

Immersive Visualization and Interactive Analysis of Ground Penetrating Radar Data

Matthew R. Sgambati¹, Steven Koepnick¹, Daniel S. Coming^{*1},
Nick Lancaster¹, and Frederick C. Harris, Jr.²

¹Desert Research Institute

²Department of Computer Science and Engineering, University of Nevada, Reno

Abstract. Ground Penetrating Radar is a geophysical technique for obtaining information about sub-surface earth materials. Geologists use the data collected to obtain a view of terrain underground. This data is typically viewed using a desktop interface where the user usually interacts using a keyboard and mouse. Visualizing the data in a slice by slice 2D format can be difficult to interpret. Instead, we created a program for an immersive visualization environment that uses tracked input devices. This is done using real-time, stereoscopic, perspective-corrected, slice-based volume rendering. To aid with the visualization the user can modify the display of the volume using integrated tools, such as transfer functions, lighting, and color maps. Users are also given data analysis tools to take application-specific measurements such as dip, strike, other angles, and distances in 3D. Compared to typical desktop interface interactions, the 6-degree of freedom user interface provided by the immersive visualization environment makes it notably easier to perform the application-specific measurements.

1 Introduction

Ground Penetrating Radar (GPR) [1] is a geophysical technique used in such fields as archaeology, environmental site characterization, hydrology, sedimentology, and glaciology to obtain 3-D information about subsurface earth materials without the expense and difficulty of excavation or drilling [2].

The data gathered by GPR requires special software in order to be visualized as 2D slice data or a 3D volume. There are many software programs that visualize GPR data [3–8]; however, these applications have not been developed to display GPR data in an immersive visualization environment (IVE) with tracked input devices. IVEs allow the user to view the data in ways that desktop displays are not capable of, such as being able to view around the data and behind it without moving the data. Geologists also need to analyze it, including taking measurements of the thickness and orientation (dip and strike) of sedimentary units. Desktop tools are typically limited to the interactions provided by input devices designed for 2D interfaces, while tools created for an IVE can use its tracking abilities, providing a different way to interact with the data.

* {sgambati, koepnick, dcoming, nick}@dri.edu, fredh@cse.unr.edu

We present an immersive application for visualizing GPR and other seismic data with topographic correction and a surface for context, and we introduce interactive analysis tools for exploring and measuring this data and visualizing the dip and strike (surface orientation) of structures. Further, we integrate these tools and other improvements into an open-source immersive volume visualization application called Toirt-Samhlaigh [9].

2 Related Work

Tools exist for analyzing and viewing GPR data on desktop computers. GPR-SLICE [5] creates 2D and 3D displays of GPR data and includes many tools, such as isosurfaces and topographic correction. Ground Vision and Easy 3D [6] support acquisition and visualization of GPR data. Another program called Easy 3D [7] visualizes data in 3D from a single channel or multi channel GPR system and provides viewing tools, such as filtering. Geoprobe [8] provides many tools to aid viewing and analysis of 3D GPR data, like multi-threaded volume attribute calculations and dynamic calculation and display of horizon-based attributes. These tools do not leverage immersive displays or 3D interaction.

There are, however, immersive tools that visualize volumetric data, some of which support geological data [10–16]. Ropinski et al. [10] used a table display to explore seismic volume datasets using context and focus visualization metaphors. Visualizer [11] supports isosurface and streamline creation, slice visualization, and custom tools. Chopra et al. [12] visualized large-scale seismic simulations by simplifying, sampling, and filtering, and supported surface rendering.

Other immersive volumetric tools use geometric representations of data, like isosurfaces and slices. Winkler et al. [13] extended a standard geoscience program to an immersive environment and displayed the desktop interface on a virtual surface. Fröhlich et al. [14] let users immersively examine geo-scientific data (seismic volumes and well logs) using a prop based interaction device and a sonification technique. Dorn et al. [15] presented a system for platform and well planning in an immersive environment, which imported and displayed surface and subsurface data. LaFayette et al. [16] visualized a GPR scan of an anthill by constructing an isosurface on the boundary between soil and air. CoRSAIRe [17] provides analysis of a fluid dataset using isosurface rendering of a simple surface, with haptic feedback according to an invisible isosurface.

Other immersive systems have dealt with measurement tools. Kreylos et al. described their immersive LiDAR tool [18], which could measure distances and angles in 3D space. Hagedorn et al. let users measure objects in an IVE [19], using line, cylinder, and ellipsoid tools.

Our system visualizes large volumetric datasets, including topographically corrected GPR data, in an immersive environment. We provide interaction tools to make generic and GPR-specific measurements, such as dip, strike, and distance. Existing tools lack the means to measure dip and strike of features in subsurface geophysical data such as GPR. We also visualize these measurements, as well as the ground surface.

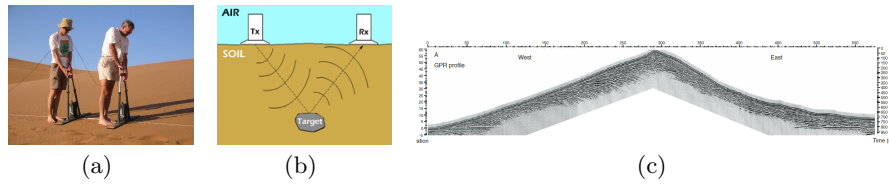


Fig. 1. (a) Researchers use a GPR unit on a sand dune to send (b) GPR pulses through the ground, reflecting off surfaces [21] and, after generating many samples, create (c) 2D subsurface profiles [22].

3 Background

3.1 Ground Penetrating Radar

GPR uses the propagation of electromagnetic waves that respond to changes in the electromagnetic properties of subsurface materials. A GPR unit typically consists of transmitting and a receiving antennae to send and receive pulses into the ground, shown in Fig. 1(a). The ways in which this energy is reflected and scattered off surfaces and objects are expressed by the relative permittivity contrast between the target and the background. GPR surveys can provide information on the stratigraphic architecture, geometry, and correlation and quantification of sedimentary structures [1].

As seen in Fig. 1(b), as the waves leave the transmitter and travel through the ground they reflect off of subsurface structures. The receiver then detects the reflected waves and records the information. These pulses not only reflect off of objects in the subsurface, including cracks and voids, but also reflect off of materials with different dielectric properties. This means that GPR can detect subsurface features along with changes in the type of subsurface material to provide a map of the variation in ground electrical properties [20].

A field GPR survey to gather data is typically performed in a grid pattern. A researcher moves along this grid with GPR equipment, taking readings at each grid point. Fig. 1(c) shows an example GPR profile gathered on a sand dune.

3.2 Application of GPR to studies of sand dunes

Sand dunes provide a favorable target for GPR studies because they have a high resistivity, which allows for good penetration of electromagnetic energy and they contain large-scale sedimentary structures that can be resolved by GPR [22]. Documenting and analyzing these sedimentary structures is important for understanding sand dune development and provides information on past climates and wind directions. Deposits of ancient sand dunes also occur in the rock record. Many of these ancient aeolian sandstones are important reservoirs for hydrocarbons [23].

Characterizing the sediments of modern sand dunes in order to understand the conditions in which they formed requires measurements of the angle and



Fig. 2. (a) A Brunton Compass [24] measures dip and strike, illustrated in (b) [25].

direction of dip of primary and secondary sedimentary structures in order to determine the wind directions that formed them. Measurements of the thickness of sedimentary units are also frequently needed. In field studies, dip and strike of beds are measured using a Brunton Compass. These measurements are, however, hard to make using existing GPR visualization software packages.

3.3 Brunton Compass

A Brunton Compass, shown in Fig. 2(a), is a tool used by geologists to determine the dip and strike angles of surfaces. The angle of dip is a measure of the surface's steepness relative to horizontal along its gradient. The angle of strike describes the orientation of the surface relative to North. The strike is measured using the strike line, a line on the surface that represents the intersection of a horizontal plane with the surface. The dip is measured using the steepest gradient from the strike line. Another way to represent strike is to use the dip direction, which is the gradient used for the dip measurement projected onto the horizontal surface that is used to create the strike line. This means that the dip direction is always 90 degrees off the strike line (Fig. 2(b)).

4 Application Design

Our goal was to improve available tools for geologists to visualize and analyze data from GPR studies of sand dunes. With a geologist, we identified several formal requirements for the tool: (a) visualize a 3D “data cube” comprising a stack of 2D profiles in Society of Exploration Geophysicists (SEG) Y [26] data format; (b) correct data alignment for topography; (c) collect dip/strike and distance measurements from the volume; (d) visualize dip/strike measurements.

We kept a few special considerations in mind, regarding GPR measurements of sand dune subsurfaces. The subsurface is fairly homogeneous, with slight variations mostly due to moisture content. These slight variations are what geologists are interested in. Therefore, we don't expect to find easily segmentable features but rather want to leverage the domain knowledge that geologists have already developed in looking at 2D transects of sand dunes.

We designed our application for use on several systems from CAVE [27] style displays to 3DTV-based displays. We assume stereoscopic perspective-corrected rendering based on head-tracking and a six degree-of-freedom input device with several buttons. We built our application on Toirt-Samhlaigh [9, 28], a volume rendering application that performs slice-based volume rendering [29] on 3D textures with bricking and an octree acceleration structure [30]. It has 1D and 2D transfer functions to map data values to colors and opacities. It has good support for both immersive displays and desktops and was built on the Virtual Reality User Interface (Vrui) [31] VR toolkit. Because Vrui abstracts the displays and input devices, our efforts focused on processing GPR data, analysis tools for GPR data, and ensuring that interface design decisions would work well on each system. Vrui provides an integrated user interface API with widgets and menus which work on both immersive and desktop systems.

While designing our application, we strove to follow the following design principles: (a) target the interface to the user domain; (b) provide methods to explore data, extract measurements, and see focus in context; (c) minimize physical fatigue of the user interface; (d) design for wide variety of immersive displays and when possible, for non-immersive displays.

5 Visualizing GPR data

To visualize GPR volume data we load a series of 2D slice files in SEG-Y format and stack them into a 3D volume. Then, we apply topographic correction to this volume, given a topography data file. We use Toirt-Samhlaigh's volume rendering (Fig. 3(a)). And we can visualize the topography as a surface with adjustable transparency, on its own or with the volume.

Topographic correction (Fig. 3) accounts for the slope of the terrain surface on which GPR data was collected. Without it, raw GPR data appears as if it was collected on a flat terrain. Topographic correction is necessary before measuring dip and strike, and for easier layer visualization. Topography data is stored as a height map of elevations surveyed at regular intervals as well as samples at peaks and ridges that do not fit the regular intervals so that they are not missed by interpolation. We vertically shift each column of data in the volume by the elevation found through bilinear interpolation of the topography data and fill above the topography with null data.

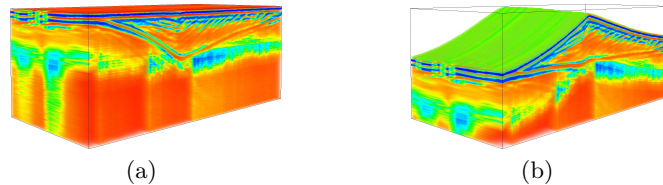


Fig. 3. GPR data of a sand dune (a) without topographic correction applied and (b) with it applied.

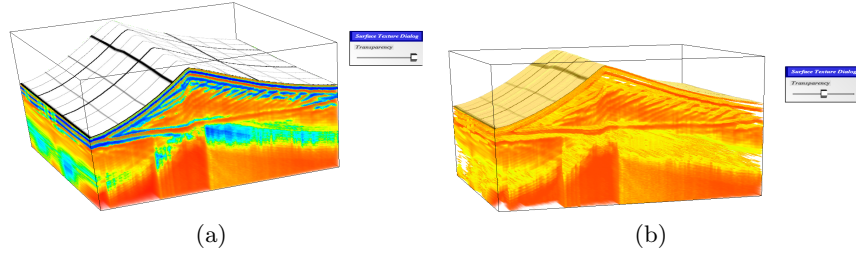


Fig. 4. Surface visualization for a topographically correct GPR dataset with (a) no transparency and (b) 50% transparency (with a different transfer function).

The *surface visualization* (Fig. 4) is a triangle mesh height field with a vertex for every column of the volume, with heights linearly interpolated from the topography data. Rendering order issues arise when rendering semi-transparent surfaces intersecting semi-transparent volumes with slice-based volume rendering. To resolve this, we apply multiple rendering passes. We first render the surface with front-face culling so that the back faces are rendered to the depth buffer. Then, we render the volume and finally re-render the surface with back-face culling. The surface still incorrectly occludes data above it, but this is null data after topographic correction.

6 Interactive Analysis Tools

In this section we describe GPR data analysis tools. Our *Brunton Compass Tool* simulates its real life equivalent, allowing the user to take non-invasive dip and strike measurements of subsurface features, which can be visualized as a non-uniform vector field of gradients. Our *Distance Measurement Tool* is specialized for collecting distance measurements of interest to geologists. We also discuss tools provided by Toirt-Samhlaigh that are useful for this domain and our modifications to some of them.

6.1 Brunton Compass Tool

To measure dip and strike we created a virtual analog (Fig. 5(a)) of the Brunton Compass Tool (Fig. 2(a)). This tool provides the user with a plane that can be placed in the VR environment with the 6-DOF input device. Based on the orientation of the plane, the user is provided with the dip and strike, along with the coordinates of the plane's center.

Dip and strike are calculated in the volume's coordinate system. First, the plane's normal is transformed into this coordinate system. Note that this coordinate system may have non-uniform scaling, which must be accounted for. Next, the cross product of this normal and the volume's up vector gives the strike line of the surface (Fig. 2(b)). Then the cross product of the strike line and the



Fig. 5. User interfaces for (a) Brunton Compass and (b) Distance Measurement Tool.

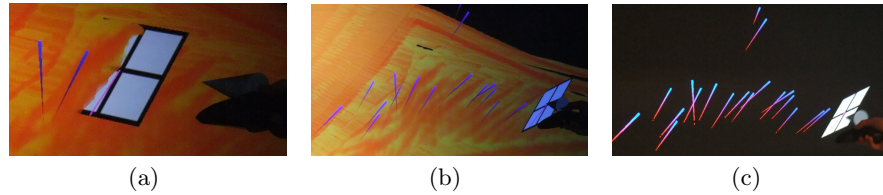


Fig. 6. Brunton Compass tool and non-uniform vector field showing its measurements: (a) closeup taking a measurement (b) volume data and gradients, (c) gradients only

normal gives the steepest gradient. The dip direction is the cross product of the normal and the strike line, in the direction of steepest descent along the gradient. The dip angle is the smallest angle between the steepest gradient and the horizontal plane defined by the volume's up vector, which also happens to contain the strike line. We calculate dip angle as the inverse cosine of the absolute value of the dot product of the dip direction and the gradient vector. The strike angle is the angle between the strike line and north, which we calculate by taking the inverse cosine of the dot product between strike and north.

For ease of use, the user can change the size of the plane, save its current values, and choose between having the plane snap to the 6-DOF input device or perform transformations relative to the input device. The plane always moves relative to the 6-DOF input device; however, with snapping enabled, the plane is transformed to the position and orientation of the device before each movement. We created a user interface that displays the following information: current measurement (dip, strike, plane center), last five saved measurements, buttons to load and save, resize plane/vector, and toggle snapping and gradients.

A *non-uniform vector field* visualizes dip and strike measurements with a cone at each measurement pointing in the direction of the steepest gradient. Saved measurements from a previous session can also be loaded.

Fig. 6(c) is a good example of the usefulness of the Brunton Compass Tool's gradients because they provide the user with an outline of the GPR data sub-surfaces structure. The vector field does not render the strike lines because we felt they became visual clutter. Fig. 6 shows the Brunton Compass in use.

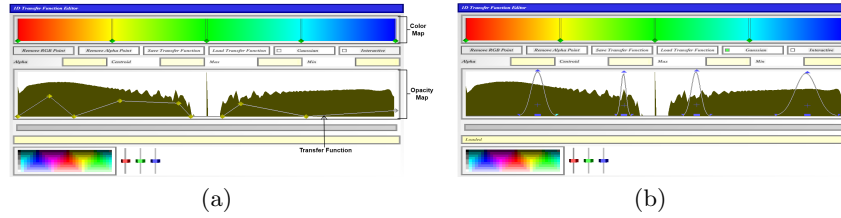


Fig. 7. 1D Transfer Function editors: (a) piecewise-linear and (b) multiple Gaussians.

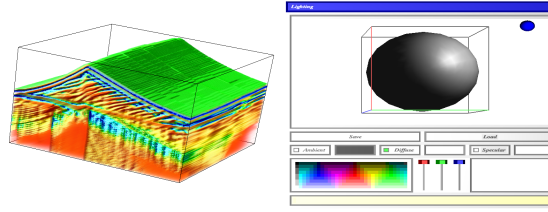


Fig. 8. Lighting being applied to GPR data with the lighting interface.

6.2 Distance Measurement Tool

To measure distances between points in 3D space, we reinvented the Distance Measurement Tool (Fig. 5(b)). VRUI provides a distance measurement tool, but upon initial testing, the geologist testing our system felt the interface provided too many options and too much information, and requested a version specialized to measurements relative to GPR. In our tool, the user creates start and end points using the 6-DOF input device to take a measurement. A marker is drawn at each point along with a connecting line segment. The user may opt to add labels to measurements when saving them: horizontal x, horizontal y, or vertical z. The following information is displayed on the tool's interface: start/end point, distance, buttons for labels, and a 'Save' button to save measurements to file.

6.3 Toirt-Samhlaigh Tools

Toirt-Samhlaigh provides useful analysis tools. With the 1D Transfer Function editor, users can modify the opacity and color values that Toirt-Samhlaigh applies to the data. They can edit the opacity map using piecewise-linear or multiple Gaussian functions (Fig. 7). Color values are linearly interpolated between control points. Users can save and load transfer functions.

The lighting feature allows the user to apply a directional light to the data. The user can change the color of the ambient, diffuse, and specular lighting, alter the direction of the light, and save and load lighting settings. Fig. 8 shows an example of lighting being applied to GPR data, as well as its user interface.

Users can attach a clipping plane tool to the 6-DOF tracked input device, and use a slicing tool to render axis-aligned slices of the GPR data. We enhanced

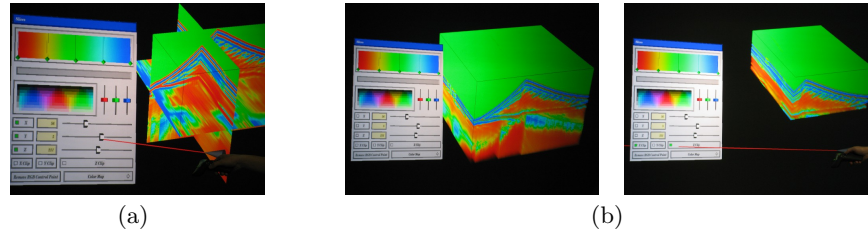


Fig. 9. Applying the Slicing Tool to GPR data to (a) view axis-aligned slices and (b) clip the volume.

the slicing tool to allow the user to treat these slices as clipping planes. Fig. 9 shows the slicing tools applied to GPR data.

7 Results and Lessons Learned

The geologist stated that this “application improves current tools used by researchers or practitioners who are interested in these datasets.” He tested this application in a six-sided CAVE-like display (1920x1920 pixels per side, active-stereo, using two 1080p projectors that overlap), on a four-sided CAVE, on a low-cost 3DTV-based immersive display (67” with 1080p at half-resolution per eye) similar to the IQ-Station [32], and on a non-immersive laptop. All were sufficient for visualization and data exploration. The immersive displays offered the advantage of 3D interaction for dip, strike, and distance measurements. The geologist listed “interactive tools; ability to see [the] dataset from different view points; extraction of quantitative information on dip and strike” as major positives. He found that interactive tools “enable extraction of quantitative information from dataset.” “Compared to field investigations, working in the CAVE is a lot easier and quicker,” he said, and “to perform actual measurements of strike and dip on the beds and surfaces imaged by these data, we would have to excavate the dune and expose these features, which would be logistically difficult and not feasible in most cases.” He often moved to a different view point to quickly confirm precise placement of the Brunton Compass Tool. And we observed that he made use of the wider field of view of the CAVE style displays to obtain more view points and as workspace for user interface elements. The 3DTV-based display became cumbersome to use as the smaller screen became cluttered with user interface elements.

Negative feedback from the geologist included “uncertainty in dip and strike measurements with scaling of datasets.” Measuring angles on a non-uniformly scaled volume can be disconcerting. Even if calculations are correct, results are non-intuitive. And there can be “variation in dip measurement due to step size” if the Brunton Compass Tool is not scaled larger than the step size.

Lighting played a more important role in understanding the structure of the data than we first expected. Gradients are small in this data, making it difficult

to obtain depth cues from occlusion or parallax (stereo or motion). With lighting applied, the increased visual gradient provided its own depth cues and increased the visual difference between nearby viewpoints, improving effectiveness of the other depth cues. Interacting with the lighting tool also provides structural cues as shading on surfaces changes.

The geologist had difficulty using a pointer to interact with small (2") 2D widgets just out of reach, but he was adept at placing and orienting the virtual brunton compass. For example, when using immersive displays, the Gaussian transfer function editor was much easier to use than the piece-wise linear transfer function editor, because it required fewer precise selection actions by the user to obtain a desired function. Sliding the Gaussian around by its center was also a quick way to explore a new dataset for interesting features. Perhaps a 2D touch tablet would be better for these 2D widgets, but carrying it might cause fatigue.

The ability to log measurements while in the environment is crucial, in lieu of a notepad. Similarly important is saving and reloading as much of the system state as possible, whether to resume later or to show a colleague.

8 Conclusions

Existing tools for visualizing GPR data are bound by the limitations of a typical desktop display and input devices. We have presented a way of overcoming the limitations of that environment by creating a system that successfully allows for the visualization and interactive analysis of GPR datasets in an IVE.

In the IVE, the user can explore the data from arbitrary viewpoints by moving around and inside the data. The tracked input devices provided the user with more natural ways of interacting with the data than are possible with typical desktop displays and input devices, as seen in Section 7.

We created two immersive analysis tools which a geologist found very useful. The Distance Measurement Tool allows users to take specialized distance measurements, while the Brunton Compass Tool allows users to take dip and strike angle measurements. The topographic correction and surface visualization help the user understand the shape of the terrain's surface. Additionally, the system provides many techniques for the user to view and interact with the data, such as changing its orientation and position, apply lighting, and transfer functions.

The system is not limited only to GPR data, however. Our enhancements to Toirt-Samhlaigh can be applied to other data types. Also, saving and loading functionality increases Toirt-Samhlaigh's user friendliness.

9 Future Work

This system would benefit from more user friendliness. A menu should be created to allow the selection of a data file to load or save. A tool to aid in data analysis could restrict rendering of data to a user-defined shape. Another tool could automatically or semi-automatically segment the data into layers which the user

could then peel off. The last tool could generate isosurfaces to help visualize the structure of the subsurfaces.

The ability to change the scale of the volume on any axis, quickly swap datasets while the program is running, or render multiple volumes would be useful. We would also like to support additional data file formats.

Finally, we plan to investigate bridging the gap between incorporating immersive visualization into scientific workflows and generating images for publication.

Acknowledgements

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