Visualizing the Greenland Ice Sheet in VR using Immersive Fence Diagrams

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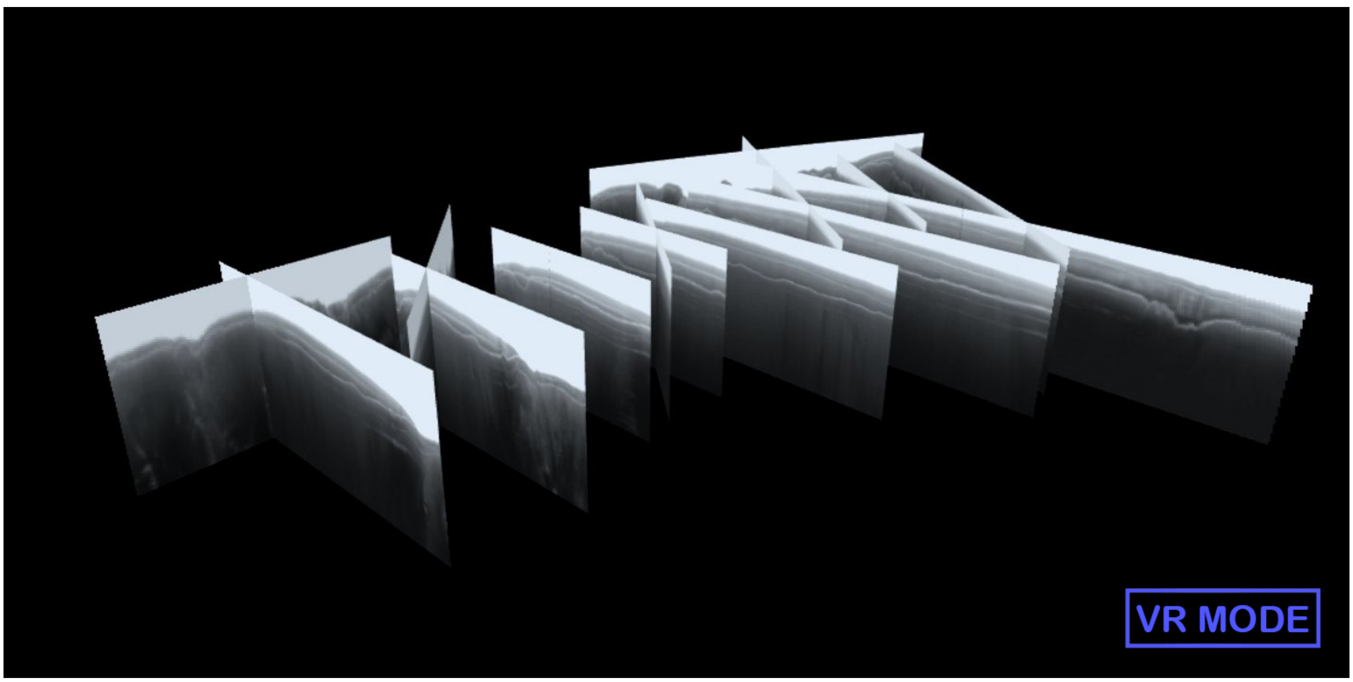

Figure 1: Screenshot of our visualization in VR, showing a fence diagram of the Greenland Ice Sheet.

ABSTRACT

The melting of the ice sheets covering Greenland and Antarctica are primary drivers of sea level rise. Predicting the rate of ice loss depends on modeling the ice dynamics. Ice penetrating radar provides the ability to capture images through the ice sheet, down to the bedrock. Historical environmental and climate perturbations cause small changes to the dielectric constant of ice, which are visually manifested as layers of varying brightness in the radar imagery. To understand how the flow of ice has progressed between neighboring image slices, glaciologists use Fence Diagrams to visualize several cross-sections at once. Here, we describe the immersive virtual reality (VR) fence diagrams we have developed. The goal of our system is to enable glaciologists to make sense of these data and thereby predict future ice loss.

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CCS CONCEPTS

• **Applied computing** → **Environmental sciences**; • **Human-centered computing** → **Scientific visualization**; **Geographic visualization**; **Virtual reality**.

KEYWORDS

fence diagrams, Greenland Ice Sheet, ice-penetrating radar

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1 THE VISUALIZATION

Fence diagrams are used to visualize overlapping images that constitute "slices" of a continuous 3D volume. These cross-sectional images are arranged spatially in accordance with their positions in the volume from which they were sliced. Fence diagrams have been used in a wide range of disciplines (e.g. stratigraphy), for both measured and simulated data, and are typically rendered for viewing on a flat 2D surface (e.g., computer monitor or printed page). Here, we describe our development of a fence diagram in virtual reality for ice-penetrating radar data, enabling an immersed user to freely reposition themselves physically within the data by changing their position, orientation, and zoom level, in order to develop a mental model of the sub-surface ice structure.

Some of the main challenges with non-immersive fence diagrams include difficulty understanding subsurface layer continuity and context, and difficulty tracking individual layers from one image to the next. Additionally, many traditionally rendered fence diagrams implement layer transparency and clipping planes in an attempt to retain context; however, multiple overlapping transparencies can obfuscate portions of images when viewed from a 2D projected point of view (POV). Immersion within the scene enables a user to view the intersecting planes from an un-occluded viewpoint, while simultaneously integrating spatial context to form an intuitive mental model.

2 THE DATA

Melting ice sheets on Greenland and Antarctica are major contributors to Earth's sea level rise [5, 12], but the variability in their melt rate is not well understood [13]. Ice sheets form distinct layers as older snow compresses under newer snow, and the characteristics of these layers vary depending on the atmospheric composition at the time of the contributing years' snowfall, such as the presence of atmospheric volcanic ash. Since the ice sheets both compress and flow over time, the layers' shapes will change accordingly. For example, the loss of ice in a local area beneath a layer will cause that layer to deform downward, toward the bedrock. These shapes in the layers of the Greenland Ice Sheet can be used for understanding and modeling historic ice movement, and thus in making predictions of future ice loss as a function of time, ocean temperature, and other variables [7].

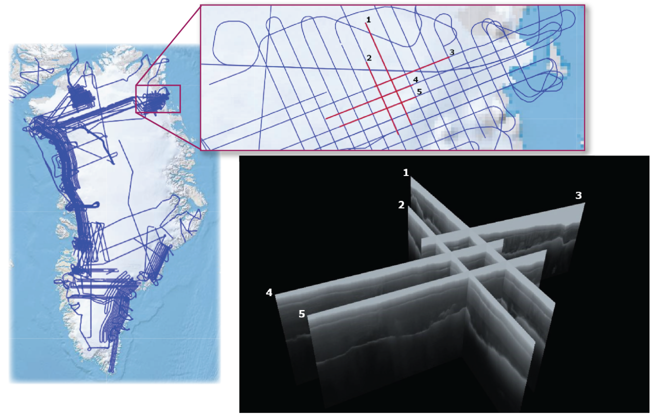

Figure 2: Example fence diagram in VR, constructed from a small subset of radar images collected along flight lines over the Greenland Ice Sheet. The blue lines show all the flight paths along which radar imagery is collected in Greenland. The inset of the map shows a small subset of flight paths (in red) that were used to construct this illustrative VR fence diagram. To create the VR fence diagram, the images are projected onto planes, which are then aligned and spatially referenced to each other. The image height corresponds to sounding depth into the ice sheet, and the image width corresponds to the along-track flight distance for that image file.

While the Greenland Ice Sheet thickness can range up to three kilometers, ice-penetrating radar flown above can provide a cross-sectional image along the flight path of the full thickness of the ice sheet, all the way down to the bedrock. A fence diagram of these images shows multiple cross-sectional slices arranged spatially in three dimensions, and have been successfully employed on two dimensional displays by glaciologists to enhance their understanding of ice flow [14].

We use processed radar data collected by the Center for Remote Sensing of Ice Sheets (CReSIS) [2]. CReSIS collects ice penetrating radar images aerially using radar antennae with a bandwidth between 150-600 MHz. The radar captures information from the height of the aircraft to below the bedrock's surface; these data are then stored in Matlab files available for public use. The images have been processed using standard radar signal processing techniques, and metadata such as position and orientation data are exported along with the image [6]. The images are padded so that the ice surface elevation is aligned for all images, and cropped so the bottom elevation is also consistent. Finally, the images and metadata are imported by our A-Frame JavaScript program and rendered as planes in the scene. Currently these images must be manually processed though the Python program before the JavaScript program handles the data.

3 TECHNIQUES, TOOLS, AND SOFTWARE DEVELOPED

The software we developed for our visualization was built using A-Frame 1.4.0 [3], an open-source web framework. A-Frame itself is built from the open-source three.js JavaScript library and makes use of the WebXR Device API, a standard maintained by the W3C Immersive Web Working Group. We chose to build using this set of tools because they are widely supported by both desktop browsers and AR/VR systems. Our visualization can be loaded in any VR headset through a VR-based web browser without need for specific VR hardware or the installation of any software.

User interaction primarily takes the form of spatial navigation, which includes 3D zooming, 3D panning, and rotation about any axis in the vertical direction. We implement a variety of spatial navigation paradigms that have been developed and tested for various VR use cases [8]. For our application, in addition to matching the free movement of the user in physical space, we determined that the most intuitive form of interaction would be the combination of two controller-based options:

- Using either the left or right handheld controller alone, grab any 3D coordinate with the side button on that controller to translate the VR environment in any 3D direction (without rotation or scaling)
- Using two handheld controllers together, grab any pair of 3D points using the side buttons of each VR controller to rotate the VR environment in the horizontal plane (as anchored by those two points); scale the VR environment (as anchored by those two points); and translate the VR environment (as anchored to the center of those two points). These three operations can be conducted simultaneously and, within our code, are applied as a single combined transformation matrix.

This navigation technique allows users to fluidly reposition themselves in the fence diagram as they develop a mental model for the relationships between layers in adjacent images.

4 GOALS, PROGRESS, AND FUTURE WORK

Our goal is to build tools that will accelerate the development of mental models by domain scientists with interests in the Greenland Ice Sheet (e.g., glaciologists), especially those working to develop computational models which predict future ice flow and melt. VR has shown similar success in other scientific and technical fields, with immersive visualizations helping domain experts to understand their own spatial and non-spatial data [9, 11]. Our iterative development process is currently focused on understanding domain requirements, collecting informal expert feedback from our co-authors, and developing system requirements. Our future work will include a large-scale user study, computational benchmarks, and ability to ingest larger amounts of data.

In addition to larger scale evaluation by third-party domain experts, we also intend for future work to allow for expert annotation of layers during VR immersion, as annotating data in VR/XR has been shown to result in quicker and more accurate work in other domains [4, 10]. Another direction for future development and study is collaborative immersion, inspired by the promise shown by multi-user immersive data visualization in other domains [1].

5 REQUIREMENTS FOR USE

While the visualization may be viewed in a limited capacity through a browser and navigated using the standard WASD keys, it is intended primarily for VR headset use. Specifically, this visualization requires any standalone VR headset with a WiFi connection, or a headset tethered to an internet-connected computer, along with a pair of handheld VR controllers. For additional observers to see what the primary user is observing, a tethered headset can share its view on the connected computer, and a standalone headset (e.g., Meta Quest 2) can cast its view to a mobile phone which can be tethered to a TV screen.

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