Conveying a Sense of Scale in 3D Planetary Environments

Martin Riegelnegg*
Supervised by: Thomas Ortner†

VRVis Research Center
Vienna / Austria

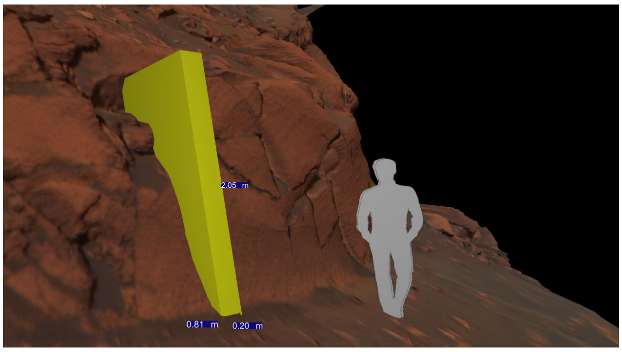

Figure 1: Martian outcrop with two representations to convey scale (scale-box and silhouette of a person).

Abstract

3D visualizations of Mars enable the remote exploration of 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 paper, 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, and levels of expertise. The designed representations include scale-bars, scale-boxes, known-object-comparison, true-layer-thickness, contour-lines, vertical exaggeration, and distance shading. We received informal feedback for each representation from a planetary scientist. The feedback suggests that our representations are capable of conveying a sense of scale in 3D visualizations of Mars for their use-cases.

Keywords: Scale, Visualization, Mars

1 Introduction

A large number of missions to Mars have been launched in the last decades studying its geology, climate, and potential for human exploration [7] and searching for evidence whether the planet ever supported habitable environments at any 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 [12].

Outcrops are a primary source for understanding geological principles [23] 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 [16]. 3D outcrop visualizations offer a number of advantages over 2D representations which can not fully portray the 3D nature of geological features [23]. 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 [12].

1.1 Problem Statement

The Martian surface is an unfamiliar environment. Studies have shown that familiarity greatly influences human size judgements [22]. Familiar objects establish a scale context in everyday terrestrial scenes, allowing for size estimations of unfamiliar objects as well as distance judgements. The lack of a scale context in Martian scenes potentially confuses viewers and may lead to wrong conclusions. Therefore, conveying scale in 3D visualizations of Mars is necessary to aid scientists in fully characterizing the geology of paleoenvironments [12], 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.

In the workshop on 3D visualization for planetary surface science held at 'VRVis' on April 6/7 2018 [11], the need for conveying scale in Martian scenes was apparent.

*martin.riegelnegg@gmx.at
†ortner@vrvis.at

Whenever images of Martian surface features were shown, immediate questions about scale were asked from the audience. In this paper we discuss aspects of conveying scale in 3D visualizations of Mars projected onto a 2D screen. We characterize the problem space and design seven scale representations for a number of use-cases and user-groups, based on feedback gathered through discussions with domain experts on several occasions. Two of our scale representations can be seen in Figure 1.

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 [26] 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.

Further, 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 [18]. 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 for use by planetary scientists, mission planning as well as 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 [6].

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.

2 Related Work

Glueck et al. [14] 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. [19] 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 [18] 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. [13] discuss communicating planetary research to the public and propose methods to visualize celestial bodies in order to make scientific data understandable to non-experts.

Scale perception is the topic of several publications in psychology. Predebon [22] [20] [21] evaluates the effects of familiarity on absolute and relative judgments of size and distance under various viewing conditions.

Wagner [25] 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.

A number of software solutions provide tools to convey scale. PRo3D [6] allows planetary scientists to work with high-resolution 3D reconstructions from Mars and offers tools for precise geological measurements. Petrel [5] 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 [1], VRGS [10], and Virtual Outcrop [9] extensively. All of them offer basic tools to convey scale, such as scale-bars and contour-lines. CloudCompare [3] 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 [4] 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 [8] is a 3D modeling application that displays the model of a person to establish a scale reference.

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 [22]. 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 the misinterpretation.

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. [26], 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 not suitable to convey area. In addition, certain characteristics of features on Mars, 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 necessary. 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. [19] 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 [18] [17]. 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. Parallel projections are not appropriate because they explicitly remove all depth cues [14]. 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 [18], 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 use 3D visualizations of Mars. *Planetary scientists* have expert knowledge and want to take accurate and repeatable measurements for features across all magnitudes of scale [12]. 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 potential *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 [13]. Expert knowledge can not be assumed, necessitating intuitive representations to convey scale effectively.

4 Design

In this section we present the design decisions of our seven scale representations in detail. We also discuss use-cases, intended user-groups, and potential limitations.

4.1 Scale-Bars

Scale-bars are a standard tool in geological visualizations. They are simple to interpret, versatile, and work at every

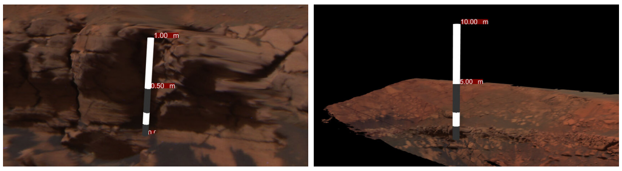

Figure 2: The lengths of our dynamic scale-bars change depending on the distance to the viewpoint. Their screen-space sizes remain constant.

magnitude of scale. Vertical scale-bars convey height. 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.

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 it can be seen in Figure 2. The steps ensure that scale context changes are not overlooked and are computed as follows: $s = \frac{d}{f}$, $l = 10^{\lfloor \log_{10} s \rfloor}$, $length = l \cdot \lfloor \frac{s}{l} \rfloor$ 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 for use 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 it can be seen in Figure 3. 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 are determined by computing the box's silhouette and finding the center of the outer edges.

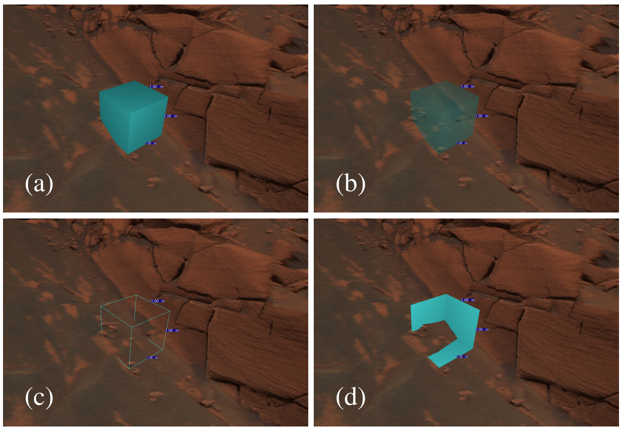

Figure 3: Four draw modes for scale-boxes: (a) solid, (b) transparent, (c) wirebox, (d) frontface culling.

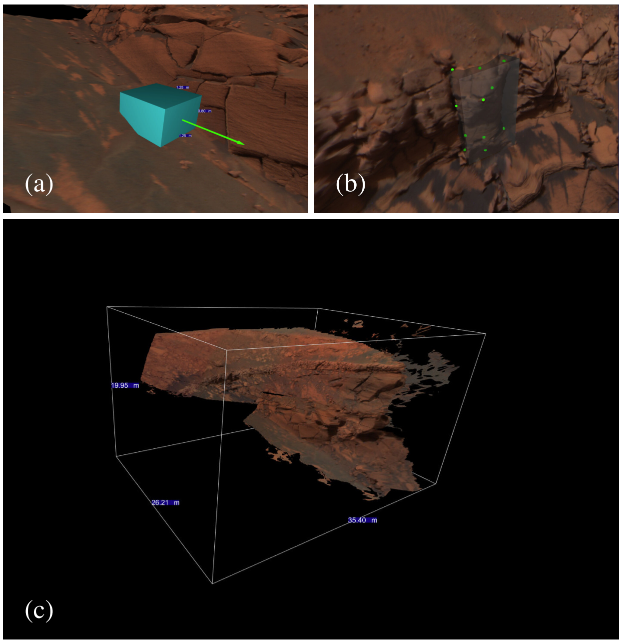

Figure 4: Adjustment of scale-box faces (a), PCA fitting of scale-box to surface feature (b), bounding scale-box for entire outcrop (c).

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 it can be seen in Figure 4 (a). 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 ren-

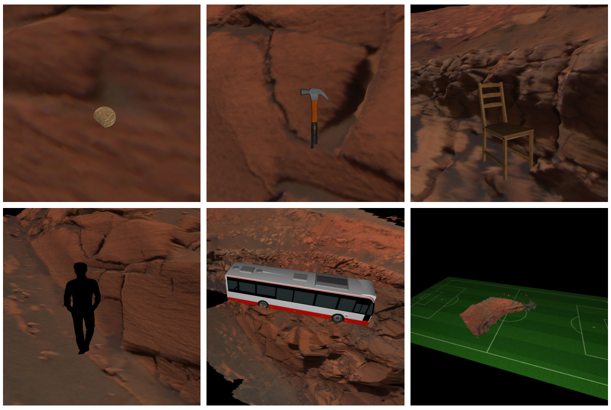

Figure 5: Known-object-comparison models: coin, hammer, chair, person silhouette, citybus, soccer field.

dered to support the users in the selection of meaningful points, as it can be seen in Figure 4 (b). 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 it can be seen in Figure 4 (c).

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

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 [22]. Geologists use this technique in their fieldwork and often place known objects, such as hammers, in the frame of outcrop images to perform measurements [15]. 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 [19]. Known objects have to be common, so that a large amount 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 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 objects in our design, 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

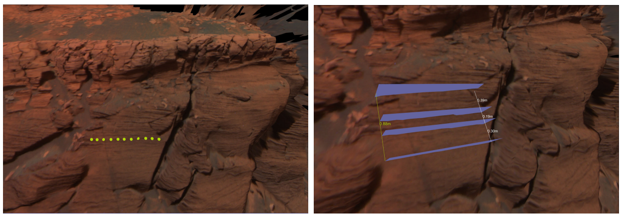

Figure 6: Picking points on a sedimentary line (left) to create a true-layer-thickness stack (right).

5. 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 [14]. 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 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

Characterizing the geology of sedimentary rocks on the Martian surface is a principle research target for planetary scientists [12]. Sedimentary layers typically run in parallel to each other. Their thicknesses reveal aspects about their formation. Measuring layer thickness is therefore critical, however, measuring a large number of consecutive layers is cumbersome with regular 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 it can be seen in Figure 6. 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.

4.5 Contour-Lines

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. Our lines show relative elevation instead and users can adjust

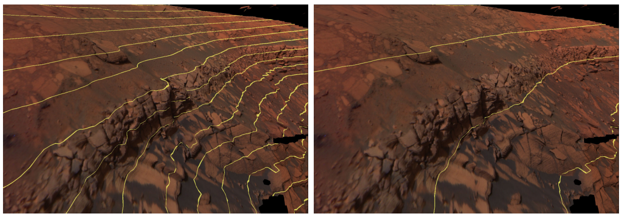

Figure 7: Adjustable spacing and offset for contour-lines. Left: 0.5 m spacing, right: 2 m spacing.

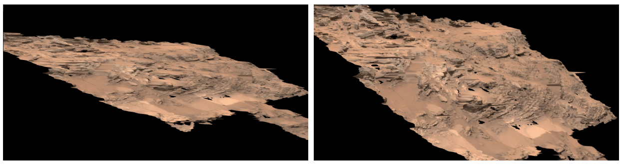

Figure 8: Scene without (left) and with two times vertical exaggeration (right).

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 7.

4.6 Vertical Exaggeration

Vertical exaggeration emphasizes vertical changes of a terrain [2] by stretching it in the direction of the sky vector. It is effective at all magnitudes of scale. The method is commonly used to accentuate mountain ranges in visualizations, where the landscape is nearly flat. Geologists employ vertical exaggeration to pronounce thin 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 8 shows a scene without ($factor = 1$) and with vertical exaggeration ($factor = 2$).

4.7 Distance Shading and Distance Lines

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, however, we also provide shading with discrete color levels for simpler interpretation. Additionally, distance lines can be rendered at discrete steps. Distance lines and distance shading can be drawn separately or combined. The alpha value for the colored area can be adjusted, so that surface features are still distinguishable. In Figure 9 the drawing options for distance shading and distance lines, including continuous and discrete shading, can be seen. It is important to note that the representation is potentially misleading, because users could expect the projected distance on the surface instead of the direct distance.

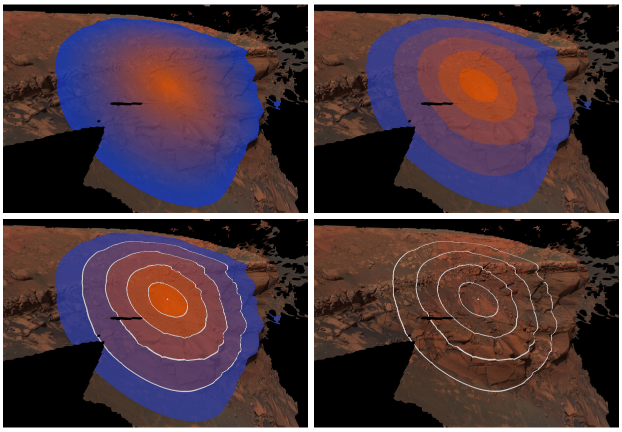

Figure 9: Continuous and discrete distance shading (top-left, top-right), distance lines (bottom-right) and combined drawing of lines and shading (bottom-left).

5 Feedback

We received expert feedback from Robert Barnes, a geologist 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 composition 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.

6 Discussion

The main goal of this paper is the definition of a problem space and the design of representations for establishing scale contexts in Martian environments. According to Sedlmair et al. [24], 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. Our true-layer-thickness representation should provide functionality to export thickness measurements to a table. Clutter could be reduced by drawing planes for the bottom and top of a stack and lines for layers in between. Distance shading is of limited use for geologists and should be examined by experts from mission planning to gather additional feedback.

7 Future Work

Future work includes an evaluation whether our representations are suitable for non-Martian visualizations. 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 impact scale perception [18]. Finally, the user-defined composition of scale representations could yield more expressive tools.

8 Conclusion

In this paper, 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 our expert suggests, that our scale representations are capable of conveying scale effectively in 3D Martian environments.

9 Acknowledgements

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