, (d) frontface culling.

are determined by computing the box's silhouette and finding the center of the outer edges.

Users place new scale-boxes with a default side-length of one meter by double-clicking a surface point in the scene. Boxes are translated and rotated with a 3D handle. The dimensions are adjusted in a GUI, causing a scaling around the center of the box. Box dimensions can also be adjusted by translating individual box faces along their normal vector, as can be seen in Figure 4.5. However, the precise enclosure of features can be cumbersome. We accelerate this task by employing principal component analysis (PCA) to compute a best-fitting box for a set of surface points picked by the users. A preview box is rendered to support the users in the selection of meaningful points, as can be seen in Figure 4.6. Geologists often enclose entire outcrops with a bounding scale-box. We pre-compute such a box for each outcrop and draw it in wirebox mode, as can be seen in Figure 4.7 (c).

Scale-boxes have a few limitations: Floating is problematic because the scenes are rendered without shadowing and the boxes can be transformed without constraints. Precise placement and fitting of boxes is time consuming, which is why we offer saving and loading of scale-box scenes. Finally, the size of a scale-box can be difficult to grasp.

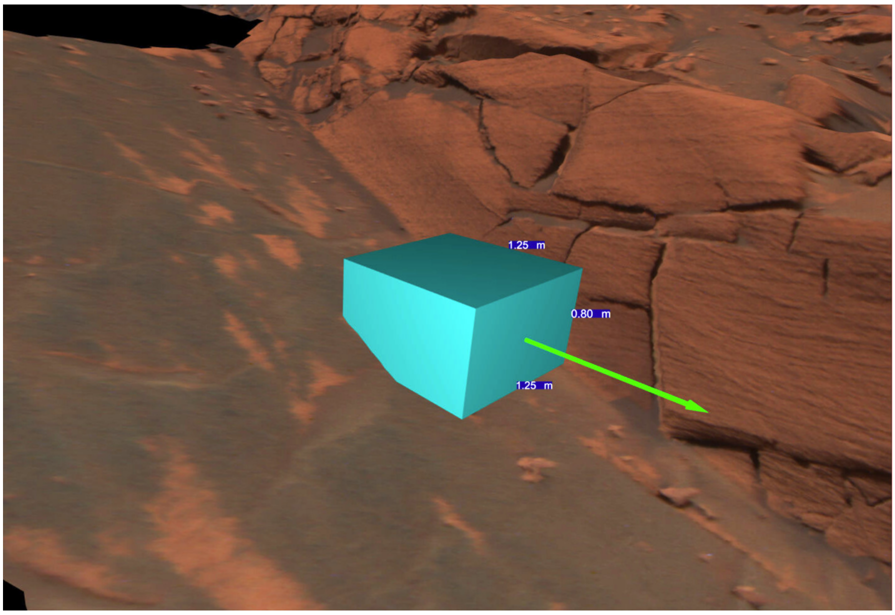

Figure 4.5: Scale-box size can be adjusted by translating faces along their normal vector.

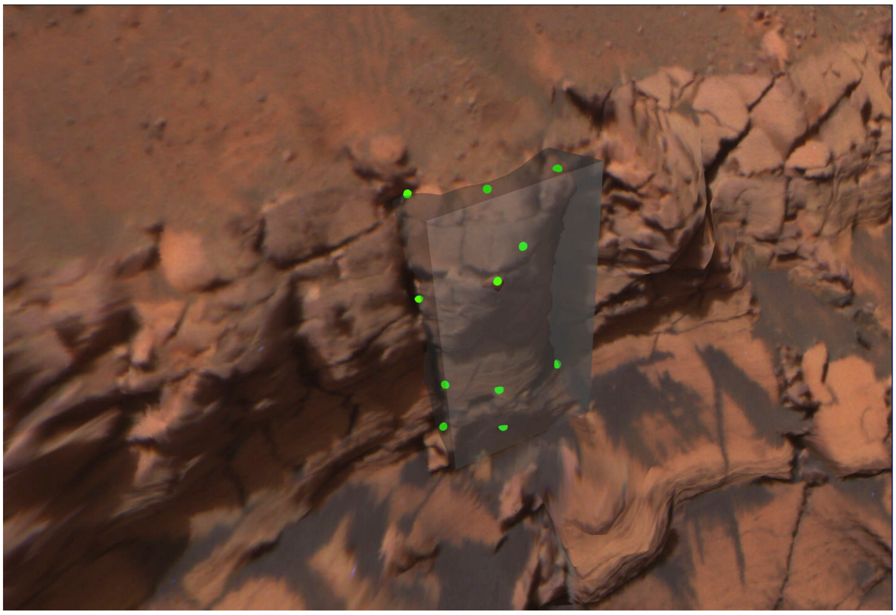

Figure 4.6: Fitting a scale-box to a surface feature with principal component analysis. Selected points are shown as green spheres and a transparent preview box is rendered to support users in selecting points.

This problem could be addressed by 3D printing boxes, so that their scale is experienced in reality, although, boxes must be small enough to be printed in the first place.

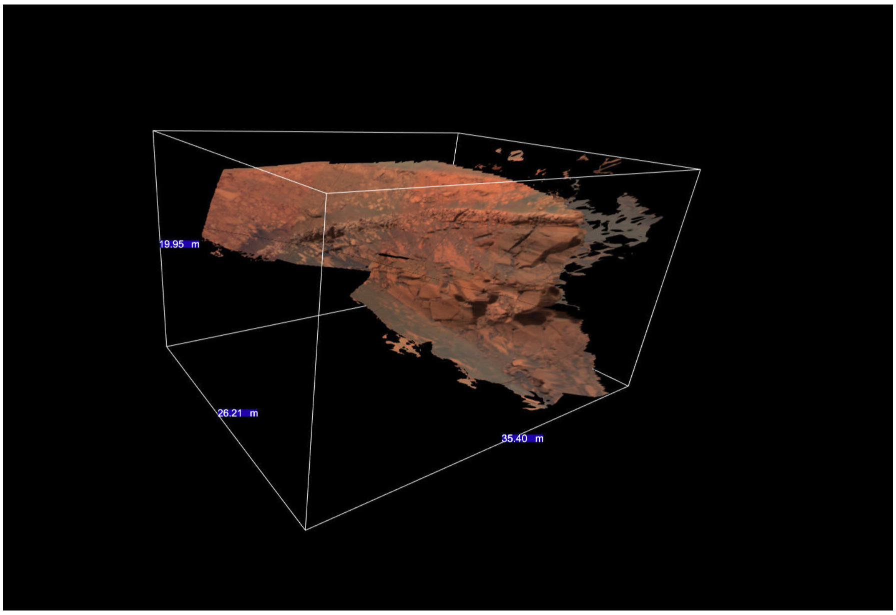

Figure 4.7: A bounding scale-box enclosing an entire outcrop.

4.3 Known-Object Comparison

Known-object comparison creates a scale context by placing familiar objects in the scene. The size of unfamiliar objects is estimated by comparing them to these familiar objects [Pre92]. Geologists use this technique in their fieldwork and often place known objects, such as hammers, in the frame of outcrop images to perform measurements [HGS+11]. Known-object comparison potentially works at every magnitude of scale given that a reasonable known object is available, however, human size judgement performs best with everyday objects at a human scale [PW03]. Known objects have to be common, so that a large number of people is familiar with their sizes. The method is effective for experts and non-experts alike. A sense of scale is conveyed in a natural way, allowing the viewers to estimate the size of unfamiliar objects with confidence, however, the method is typically not suitable for precise measurement tasks.

Several types of scale are conveyed depending on the selected known object. A person for instance conveys height, while a soccer field conveys area. We offer six known object models in our application, including a coin, a hammer, a chair, the silhouette of an average-sized person, a citybus, and a soccer field. The provided models can be seen in Figure 4.8. Users can place multiple known objects in the scene. A 3D handle lets them translate and rotate the objects.

Floating problems can arise for the same reasons as with scale-boxes. Position pegs could alleviate these problems [GCA+09]. The main limitations of known-object comparison are due to ambiguous models. Their scales may vary largely, preventing confident estimations by the viewers. We chose objects that do not vary too much in size for our

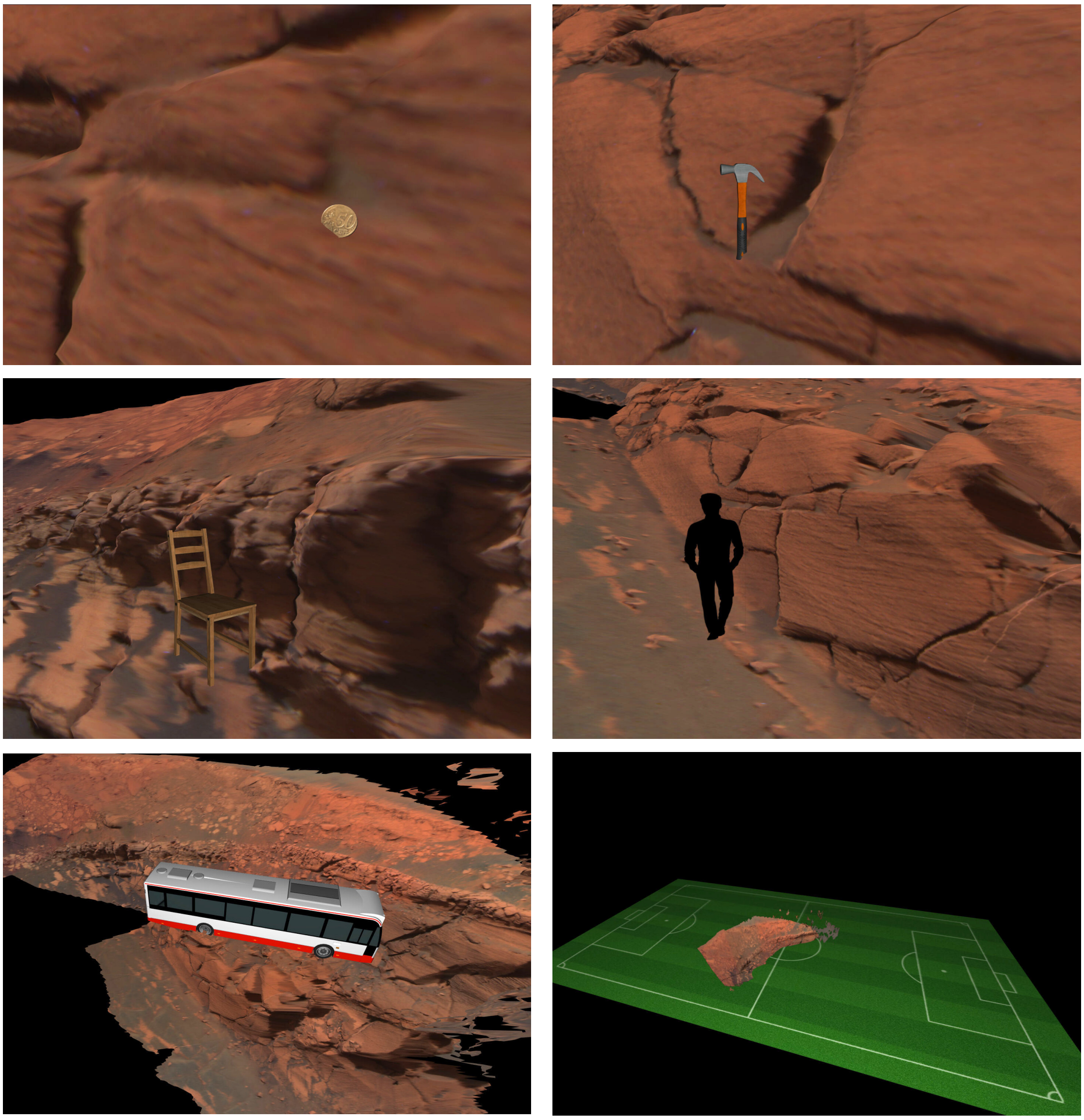

Figure 4.8: Known-object comparison models: coin (diameter = 25 mm), hammer (length = 35 cm), chair (height = 1 m), person silhouette (height = 1.75 m), citybus (length = 12 m), soccer field (length = 100 m).

design. Furthermore, objects that are not familiar enough can not be used for comparison. Also, the sizes of large objects are difficult to grasp. A large area could be conveyed by drawing the outlines of a country onto the surface, however, such an approach is not included in our implementation.

4.4 True-Layer-Thickness

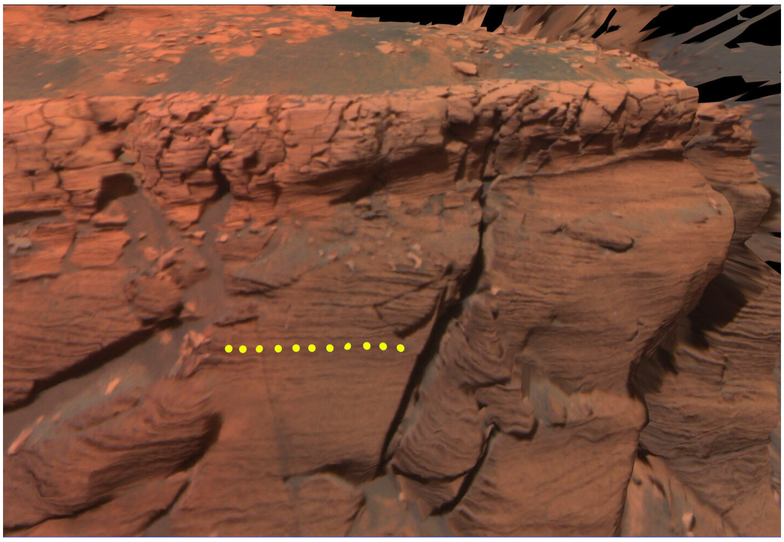

Figure 4.9: Picking points on a sedimentary line to create a true-layer-thickness stack.

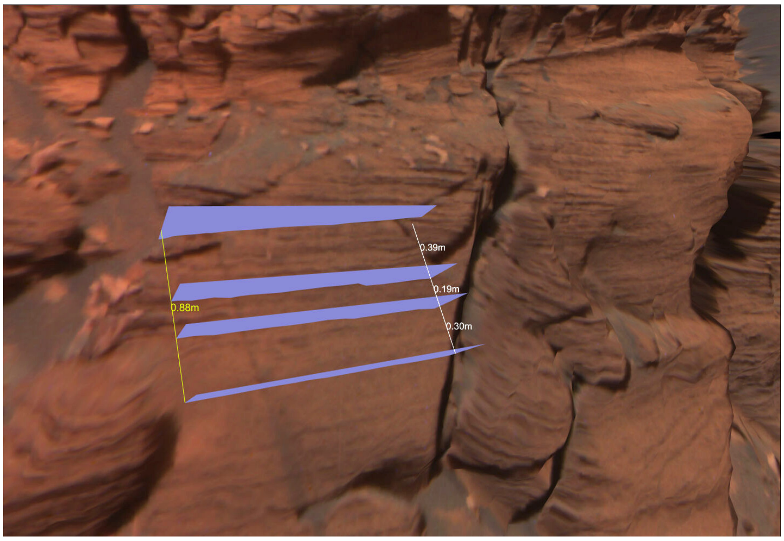

Figure 4.10: A true-layer-thickness stack. Labels on the right side of the stack display thickness values between consecutive layers. The label on the left side shows the total distance between bottom and top plane.

Characterizing the geology of sedimentary rocks on the Martian surface is a principle research target for planetary scientists [BGT+18]. Sedimentary layers typically run in parallel to each other. Their thicknesses reveal aspects about their formation in their geological past. Measuring layer thickness is therefore critical, but measuring a large number of consecutive layers is cumbersome with existing tools. Our true-layer-thickness representation was designed following discussions with planetary scientists and aims to speed up this task.

Users create a true-layer-thickness stack by picking points on a sedimentary layer, as can be seen in Figure 4.9. A plane intersecting the selected layer is fitted and forms the base of the stack. Planes, that are added to the stack, have the same normal vector as the base plane. Users can translate planes along their normal vector to fit them to consecutive layers. Labels on the side of the stack display thickness values in meters between consecutive layers, as well as the total distance between top and bottom, as can be seen in Figure 4.10.

4.5 Contour-Lines

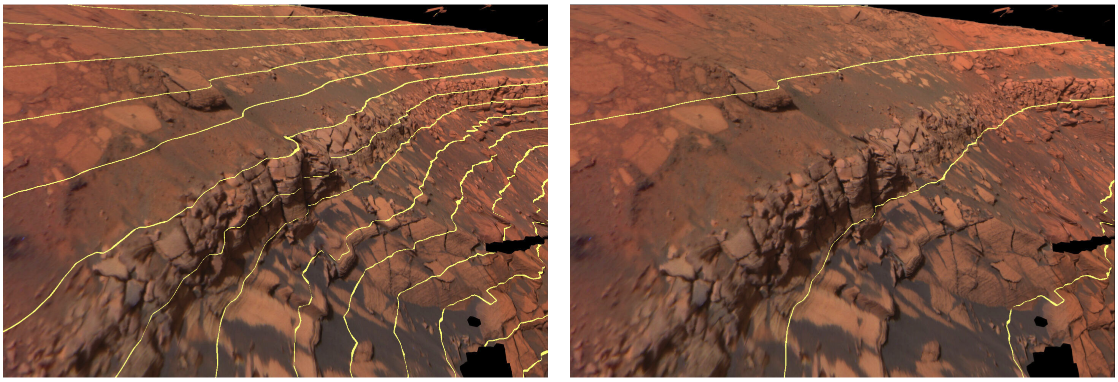

Figure 4.11: Adjustable spacing and offset for contour-lines. Left: 0.5 m spacing, right: 2 m spacing.

Contour-lines reveal the spatial layout of a landscape. They are effective for conveying vertical extent and steepness at all magnitudes of scale and are a standard tool for geologists. Correct interpretation requires expertise, however, they can be meaningful to non-experts as well. Contour-lines typically represent absolute elevation. However, our lines show relative elevation instead and users can adjust the offset and the spacing between lines. This allows them to position lines precisely on horizontal sedimentary layers and provides them with an understanding of layer thickness and orientation. Relative-contour lines with varying spacing can be seen in Figure 4.11.

4.6 Vertical Exaggeration

Vertical exaggeration emphasizes vertical changes of a terrain [Arc19b] by stretching it in the direction of the sky vector. It is effective at all magnitudes of scale, while the method is commonly used to accentuate mountain ranges in visualizations, where the landscape would appear flat. Geologists employ vertical exaggeration to pronounce thin

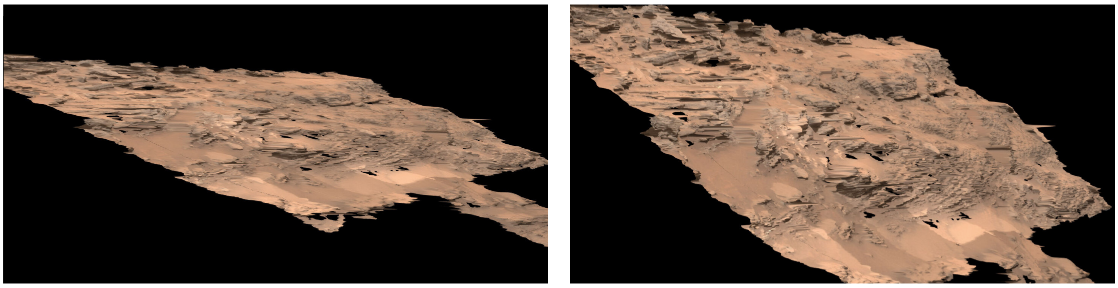

Figure 4.12: Scene without (left) and with two times vertical exaggeration (right).

sedimentary layers for better visibility. Landing site selection and the search for rover traverses also benefit from vertical exaggeration, because it can expose potential hazards. Our implementation provides users with a GUI to adjust the exaggeration factor. The terrain is stretched if $1 < factor$ and flattened if $0 \leq factor < 1$. Figure 4.12 shows a scene without ($factor = 1$) and with vertical exaggeration ($factor = 2$).

4.7 Distance Shading and Distance Lines

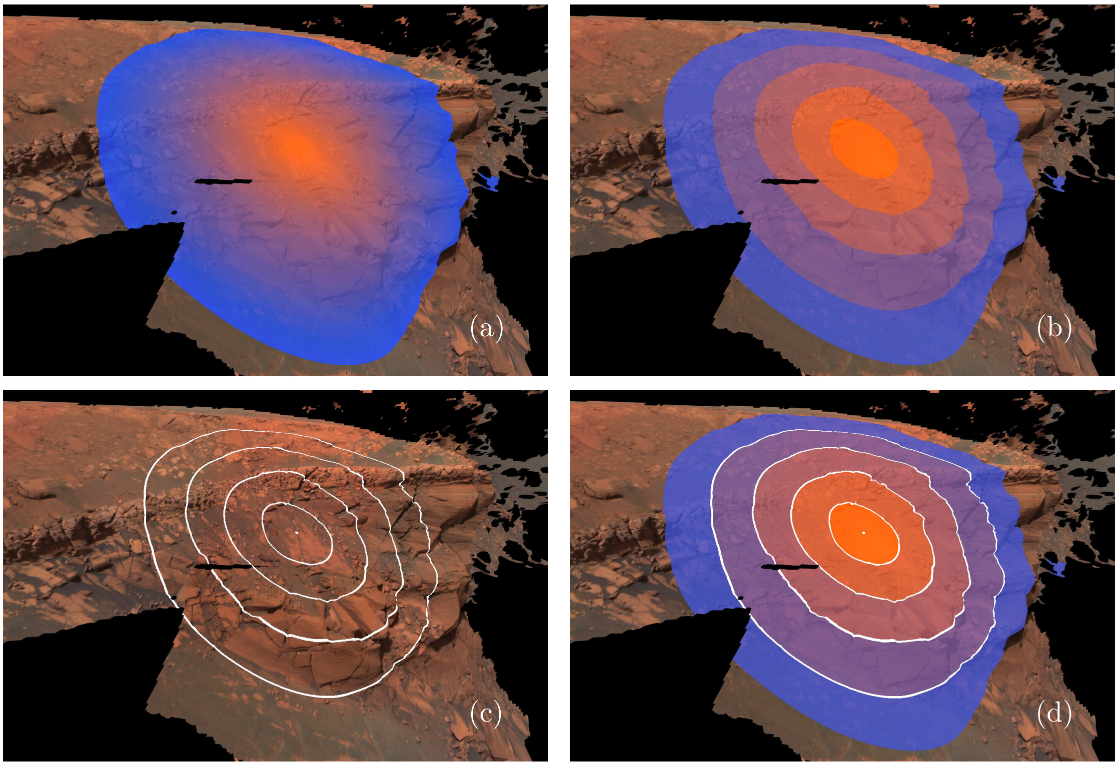

Figure 4.13: Continuous (a) and discrete distance shading (b), distance lines (c) and combined drawing of lines and shading (d).

3D visualizations of Mars lack important depth cues due to their rendering characteristics, the projection onto a 2D screen, and the unfamiliarity of the terrain. Even experts who are not familiar with a particular dataset struggle to judge distances reliably. Our representation conveys distance explicitly and is suited for all magnitudes of scale. We color the surface depending on the distance to the camera or a user-selected point within a user-selected radius. This creates circular shapes with a continuous color gradient, but we also provide shading with discrete color levels for simpler interpretation, resulting in concentric spheres. Additionally, distance lines can be rendered at discrete steps. Distance lines and distance shading can be drawn separately or in combination. The alpha value for the colored area can be adjusted, so that surface features are still distinguishable. Figure 4.13 shows the drawing options for distance shading and distance lines, including continuous and discrete shading. It is important to note that the representation is potentially misleading, because users could expect the projected distance on the surface instead of the Euclidean distance.

4.8 Landing Ellipses

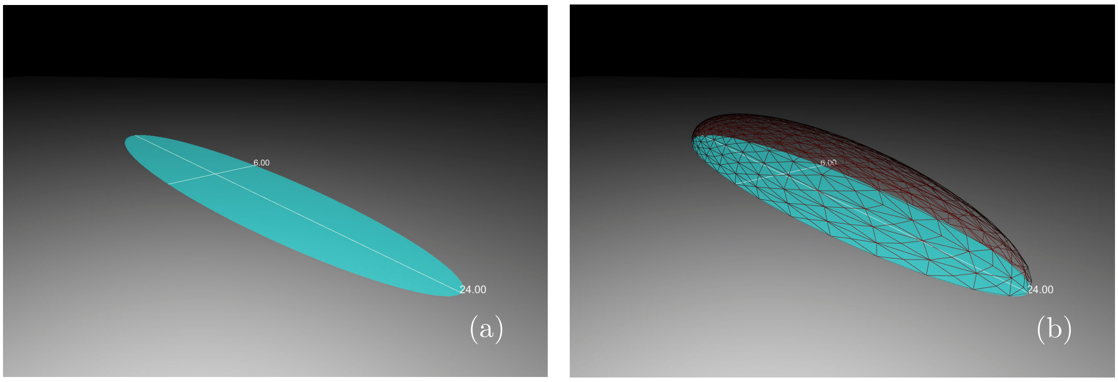

Figure 4.14: Landing ellipses are calculated by intersecting the surface with an ellipsoid (a). Labels indicate the length of the axes in meters. The ellipsoid intersecting the surface can be seen in (b).

A landing ellipse describes the area in which a spacecraft is most likely to touch down. They are rendered by intersecting the surface with an ellipsoid and coloring the enclosed area. Figure 4.14 shows a landing ellipse (a) and the ellipsoid used for intersecting the surface to calculate the ellipse (b). This approach only works for reasonably large areas where undulations of the terrain do not affect the resulting intersection shape too much. On a small patch with lots of elevation changes, the intersection would not result in an ellipse. This is the reason why landing ellipses are typically used in 2D map views.

Users can adjust the length and width of our landing ellipses in a GUI. For quick placement, users pick three points on the surface. The first axis of the ellipse is defined by the first and second point. The distance of the third point to the first axis defines the length of the second axis. Ellipses can be colored for better visibility and can be moved by selecting a new center point on the terrain. Lines and labels displaying the length of the axes in meters are drawn on top of the ellipse.

CHAPTER 5

Implementation

The implementation for this thesis is written in F# [FSh19b] and based on the Aardvark.Media framework [Aar19b]. F# is a functional-first programming language in the .Net environment of Microsoft and the implementation largely follows functional programming paradigms. This chapter gives an overview of the Aardvark.Media framework and the structure of the implemented application.

Aardvark is an open-source platform for visual computing with functionality for real-time graphics and visualizations. It offers state-of-the-art incremental rendering and is mostly written in F# [Aar19a]. Aardvark.Media provides a functional front-end and UI for the Aardvark rendering and base libraries [Aar19b]. It employs an ELM style architecture for application development.

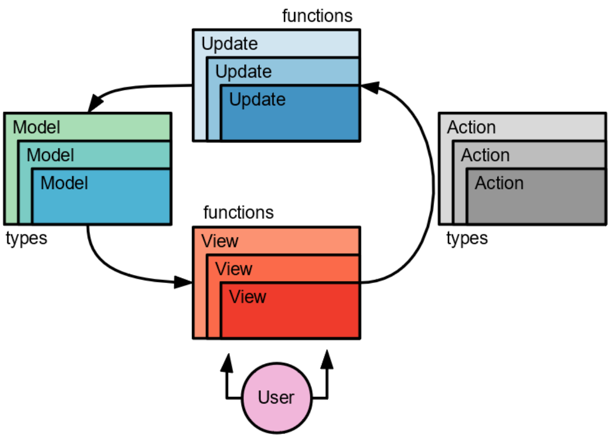

Figure 5.1: ELM architecture and composition [ELM19].

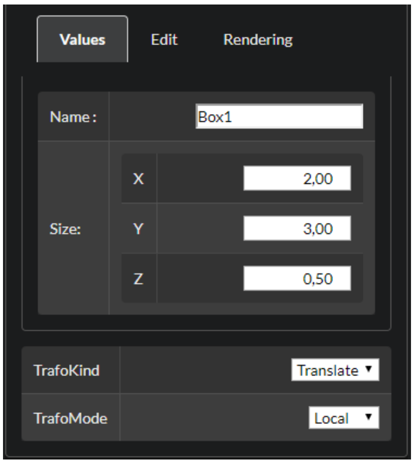

Figure 5.2: UI controls of the scale-boxes app.

ELM enforces a unidirectional dataflow to reduce complexity and consists of a view, actions, an update function, and a model. Aardvark.Media applications follow the same principle. The model stores the application state and is visualized by the view. Users interact with elements in the view and trigger actions, which are consumed by the update function to generate an updated model. Aardvark.Media apps can be composed to form larger applications that consist of model, update, view, and actions as well. Composition of smaller building blocks makes Aardvark.Media applications maintainable [ELM19] and readable. Figure 5.1 illustrates the architecture of an Aardvark.Media application composed of smaller applications. All shaders in the implementation are written using FShade [FSh19a], a library extending F# with domain specific languages for shader programming that is well integrated in the Aardvark ecosystem and supports both OpenGL and Vulkan.

The implemented application follows functional programming paradigms and is composed of individual scale-clue apps, which are themselves composed of smaller apps and primitive data types. Every app adheres to the ELM architecture, thus contains a model, actions, a view for rendering and UI controls, and an update function that consumes actions and returns updated models. The UI controls in the views are displayed using common web technologies like HTML, CSS, Javascript, and is styled with Semantic UI [sem19]. Some UI controls of the scale-boxes app can be seen in Figure 5.2.

CHAPTER 6

Feedback

We received expert feedback from Robert Barnes, a postdoc and planetary scientist at Imperial College London. In general, he affirms that our representations convey scale in geological use cases effectively.

Scale-bars are one of the most important tools for geologists, according to the expert. He notes, that our scale-bars are convenient because they offer vertical and horizontal orientations to convey height and length respectively. The simple placing of multiple scale-bars allows him to assess the spatial extent of larger areas, while our striping pattern supports size judgements of smaller features. Aligning horizontal scale-bars to the view plane lowers ambiguity caused by perspective projection. Furthermore, he states that our dynamic scale-bars are helpful when zooming.

Scale-boxes receive positive feedback for their versatility, in particular the automatic enclosing of outcrops with a bounding scale-box. According to the expert, our PCA approach to fit boxes to surface features, as well as the adjustability of box faces is useful, as it speeds up the fitting process. Furthermore, the four draw modes are practical. He prefers the simplicity of scale-bars in most situations, as adjusting scale-boxes is tedious. It is also difficult to fit a box precisely. They are, however, well suited to convey volume and 3D extent. He also mentions that it can be difficult to grasp the size of a virtual box and suggests 3D printing of boxes as a possible solution.

Known-object comparison is one of the most effective methods to convey a sense of scale, according to the expert. He notes the intuitive establishment of a scale context and appreciates the suitability of our representation to prepare screenshots for publications. However, the absolute size of the models can be ambiguous. This could be addressed by drawing a label displaying the model's true size.

Also, our true-layer-thickness representation receives positive feedback. The expert states that it significantly reduces the time to perform thickness measurements. However, our representation suffers from cluttering. It could be improved, by drawing planes just for the top and bottom layers and lines for the other layers in-between. This would reduce clutter especially for thin layers. Another useful feature would be the export of thickness values to a table.

Contour-lines are a standard tool for geologists. Our lines receive good feedback for their functionality to adjust the offset and the distance between lines. Due to this flexibility, they are capable of conveying vertical extent, steepness, and layer thickness, as well as exposing spatial relationships. According to the expert, labels displaying height values and colored lines including a color scale would improve the representation further.

Geologists use vertical exaggeration extensively. The expert gives positive feedback to the simple user interaction of our representation. He notes that a combination of vertical exaggeration with contour-lines would be useful.

Distance shading is assessed to be of limited use for geologists in most situations. It could, however, be useful for examining larger areas where perspective projection impairs depth perception. The representation may be misleading because it does not show distance projected onto the terrain.

Landing ellipses are not used by our expert and are rather a tool for mission planning. The expert mentioned that there is currently little use for such a tool as all missions in the near future already decided on their landing sites.

6.1 Known-Object Comparison Pilot Experiment

We presented two scenes (A,B) with known-object comparison to 20 test persons without expert knowledge. First, the scenes did not include known objects and test persons had to estimate the length of a red line on the surface. After that, the scenes were shown including known objects. Scene A included a hammer and scene B included a city bus. The length of a red line on the surface had to be estimated by the test persons again. Figure 6.1 shows the four test images. The red line in scene A is approximately 0.6 meters long and the red line in scene B is approximately 11 meters long. The estimations for every test image were divided by the respective line length to calculate a scale estimation factor. A factor of one means that the length was estimated correctly. Table 6.1 shows a statistical summary for the resulting scale estimation factors. The results for the scenes without known objects is plotted in Figure 6.2. The green line indicates a correct estimation ($factor = 1$). The results for the scenes including known objects is plotted in Figure 6.3. Figure 6.4 shows the results in combination. The values in Figure 6.2 and Figure 6.4 are plotted using a logarithmic scale, because estimations without known objects varied a lot.

A larger sample and more test examples would be needed to draw reliable conclusions. Also, a different experimental setting, by comparing the technique to another approach as a baseline, would give the results more weight. However, the test results indicate that known-object comparison is a powerful technique to intuitively convey a sense of scale. The scenes without known objects were confusing. Figure 6.2 shows the wide

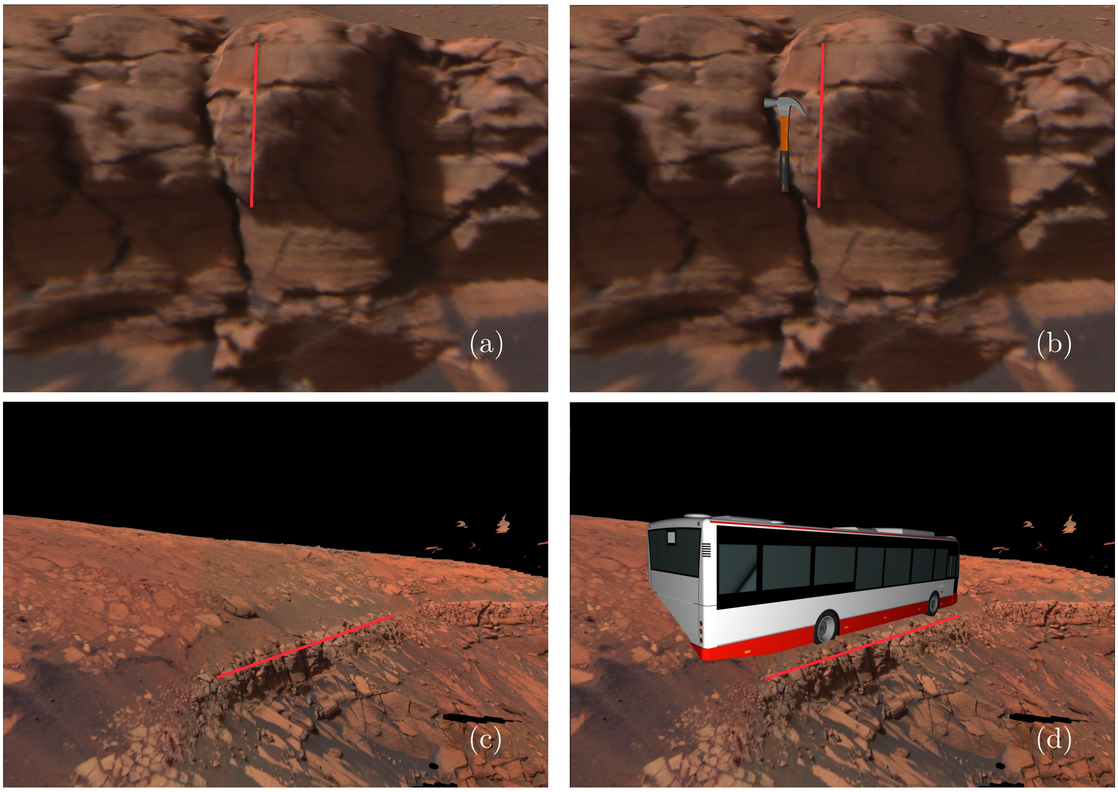

Figure 6.1: Known-object comparison test images without scale-clues (a,c) and with known objects for support (b,d).

Scene	A without	B without	A with	B with
Min.	0.1	0.1	0.5	0.64
1st Qu.	8.3	59.1	0.75	0.91
Median	33.3	454.5	0.83	1.1
Mean	119446	91395.7	0.93	1.22
3rd Qu.	58.3	4318.2	1.04	1.36
Max.	2291666.7	1575454.5	1.67	2.45

Table 6.1: Known-object comparison test results - scale estimation factors.

range of estimation factors with most of the test persons overestimating the scale in both scenes. Test persons reported that they had no confidence in their estimations when no known objects were included. Figure 6.3 shows that the range of estimation factors is much smaller with known objects in the scenes. The estimations of most test persons are very close to the real scale, with even outliers in the boxplot only overestimating scene B by a factor of around 2.5. Test persons reported that they had an immediate and natural sense of scale once known objects were included and were very confident in

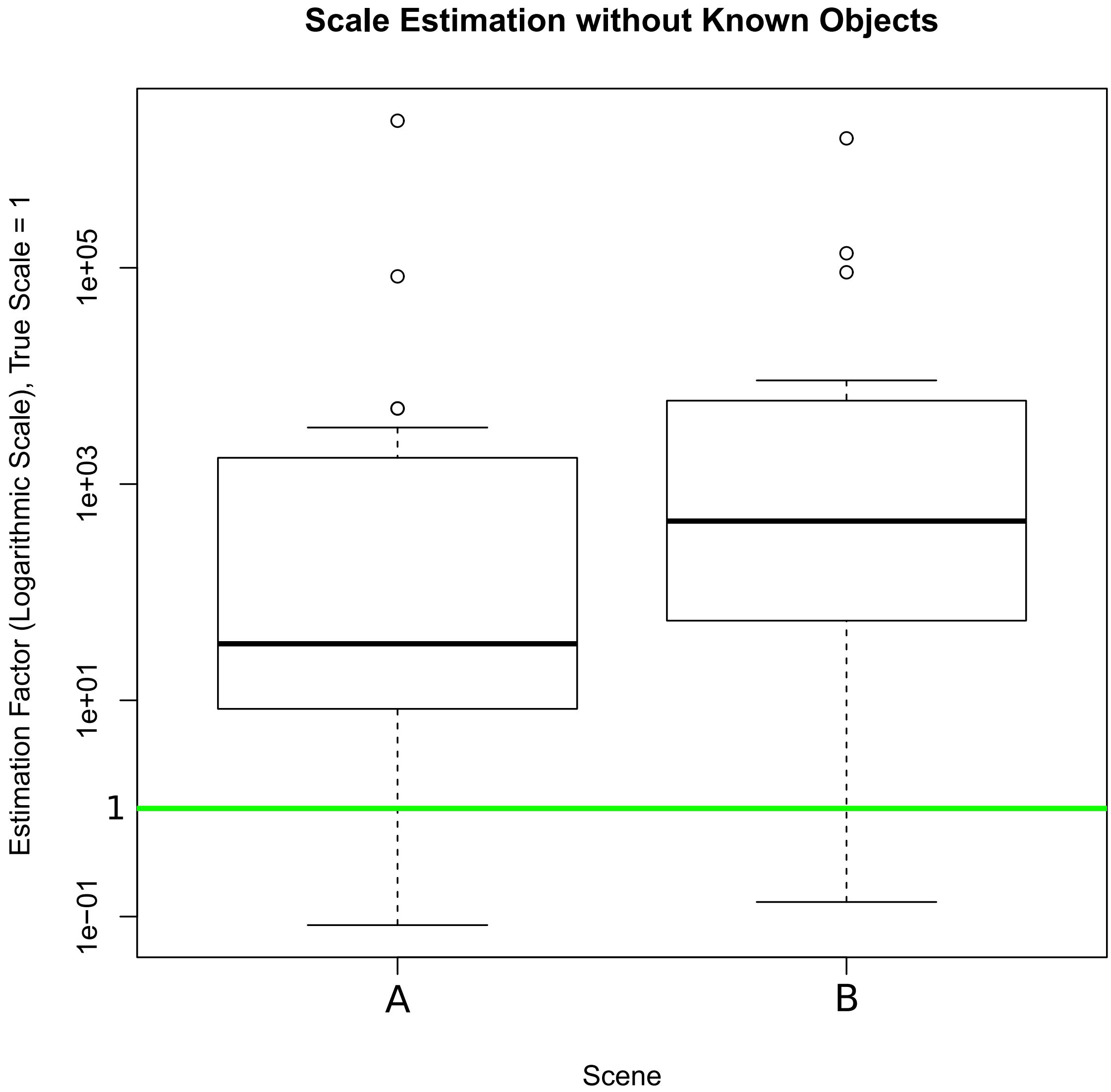

Figure 6.2: Known-object comparison test results - scenes without known objects (the green line shows a scale estimation factor of one = correct scale estimation).

their estimations, even though they did not know the exact size of the hammer or the bus. This hints that known-object comparison is capable to overcome confusion about scale, in particular for non-experts.

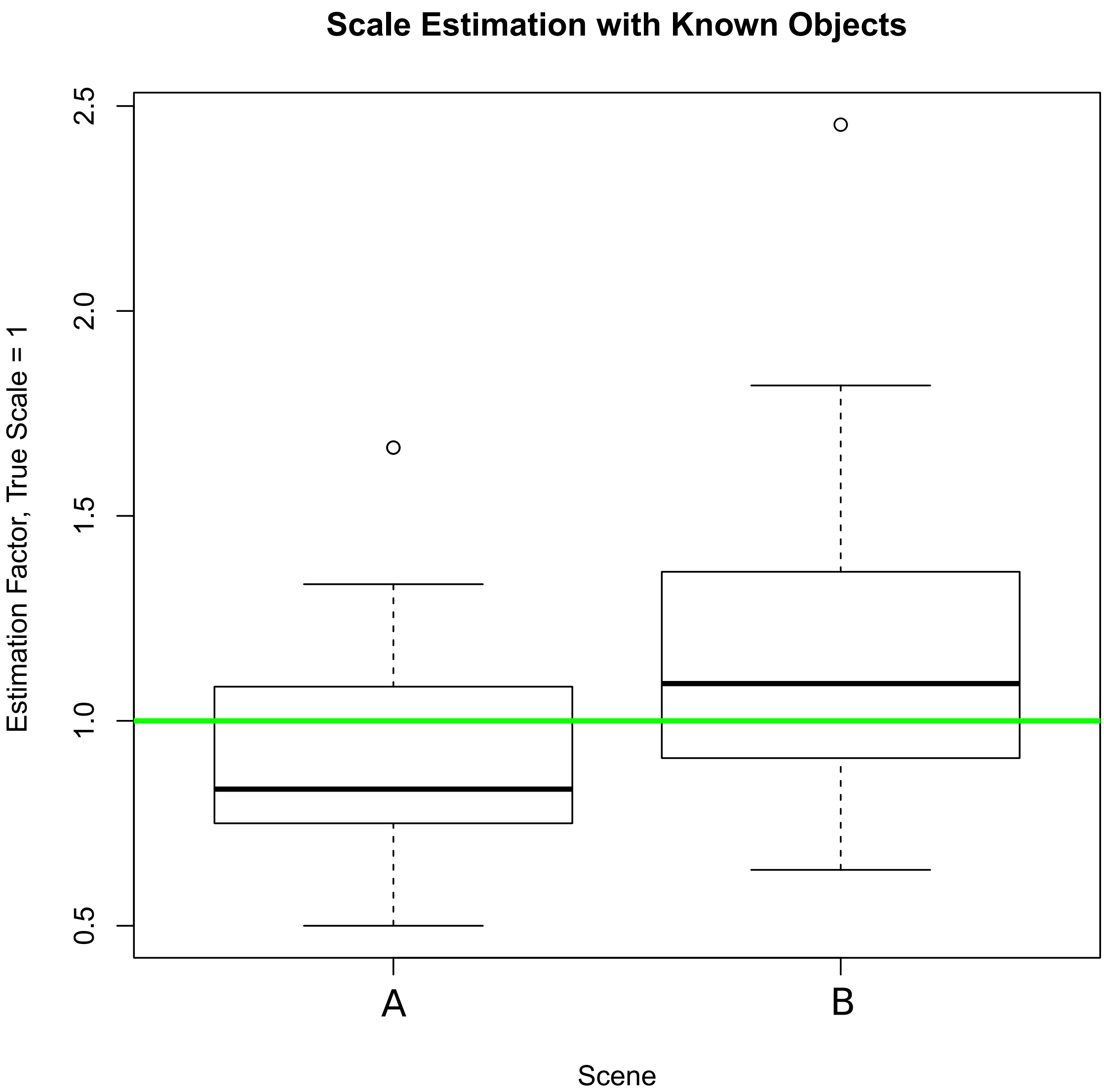

Figure 6.3: Known-object comparison test results - scenes including known objects.

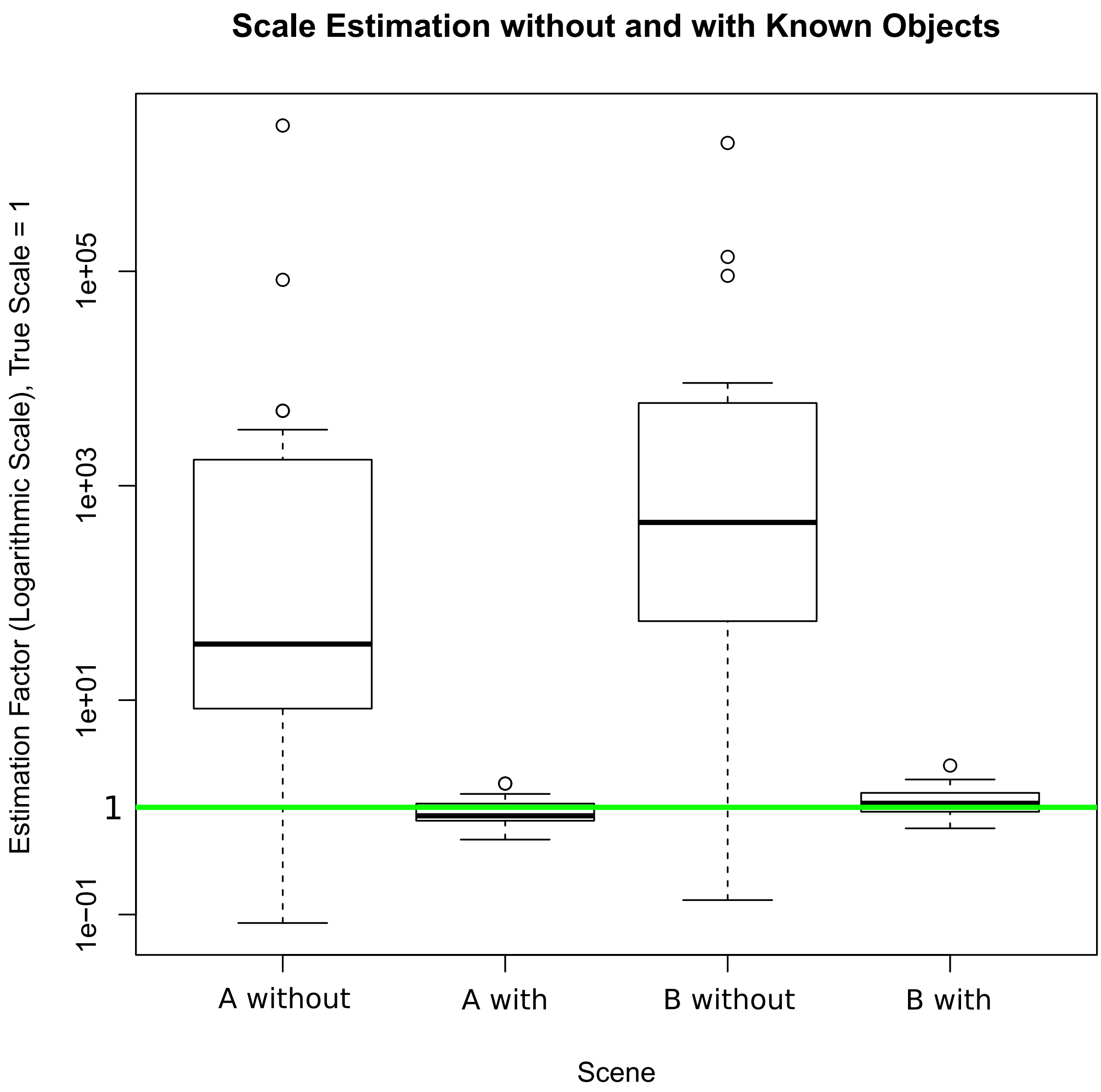

Figure 6.4: Known-object comparison test results - scenes without and with known objects.

CHAPTER 7

Discussion

7.1 Discussion

The main goal of this thesis is the definition of a problem space and the design of representations for establishing scale contexts in 3D Martian environments. According to Sedlmair et al. [SMM12], problem characterization and abstraction is a first-class contribution of a design study. In general, our representations received positive feedback from our expert and achieved their design goals. Based on this feedback, they are capable of conveying scale in 3D visualizations of Mars. Evaluating each design in detail would be required to draw generalizable conclusions, however, known-object comparison in particular seems to be an intuitive, yet powerful method for the communication of findings to experts and non-experts.

The collected expert feedback suggests the following improvements for at least some of our implemented representations. Known-object comparison could be extended with models for additional magnitudes of scale and the functionality to draw contours of countries onto the surface. Contour-lines would be improved by coloring and drawing labels. Vertical exaggeration would benefit from a composition with contour-lines. Clutter in our true-layer-thickness representation could be reduced by drawing planes for the bottom and top of a stack and lines for layers in-between. It should also offer tabular export of thickness measurements to further accelerate the workflow of the users. Distance shading and landing ellipses are of limited use for geologists and should be examined by experts from mission planning to gather additional feedback.

7.2 Future Work

Future work includes an evaluation whether our representations are suitable for non-Martian visualizations and an in-depth user study. The effects of texture quality on scale perception in 3D reconstructions should also be explored. In addition, conveying scale in AR, VR, and real 3D should be explored. Even though, stereoscopic vision preserves some size and distance cues, the scale of an unfamiliar environment at various zoom-levels is still difficult to judge. Furthermore, conveying a sense of orientation and scale in combination should be investigated, because orientation and navigation can impact scale perception [Pel18]. Finally, the composition of scale representations could yield more expressive tools.

7.3 Conclusion

In this thesis, we characterize the problem space of conveying scale in 3D visualizations of Mars projected onto a 2D screen. We give an overview of problems arising through various types and magnitudes of scale, as well as the requirements of common use cases and user groups. We designed representations to alleviate these problems and implemented a prototypical application to test our designs. Feedback from a domain expert and our pilot experiment on known-object comparison suggests that our scale representations are capable of effectively conveying scale in 3D Martian environments.

List of Figures

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