TERRAGUIDE: A MULTI-SURFACE ENVIRONMENT FOR

VISIBILITY ANALYSIS

by

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Abstract

Terrain visibility analysis is a challenging task that is currently supported by complex tools with cumbersome user interfaces. In this thesis, we present TerraGuide, a novel multi-surface environment for exploratory terrain and visibility analysis. TerraGuide is based around a large interactive tabletop that displays a digital map from the top-down perspective. TerraGuide provides three tightly coupled visibility analysis techniques: a viewshed shows visibility in a cone drawn from the user’s touch point on the table, a panoramic view provides a 3D first-person view on a separate display, and a helicopter view allows the user to see terrain in 3D on a handheld tablet positioned over the table.

We designed TerraGuide using three principles: TerraGuide computes views in real-time, TerraGuide couples views on different surfaces tightly, and users can easily switch between different views. These design principles affect the participants’ strategies and preference among techniques when using the TerraGuide system for terrain analysis tasks.

A two-part user study compared these techniques and identified users’ strategies in solving a complex terrain analysis problem. The first part of the study compared the three techniques and measured performance, preference, confidence, and cognitive load during a simple analysis task. We found that the helicopter view improved participants’ completion time and accuracy when identifying the highest and lowest points on the terrain. In addition, the use of the 3D panoramic view worsened task completion time, yet increased participants’ confidence in their analysis. The second part of the study determined participants’ strategies when performing a more complex task. We identified three strategies used by participants and found they overwhelmingly adopted a bi-manual use of the tabletop viewshed and tablet-based helicopter techniques. This thesis gives insight into how multi-surface environments can be designed to allow for complementary use of techniques and fluid switching between them.
Co-Authorship


- Chapter 4, the context for TerraGuide and the explanation of the OrMiS system draws from this paper.


- Chapter 2 and Chapter 4 draw from this paper.


- The studies mentioned in section 4.2.3 are explained in this paper.


*Accepted. Awaiting publication.*

- This paper describes the TerraGuide system and the user evaluation.
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Chapter 1

Introduction

Activities such as urban planning [60], military command and control [8, 57], wildlife observatory design [21] and search and rescue [3] require line of sight analysis of physical geography. For example, an urban planner may wish to know the effect on the skyline of constructing a new apartment building, while a mobile systems engineer may wish to determine the highest-coverage locations for a set of cellular transmission towers. One reason people find terrain analysis difficult is because it requires them to construct a mental model of 3D geography from representations such as a 2D map [35]. Simple 3D visualization of terrain is not sufficient on its own, since terrain analysis problems may require an understanding of line of sight from multiple locations simultaneously. For example, picking the best location for a group of cell towers requires an analyst to understand the combined coverage from a set of candidate locations.

In general, terrain analysis requires the analyst to answer questions such as “What places are visible from a given set of observation points?” and “At what points is the given location visible?” [35]. Despite the development of new digital technologies for terrain analysis, universities devote entire courses to this problem (e.g., [22, 43]).

Traditionally, geologists and military personnel perform terrain analysis using paper maps where contour lines and shading show terrain elevation. Analysts can place acetate sheets over maps and annotate using pens. More recently, Geographic Information Systems (GIS) use digital representations of maps, permitting special-purpose visualizations for terrain analysis. These include viewshed visualizations [44], line of sight tools [13], 3D panoramic views [21], and magic lenses [11]. Current GIS visualizations often suffer key usability problems, however, hindering their adoption. For example, the ABACUS military simulation tool [51] can show a 3D panoramic view from a given map location, but requires a multi-step dialogue box and several
seconds to generate the view. Additionally, line of sight visualizations are typically decoupled from the underlying map view, making it difficult for users to move quickly between the map and the visualization [13, 14, 21].

Researchers are exploring the use of large digital tabletops for collaborative geospatial analysis tasks [11], military planning [8], and disaster response [50]. Digital tabletops naturally support collaborative work by enabling face-to-face communication, pointing and gesturing, and seamless awareness of others’ activities [26]. These properties have led researchers to explore the benefits of digital tabletops for computer-supported collaborative work in co-located situations such as terrain analysis. However, many of these systems do not adequately support the terrain analysis needed for realistic military scenarios.

Terrain analysis is a difficult process and current tools do not adequately support analysts. Current systems often offer cumbersome user interfaces that hinder the adoption of useful tools for terrain analysis. In this thesis, we propose a novel multi-surface environment that aims to provide analysts with real-time terrain information through simple touch interaction. We validate our system through a user study that shows adoption of new view techniques using bimanual interaction.

Inspired by traditional geographic visualization techniques and recent experimental digital tabletop applications, we address the problems of terrain analysis through a novel multi-surface environment. Our tool, named TerraGuide, centres around a digital map presented on a large interactive tabletop surface, augmented by a secondary display and a hand-held tablet. We developed three techniques to aid with terrain analysis: a *viewshed* shows visibility in a cone drawn from the user’s touch point on the table; a *panoramic view* provides a 3D first-person view on a separate display, and a *helicopter view* allows the user to see terrain in 3D on a handheld tablet positioned over the table. Previous systems have demonstrated visualizations similar to
these; however, the novelty of TerraGuide comes from the real-time and fluid combination of these interaction techniques.

We adapted a traditional viewshed technique to run in real time on a touch tabletop allowing for simple navigation and exploration of a digital terrain. TerraGuide displays a low-resolution viewshed when a user moves the viewshed around the terrain. TerraGuide displays a high-resolution image when the user stops moving the viewshed.

The panoramic view shows an exact representation of the viewshed rendered into a 3D first-person perspective. A vertical screen in front of the tabletop displays the panoramic view. It is available as a supplementary reference for the user, used in conjunction with the viewshed.

The helicopter table view enables the user to explore the terrain from any position above the tabletop. As the user sweeps the tablet above the tabletop, TerraGuide displays a real-time 3D rendering of the terrain on the tablet based on its position and orientation. The tablet uses optical tracking for a smooth and fluid user experience with no perceptible latency.

The design of TerraGuide as a multi-surface environment follows three principles: TerraGuide computes views in real-time, TerraGuide couples views on different surfaces tightly, and users can easily switch between different views. These design principles affect the participants’ strategies and preference among techniques when using the TerraGuide system for terrain analysis tasks.

We performed an exploratory study evaluating TerraGuide and its user experience. The first part of the study evaluated participants’ performance, preference, confidence, and cognitive load during a simple analysis task with combinations of the different techniques. The first part of the study provides us with quantitative information we can use to compare the different techniques. We found that the helicopter view improved participants’ completion time and accuracy when identifying the highest points on the terrain. In addition, the use of the 3D panoramic view worsened task completion time, yet increased participants’ confidence in their analysis.
Interestingly, it was more difficult for participants to locate and compare the lowest points than the highest points on a digital terrain.

The second part of the study determined participants’ strategies when performing a more complex task. This part of the study provides us with qualitative information through video recording of participants completing a realistic terrain analysis task. We found that the viewshed technique was widely used for detailed analysis and that participants adopted bi-manual use of the viewshed and helicopter techniques. After the study, we conducted a semi-structured interview inquiring about participants’ strategies preferences. We use the collected participants’ comments to support our findings.

We aim to design, develop and evaluate a simple system for terrain analysis that provides visibility information in real-time through multiple views. Our central contribution is to show how interaction techniques on multiple surfaces can be designed to allow fluid, combined use of multi-surface techniques and easy change between these techniques. Our results are of interest both to designers of systems supporting terrain analysis and to designers of multi-surface environments in general.
Chapter 2

Visibility Analysis and Military Planning

In this chapter, we describe terrain and visibility analysis and demonstrate why people find it hard to perform. We provide the background knowledge of terrain and visibility analysis using examples from telecommunications, urban planning, archaeology, and focus on the military domain. We chose to emphasize terrain analysis in the military domain for two reasons; first, visibility analysis is a necessary component of military missions and exercises. Second, the military domain provides concrete examples of personnel conducting visibility analysis. We also explore battlefield visualization, which is crucial to military planning and demonstrates the importance of visibility analysis.

2.1 Terrain and Visibility Analysis

Terrain analysis is the process of interpreting geographic features, weather, vegetation, and light to predict their effect on the given task [75]. For example, terrain analysis is used to understand how the slope of a terrain affects water runoff [77]. Visibility analysis is a sub-domain of terrain analysis that focuses on line of sight and visibility within a terrain. Merriam-Webster’s Dictionary defines line of sight as “a straight line from an observer’s eye to a distant point” [38]. Objects in between this line impede the observer’s line of sight and thus, obstruct the view to the terrain behind the object. Visibility refers to the perspective of an observer, such as the field of view of a soldier. Determining what is visible from a location can affect, for example, the value of real estate, the placement of communication towers, or the location of a defensive bunker. Visibility analysis can be applied to domains such as communications [49], archaeology [78], urban planning [60], and military planning [75].
Visibility analysis involves assessing the elevation of a terrain to determine the areas of land visible to observation points. For example, telecommunications analysts perform visibility analysis to determine the placement of cellular telephone towers in a city. Towers are placed in a network to provide telephone coverage for customers [46]. Terrain artefacts, such as mountains and tall buildings, may affect the signal and coverage of the towers disrupting the telephone network. These constraints limit the possible arrangements of the towers and present a difficult task for analysts to complete [46].

Another example of visibility analysis comes from glacial archaeology. Analysts use visibility analysis to locate areas of glaciers that may be exposed to natural elements such as rain, wind, or sunlight [53]. These areas are vulnerable to decomposition and are urgently sought after for protection, especially with the increase in levels of glacial retreat. Archaeologists conduct visibility analysis on the surrounding environment to predict at-risk areas in advance. Using visibility analysis, geologists may be able to prevent further glacial breakdown by protecting these archaeological sites [53].

Terrain and visibility analysis can be difficult due to the need to consider multiple competing factors [46]. For example, consider an urban planner in charge of locating a new subdivision in a city. The planner has chosen to build the subdivision on an area of wetlands that feeds a pre-existing lake. The placement of new homes in this area will interrupt the ecosystem and the urban planner chooses a new area on a hill as the next candidate for the subdivision. However, building homes on this hill will negatively impact the skyline of residents from the main part of the city, causing the value of existing homes to decrease. Hoping to avoid this, the planner chooses another section of land that sits lower on the hill. However, cell phone coverage is limited in this area due to the restricted visibility caused by the hill. This example shows how numerous factors affect the task of locating a subdivision.
We have described terrain and visibility analysis and have given examples of this process in the domains of telecommunications, glacial archaeology, and urban planning. We now describe and provide examples of visibility and terrain analysis in the military context.

2.2 Military Terrain and Visibility Analysis

One of the first recorded uses of visibility analysis with line of sight dates to the 18\textsuperscript{th} century siege of Ath in Belgium. French military engineer Prestre de Vauban (1633-1707) created a map of the town depicting the weapon fan of artillery batteries and their line of sight \cite{12}. The French military used this map to locate batteries around Ath in a formation that would increase the number of areas affected by artillery fire and thus inflict more damage to the city.

Terrain analysis is important to successful military planning \cite{75}. The Canadian Armed Forces employs personnel dedicated to performing terrain and visibility analysis. These personnel, called geomatics technicians, are responsible for capturing, preparing, and managing geographic data from different sources including digital maps, observations and notes from the field, paper maps, satellite imagery, and aerial photography. They use specialized equipment and programs to perform three-dimensional spatial analysis on the terrain in military scenarios. It is their responsibility to provide terrain information and analysis used during the planning and operation of missions \cite{22}.

Visibility analysis requires considerable skill and training \cite{9,10}. All personnel in the Canadian Forces (including the Air Force and Navy), regardless of rank or role complete training in terrain analysis. Those in charge of making decisions based on terrain typically complete several courses on the subject. Geomatics technicians in the Canadian Forces, for example, must complete 20 months of schooling at Algonquin College and the Army School of Military Mapping after their completion of Basic Military Training \cite{23}. Private Brandy Alexander from Kamloops, British Columbia gives her thoughts on her role as a geomatics technician and
performing terrain analysis: “If you’re interested in maps, definitely if you’re interested in problem-solving and challenging yourself - it requires a lot of thought and patience, but it also is very rewarding. For us, it’s a pretty demanding and exciting job” [22]. Geomatics technicians provide terrain information to commanders who use this information to aid them in the planning of military operations. Commanders use information from geomatics technicians to perform battlefield visualization, where they keep a mental model of the current state of the battlefield.

2.2.1 Battlefield Visualization

Battlefield visualization is an activity where a commander (or analyst) combines all relevant information, including the terrain, into a mental representation of the battlefield. The US Army Training and Doctrine Command describe battlefield visualization:

“The process whereby the commander develops a clear understanding of the current state with relation to the enemy and environment, envisions a desired end state which represents mission accomplishment, and then subsequently visualises the sequence of activity that moves the commander’s force from its current state to the end state” [72]

The commander mentally visualizes the plan of action that best suits mission success. The commander must understand all factors on the battlefield, including the terrain, before executing his or her plan. A skilled commander can synthesize all relevant information from different sources into a unified mental model. Thus, the commander must understand how terrain influences all aspects of a military operation. Traditionally, paper maps and acetate overlays have contributed to understanding the battlefield. Recently, digital maps and geographic information systems have started to take the place of paper maps and have been proven to work successfully
in real battle scenarios [35]. Allowing a commander to visualize the battlefield more quickly and easily can benefit informed decision-making and mission success.

2.2.2 Performing Terrain Analysis

To demonstrate the complexity and difficulty of terrain and visibility analysis we will explain how a commander might plan a hypothetical military operation. The key aspects of terrain from a military perspective are formulized by Observation and fields of fire, Avenues of approach, Key and decisive terrain, Obstacles, and Cover and concealment (OAKOC) [74]. Commanders and analysts base their military decisions involving terrain on these key factors.

- **Observation** is the total field of view for a soldier; aided either by binoculars or with his or her naked eyes. *Field of fire* is the maximum range and area of his or her weapon systems.

- **Avenues of approach** describe the route a soldier, group of soldiers, or unit will take to get to their objective. Line of sight and visibility analysis is important and must be considered when designing avenues of approach [75].

- **Key and decisive terrain** describes areas of terrain that are advantageous for a military force to hold. For example, a defender would want to hold terrain that would give them a better chance of defending their position. The terrain may have manufactured features, such as a bridge, that would give the controlling force a tactical advantage.

- **Obstacles** are natural or synthetic objects in the terrain that may interfere with the traversal of terrain. Obstacles can include barbed wire, a tank ditch, tank barriers, buildings, rivers, gorges, mountains, and mine fields. Obstacles can be used to keep the enemy away from key terrain or to direct the enemy to follow a certain path [75].

- **Cover and concealment** determines how commanders deploy soldiers in the terrain. Cover and concealment can offer protection to friendly and enemy forces. Therefore, a
commander must consider how the enemy will cover and conceal as well as how to protect his own soldiers. Cover can be naturally found in the terrain, such as rocks and vegetation, or created by using sand bags or bunkers. Concealment does not provide cover and therefore does not directly protect soldiers under fire. An example of concealment would be wearing camouflage or hiding in long grass [75].

Military commanders consider all of the above factors when planning an operation. For example, when choosing locations to set up defensive positions, commanders ensure that all avenues of attack are covered. Similarly, when planning avenues of approach, commanders choose safe routes that reduce visibility to hostile forces [24]. To demonstrate this complexity, consider the analysis of a terrain to establish an avenue of approach or route. The analyst must think like an attacker and defender; the attacker looks for routes that provide the best cover and concealment from enemy observations and fields of fire. The defender identifies the possible avenues through visibility analysis. The defender places obstacles on these routes and determines avenues that are susceptible to ambushes or counter-attacks. In addition, the route must be wide enough to accommodate the unit; for example, a tank squad needs more room to manoeuver than an infantry squad. Furthermore, commanders may design routes for speed, safety or a balance between them. A safer route could require a lengthy traversal that may not be acceptable in a time-pressured scenario. Thus, finding a balanced route that is both safe and practical can be a complicated process involving numerous factors.
Figure 2.1. A) The top down view of an area. The blue dot represents a soldier defending the area of land to his south, the blue shaded circle. He is facing north. The orange circles represent possible areas from which the enemy may approach. B) The soldier’s perspective from his defensive position. Note the two hills (1 and 2) on his left and right.

Line of sight and visibility analysis is important when considering observation, fields of fire, and cover and concealment. Using knowledge of the terrain, such as elevation, analysts can perform line of sight analysis to gain insight about these aspects. For example, consider a soldier setting up a defensive position in Figure 2.1A. The soldier must defend the area represented by the blue circle. The orange circles represent area that is not visible to the soldier because they are located behind hills. The terrain that is level with or higher than the soldier’s position blocks visibility. Thus, he or she does not have observation or fields of fire on these areas (Figure 2.1B). The orange area provides cover and concealment for the attacker. If the enemy has performed proper terrain analysis, they will choose to approach the soldier from the orange areas, behind the hills. The commander may feel it is necessary to move the soldier, or place another soldier in a position that provides observation and fields of fire to the orange areas.

2.3 Conclusion

In this chapter, we described what terrain and visibility analysis are and why they are used. This chapter demonstrates the importance of terrain visualization and visibility analysis in the
military and other domains. We provided examples of terrain and visibility analysis from the military perspective and discussed the important role geomatics technicians play in the Canadian Forces. In the next chapter, we will describe common tools used for visibility analysis as well as experimental tools that have the potential to change how analysts conduct terrain and visibility analysis.
Chapter 3

Traditional and Digital Support for Terrain Analysis

Terrain analysts use multiple tools and techniques to aid their decision-making. In this chapter, we describe traditional and digital techniques that support terrain analysis and experimental techniques using novel devices. For this chapter, we will use the term *technique* to describe interactive visualization that provides information about a terrain. Visibility analysis *techniques* reside within specialized *tools*. These tools can be geographic information systems (GIS) or specialized applications for military planning. Geologists initially developed techniques around paper maps. More recently, techniques have evolved within sophisticated digital tools. We used these existing techniques as inspiration for the visibility analysis techniques we incorporate into our TerraGuide tool.

3.1 Paper Maps

Traditionally, geologists performed terrain analysis using paper maps and acetate overlays containing information such as contour lines, roads, and vegetation. Today, analysts often collect and store this information digitally. Many analysts, however, still prefer to work on paper maps rather than computers [31]. Today, users can find many of the techniques for terrain and visibility analysis that we describe in this chapter on both paper maps and current digital GIS.

3.1.1 Bird Tables and Sand Tables

In command and control environments, a ‘Bird Table’ is a physical table, usually located in the center of the command room, which contains the paper maps and acetate sheets for the current situation. The name ‘bird table’ perhaps originated from the concept of a ‘bird’s-eye-view’.
Officers gather around the bird table to take instructions from the commander or to plan attack and defense collaboratively.

Similarly, a sand table contains a constrained model of terrain built out of sand. Sand tables are used for planning, war gaming, and teaching military tactics to students [79]. They provide a tangible area of the geographic terrain [69]. Today, sand tables have lost popularity in favour of virtual representations of terrain using digital maps.

![Figure 3.1. A U.S. Military sand table used in the forward operating base.](http://upload.wikimedia.org/wikipedia/commons/thumb/b/ba/US_Navy_040902-N-5152S-027_Commodore_Margarinto_Sanchez%2C_Jr.%2C_Rear_Adm._Charles_Kubic_and.Cmdr._Clayton_Mitchell%2C_gather_around_a_sand_table_in_the_forward_operating_base.jpg/1024px-thumbnail.jpg)
3.2 Digital Maps

More recently, digital representations of maps have become standard for geographical analysis. Digital maps allow for easier transfer of information compared to paper maps. Digital maps can be stored on computers or portable hard drives and colleagues can share maps over networks and the World Wide Web. Digital maps have also led to powerful techniques to assist terrain analysis. Using digital terrain models (DTMs), algorithms can determine line of sight and can generate 3D models of terrains [35]. Digital maps allow users to show and hide information layers (e.g. for population density, elevation information, slope, electrical grids or water runoff) and change the scale of the map [15]. However, some advantages of paper maps are lost, such as being able to collaborate around a map on a table or annotate the maps with pens.

3.2.1 Creating Digital Maps

Geologists obtain digital terrain elevation in multiple ways including stereo photogrammetry, real-time kinematic global positioning system (GPS), topographic maps, Doppler radar, and Light Detection and Ranging (LiDAR). LiDAR is a popular method for creating high-resolution DTMs due to its accuracy and good resolution [6,37,68]. The process involves equipping a vehicle or tripod with a laser scanner, a high-quality GPS receiver, and an inertial measurement unit (IMU) [6]. The scanner on the vehicle receives the light from the laser that bounces off the terrain. The IMU provides data about the scan angle and the vehicle’s or tripod’s position. The distance the light travelled is calculated using this information and is stored with corresponding geographic point coordinates. Analysts create the digital terrain model by combining the collected data points. The sampling rate when collecting terrain data determines the resolution of the DTM. Increasing the sample rate increases the resolution of the model. Typical spatial resolution of a high-quality LiDAR scan is 0.5 to 2 meters and a vertical accuracy of 15 centimeters [37].
3.2.2 Types of Digital Terrain Models

There are two primary digital models of terrains. The first type of DTM is a Digital Elevation Model (DEM), also called a Regular Square Grid (Figure 3.2A). DEMs consist of a gridded array of elevation points with a constant distance between each point. Many locations around the world are becoming freely available as DEMs [76].

The second type of DTM is a Triangulated Irregular Network (TIN). TINs contain a series of non-overlapping triangles. Each vertex of a TIN contains elevation information about a terrain (see Figure 3.2B). TINs are generally created from DEMs to conserve space [37]. TINs use an irregular distribution of elevation points as opposed to the regular distribution of points found in DEMs. TINs use fewer points in areas that have similar elevation. However, in areas of interest, or where elevation change is occurring rapidly, more triangles are used. TINs compress areas of similar terrain into larger triangles using fewer elevation points. Thus, TINs require less storage space than DEMs but may not retain the same fidelity of the sampled elevation [37]. Figure 3.2 shows this effect.
Figure 3.2. A DEM (A) and a TIN (B) rendering of Bowen Island off the coast of British Columbia. The maps have hypsometric tinting applied.\(^2\)

### 3.3 Methods of Visualization and Analysis of DTMs

Geologists obtain high resolution DTMs using LiDAR and other surveying techniques. An analyst uses visualization techniques to make informed decisions about the terrain. Here we describe several popular techniques for visualizing digital terrain information.

#### 3.3.1 Contour Lines

Computer algorithms or geologists generate *contour lines* from DTMs to allow analysts to get a sense of the shape and elevation of the terrain (Figure 3.3). A contour line denotes terrain of equal elevation. On a map with multiple contour lines, it is possible to infer the shape of the terrain. The contour interval is the difference in height between adjacent contour lines. Thus, when lines are closer together, the elevation change is faster, and the terrain is steeper. Features

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\(^2\) Created by Matthew Oskamp and Robin Harrap. Used with permission.
of contour lines such as line weight, colour, type, and numbers convey additional information such as the arithmetic values of the elevation [71].

When trying to find a safe route for vehicles through a combat zone, a military planner might use a contour map overlaid with an acetate sheet. The planner draws the route on the acetate with a marker, using the contour lines to visualize the visibility of vehicles following the route. This requires analysts to extract a mental model of the terrain from its map representation [35].

Analysts can inexpensively place or print contour lines on paper maps. However, they are not ideal for complex automated terrain analysis because they are not readily available digitally. Some digital maps are created by hand using contour maps as a reference [37].

Figure 3.3. A labeled contour map of a mountain from the Appalachian Mountains in Maine, United States³

³ MapXpert user via Wikimedia Commons. http://commons.wikimedia.org/wiki/File:Cntr-map-1.jpg#filelinks
3.3.2 Hill Shading

*Hill shading* (or shaded relief) simulates how terrain looks under sunlight. Cartographers generate shadows on terrain by placing a virtual sun in the sky (Figure 3.4A). Analysts can change the azimuth and altitude of the sun to create different effects. This helps viewers recognize the shape of land features on the map. Interestingly, when a shaded relief map is created with the light source coming from the lower right-hand side of the map and casting shadows towards the upper left, people experience *relief inversion*, where valleys appear as ridges and vice-versa [34]. For this reason, analysts usually generate shaded relief maps using an imaginary light source located at the upper left of the map.

3.3.3 Hypsometric Tinting and Slope Shading

*Hypsometric tinting* involves colouring a map based on the elevation values of the underlying terrain. Analysts can use hypsometric tinting to depict graduations in elevations by colour gradients. A common colour scheme uses blues for low elevations, yellow/greens for medium, and reds at the highest elevation. Figure 3.4B shows the moon with hypsometric color-scheme graduating from purple (low) to red (high). *Slope shading* is similar to hypsometric tinting except the gradient uses colours to indicate the steepness of terrain.
Figure 3.4. A) Shaded relief map\textsuperscript{4} and B) hypsometric tinting from purple (low) to red (high) representing elevation of the Mare Orientale area of the Moon\textsuperscript{5}.

3.3.4 Line of Sight and Viewshed

As defined earlier, line of sight refers to the straight line from an observer’s eye to a point [38]. A cross section profile or a top down view of the terrain indicates the part of the terrain that is visible to an observer and the objects that may be interfering with visibility (Figure 3.5A).


Figure 3.5. A) Line of sight output from ArcGIS. The black dot is the observation point and the red dot is the target. A green line represents visible terrain and a red line represents terrain not visible to the observer. B) A viewshed displaying areas of the terrain that are visible and invisible from a single observation point. The coloured areas represent visible land and no colour represents areas that cannot be seen from the observation point.

A viewshed is one of the most common geographic visualization techniques used to interpret elevation data on digital maps [44]. A viewshed shows the parts of terrain that are visible from a specific location on the map (Figure 3.5B). A viewshed is traditionally displayed as a 2D arc (pie slice) where visible terrain is shown in one colour and invisible terrain shown in another colour (or not shown). The viewshed tool provides answers to questions such as, “What places are visible from the given observation point?” and “How many places is the given observation point visible to?”

Viewshed tools in existing systems are typically cumbersome to use, requiring multi-step dialogues and lengthy rendering times. For example, the viewshed tool in the popular GIS ArcGIS [81] takes nine parameters to operate (spot, offset – observer, offset – point, azimuth –

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6 Created by Matthew Oskamp and Robin Harrap in ArcGIS. Used with permission.
left, azimuth – right, vertical angle – upper, vertical angle – lower, radius – left, radius – right) and depending on the task and computer hardware, can take minutes or hours to compute [21].

3.3.5 Panoramic Views

Panoramic views generate a 3D view of the terrain from a given perspective. 3D perspectives of digital terrains have been shown to give a better understanding of the shape of terrain and are generally liked by users [18, 27, 59]. Panoramic views and viewsheds can be complementary. For instance, when analyzing the Rocky Mountain landscape, Germino et al. found that 2D viewsheds were superior for quantifying the dimensions of a terrain (i.e. areal extent, relief, depth), while computer-generated 3D panoramic views at ground level performed better for representing the composition of a terrain (i.e. land cover, diversity, edge) [21].

However, there is continuing debate on the types of analysis tasks that benefit from 3D perspectives [66]. Even though users generally prefer working with 3D panoramic views, studies have revealed that panoramic views may not be beneficial for all spatial navigation tasks [32].

ABACUS, a military simulation tool, provides a representative example of a panoramic view [51] (Figure 3.6). The primary view in ABACUS is a battlefield represented by a 2D digital map. Analysts can use the panorama tool to generate a soldier’s first-person view. Users must navigate a cumbersome dialogue to specify the desired view and then wait through a slow rendering phase. This system does not support rapid exploration of terrain.
3.4 GIS and Military Simulation Applications

Several applications use digital maps and the above techniques for terrain analysis. ArcGIS is an application created by ESRI (Environmental Systems Research Institute) for working with maps and geographic information. Analysts can use the software for managing, analyzing, and sharing geographic information. In 2010, ESRI had 40.7% of the global market share, particularly from ArcGIS Desktop [16].

The Canadian military uses three main applications for military planning and simulations, ABACUS (Advanced Battlefield Computer Simulation, see Figure 3.6), JCATS (Joint Conflict and Tactical Simulation), and BattleView. Simulation and planning tool interfaces are composed of a full-screen map view with a large set of accompanying controls. The units are displayed directly on the map using NATO MIL-STD-2525B symbols [40], which is a standard for military map marking for land based formations and units (Figure 3.7). Interface controls allow operators to set the position, orientation, heading, and rules of engagement of units, to organize units’ hierarchy, to perform combat operations, and to create routes.

[Figure 3.6. The perspective view technique in ABACUS\(^7\).]

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\(^7\) Used with permission from the Army Simulation Centre.
3.5 Novel Techniques for Terrain Analysis

Researchers have proposed, developed, and tested new interesting techniques for terrain analysis in a laboratory environment. Therefore, analysts do not yet use most of these experimental techniques in practice.

3.5.1 Interactive Tabletops

Large tabletops naturally support collaborative work by enabling face-to-face communication, pointing and gestures, and seamless awareness of others’ activities [26]. These properties have led researchers to explore the benefits of digital tabletops for computer supported collaborative work in co-located situations such as terrain analysis.

Digital tabletops offer user interaction techniques, such as touch and pen [65], hand gestures [20], and eye and gaze tracking [29]. Digital tabletops support touch input and naturally fit the form factor for working with maps. For example, map-based functionality such as zooming,
panning, and dynamic update of map contents to provide different information layers (analogous to acetate sheets) can be readily supported on digital tabletops [65].

uEmergency [50] for example, supports forest fire responders by providing real time geographic information on a large tabletop. uEmergency displays a shared interactive map as well as individual windows and widgets for each user. The same approach is also used in eGrid [59], which provides multiple rotating views of the same map to support the analysis of a city’s electrical grid. This approach of splitting the same map into multiple views on a tabletop display supports individual work while maintaining workspace awareness.

Thumbles [46] are robotic tangible pucks used on an interactive tabletop. They can aid complex spatial layout problems such as telecommunication tower layout. Thumbles allow users to physically move towers around and receive immediate feedback on areas of coverage. The system automatically moves the pucks (towers) to areas that will improve total coverage and reduce areas of redundant coverage. Thumbles can aid an analyst in the placement of communication towers on a flat 2D map by automating constraints such as zoning regulations and minimum and maximum distances between towers. However, Thumbles do not use visibility analysis on 3D digital terrains.

3.5.2 Tablets

Recent systems use tablets to aid geospatial exploration and analysis. Tablets are small handheld computer devices with an interactive display that interacts through touch and occasionally pen input. The Tangible Disaster Simulation System [36] divides the output space by combining a tabletop display with two external screens; the first shows a 3D first-person perspective of the map, and the second displays information describing the underlying disaster simulation. Preliminary evaluations show that users enjoy the multi-display approach of the
system that allows one user to interact with the map while the other monitors the results on the external screen.

Tablets can act as Magic Lenses [5] to reveal information on the table using their physical location. Bier et al. introduced Magic Lenses in 1993 as tools that allow visual filtering over a 2D frame of reference [5]. For example, a static map serves as a frame of reference and a user places a clear lens over the map. The region of the map shown through the magic lens is able to change to reveal different information such as population density. Magic Lenses have since evolved and are used with mobile phones [54] and exploring 3D spaces or volumes [70]. Tablets have been shown to work well for exploring a 3D volume in combination with tabletops [70] and have been used for their portability and accessibility [11]. However, researchers have conducted limited research in the area of geospatial exploration.

In Skyhunter, Seyed et al. used a tabletop-based multi-surface environment with tablets to explore geographic regions of oil reservoirs. Users could visualize seismic information corresponding to the placement of their tablet on the table (showing a map) [11]. Users could share information between devices by using a set of pre-defined gestures.

The metaDESK [73] project by Ullmer and Ishii 1997 combined a tablet and tabletop to explore a virtual 3D campus. Users place tangibles on an interactive tabletop that displays a 2D map. An arm-mounted ‘active lens’ displays a spatially contiguous 3D view of the 2D map on the tabletop. The active lens displays a 3D perspective of the MIT campus. By moving the lens, users could navigate the 3D space and zoom in to areas of interest. Users encountered several issues with navigation when working with the metaDESK: users relied on kinaesthetic cues and the 2D desk map to navigate the active lens to a new 3D perspective, rather than navigating through the 3D landscape [73]. In addition, the perspective shown on the active lens was rendered perpendicular to the tabletop, not from the vantage of the user’s eye position, causing confusion in some users [73].
3.5.3 Multi-Surface Environments for Terrain Analysis

Seyed et al. describe Multi-Surface Environments (MSEs) as, “A system where interaction is divided over several displays, such as digital tabletops, wall displays, and personal devices like tablets or mobile phones” [61]. The different devices used in MSEs allow for a variety of interaction and collaboration techniques. Recent studies into MSEs have targeted the effects of different device configurations on users and the collaboration between them. However, there is limited research on what interaction techniques are most effective for geospatial data [62].

The BUILD-IT [17] system is a tangible planning space where users arrange bricks (representing virtual objects) on an interactive surface and used a vertical view to render a virtual scene. Engineers designing assembly lines and building factories collaborate using the BUILD-IT system and organize the plans for the factory with tangible objects. A vertical screen shows the 3D virtual representation of the factory to provide feedback to the planners and allow them to visualize the scene from a different perspective. BUILD-IT uses multiple surfaces to give designers another perspective on their work. However, due to technical limitations at the time, the system did not run in real-time and the vertical screen displayed scaled down geometric shapes. Although terrain and visibility analysis was not the focus of this system, the concept of providing a secondary screen for an alternate perspective can be used for working with maps and 3D terrain.

3.5.4 Virtual Reality

Virtual reality immerses the user into a computer-generated environment. Using virtual reality headsets users can explore and get a physical sense of their surroundings. Digital geographic environments viewed using virtual reality headsets allow for an immersive visualization of digital terrain. Hedley et al. proposed a hybrid virtual-augmented reality system for collaborative GIS. Users look at a paper map on a tabletop and see a stereoscopic three-dimensional virtual terrain. Users can walk around the table to view the terrain from multiple
angles and move their head closer to the map for a more detailed view. Preliminary results showed that users found the system easy to use [28]. Recently, virtual reality headsets, such as the Oculus Rift, are becoming commercially available and affordable. ESRI has announced new plugins for Oculus Rift to integrate virtual reality into GIS using the game engine Unity 3D [45].

3.6 Conclusion

In this chapter, we described the main techniques and tools used for terrain and visibility analysis. Analysts use these advanced visualization techniques to understand the terrain better. We also introduced experimental techniques that have the potential to change the way analysts perform terrain analysis.

We can use a combination of these traditional and experimental tools to create a system designed for terrain analysis focused around a digital tabletop. As we have discussed, digital tabletops naturally support map-based tasks and can provide a frame of reference for a 2D map. The tabletop should support common visibility analysis techniques found in current GIS such as viewsheds and panoramic views. In addition, with current technology we can develop real-time terrain visualization techniques using magic lenses to explore 3D elevation information provided by digital maps. This was our main goal when designing TerraGuide. TerraGuide is a multi-surface environment that allows people to perform visibility analysis tasks with little training or practice. In the next chapter, we will provide the context and motivation for developing TerraGuide. We will describe several issues in the current military simulation paradigm. We will show how our tabletop system OrMiS (Orchestrating Military Scenarios) was designed for simple, collaboration interaction in military simulation and planning scenarios.
Chapter 4

Context: a Tool for Military Simulation

In the previous chapters, we provided background information on terrain and visibility analysis and the tools used when performing analysis. In this chapter, we will discuss OrMiS a tool used for Orchestrating Military Simulations. We developed TerraGuide to explore possible techniques for terrain analysis based around an interactive tabletop. We found limitations in the ability to perform terrain and visibility analysis using OrMiS. In this chapter, we provide the context for TerraGuide and describe how and why OrMiS was developed. We will describe the process of training military personnel through simulation and the issues present in the current paradigm. We designed OrMiS to address these issues and provide a collaborative military planning system around a digital tabletop. Terrain and visibility analyses are a key component in military simulations. However, OrMiS only provides only rudimentary support for these types of analyses.

OrMiS was designed and developed by a group of people at the EQUIS Lab at Queen’s University. The lead designers and developers were Dr. Christophe Bortolaso and Matthew Oskamp. Florian Eysseric and Jeremy Bourdiol made important contributions. OrMiS’ design was influenced by earlier prototypes created by Andrew Heard, Eric Ingle and Amir Sepasi. My key contributions in the development of OrMiS was the terrain system, including the generation and display of three dimensional terrain and allowing routes to distinguish between types of terrain (water, forest, road, grass).

I was the lead designer and developer of TerraGuide, which forms the core contribution of this thesis.
4.1 Military Training

Military training allows soldiers to practice their skills before engaging in live operations. Trainees can practice real-life scenarios in a safe, controlled environment without risking injury or destruction to property. Also, instructors can demonstrate lessons through planned scenarios and events [55]. For example, soldiers practice on simulated, defused improvised explosive devices (IEDs) before encountering them in the field so they can be familiar with the process and not be harmed while they are learning [55].

4.1.1 Simulation-Based Training

Fully developed military training exercises can be prohibitively expensive as they can involve thousands of people, land vehicles, and aircraft. For example, a command and control (C2) training scenario can involve directing multiple battalions (thousands of troops) through a battlefield the size of Kingston, Ontario (the location of Queen’s University, approximately 2,000 km²) encountering enemy forces, such as tanks and artillery batteries. Staff officers use computer simulations of military scenarios to train. Staff officers receive information and give orders to units in the field. Simulation-based training is used because it provides a manageable, low-cost way of training staff officers in large scale scenarios [55]. The Canadian Forces has strong expertise in simulation-based training because it provides an affordable alternative to large-scale real-life training exercises [55]. Simulation-based training can involve video game technology, such as Virtual Battlespace 2 [7], a program based on the popular game ARMA 2. These games are used to simulate the soldiers’ movements and actions on the battlefield and their activities, such as being transported in a light-armoured vehicle (LAV) or flying a helicopter [55]. Other simulations can involve an array of networked computers running specialized software to simulate the movement of units on a battlefield. Specialized military training applications feed
positions of virtual units into the program used by trainees. Trainees can thus practice realistic command in specific scenarios, without involving real people who may be at risk of injury.

Our knowledge about simulation-based training comes from three separate visits to the Army Simulation Centre in Kingston, Ontario. During these visits, we conducted field observations and supplementary interviews with simulation experts working behind the scenes. We refer to these experts as interactors.

![Diagram](image)

**Figure 4.1. Typical configuration for running a command and control simulation exercise.**

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*Created by Christophe Bortolaso and Matthew Oskamp. Based on observations at the Army Simulation Centre*
Some tools for simulations superficially resemble real-time strategy games such as StarCraft, where players frantically move units over a map while attempting to defeat other players. However, this resemblance is misleading. Simulated exercises are slow-paced, often running over several days. The simulations are literally real-time: it might take an hour for a simulated tank squadron to travel 20 kilometers once the interactor has issued movement directions. Interactors frequently have a book or newspaper to keep them occupied during long periods of inactivity.

4.1.2 Interactors

Interactors work behind the scenes moving virtual troops during command and control simulation-based training scenarios. According to our observations, depending on the scenario, ten to twenty interactors sit in a control room in front of traditional desktop computers running simulation software (Figure 4.1 and Figure 4.2). Usually, interactors are retired military officers who have experience in command and control. The Army Simulation Centre normally assigns interactors a group of related units to control. They are responsible for responding to orders from trainees and guiding the outcome of the training scenario. This involves orchestrating and moving units along unspecified routes. Typically, a small number of interactors are responsible for controlling all the movements of the enemies on the battlefield; however, interactors can change the simulation on the fly to stress a point or demonstrate a lesson. For example, interactors can agree to destroy a key unit (e.g. a tank) to force the trainees to take a new action or different avenue of approach.

Interactors perform terrain analysis when making decisions based on avenues of approach or setting up defensive positions during the simulation. The desktop applications used by interactors provide support for terrain analysis (see Chapter 3.4).
4.1.3 Problems with C2 Simulation-Based Training

We identified two main problems with the current infrastructure through three separate in-house observations at the Army Simulation Centre and through extensive interviews with the Senior Synthetic Environment Integrator Doug Brown and discussions with military personnel responsible for designing and conducting simulation-based exercises.

1. The computer applications used for simulations are hard to learn. Interactors participate in simulations only a few times a year and as a result, several days of training are required prior to each simulation. The interfaces of existing PC-based simulation tools are complex, and thus require significant training and expertise to use. It is difficult to find interactors who are experts both in military C2 and in the simulation tool. A lack of qualified personnel limits the number and size of simulated exercises.

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9 Used with permission from the Army Simulation Centre.
2. The applications used by interactors and the arrangement of the workspace weakly support synchronous collaborative tasks (Figure 4.1). Throughout the simulation, interactors are required to collaborate. They may need to re-plan their strategy or lesson. For example, when moving troops, each interactor needs to account for the visibility of the terrain by their units (to lower the risk of ambush), and ensure they will reach a location at the same time as another group of units controlled by a different interactor. The existing tools poorly support tightly coordinated actions between interactors. This is largely due to the physical setting, where interactors sit at individual PCs and have difficulty communicating with each other and maintaining a global awareness of other interactors’ actions within the (digital) battlefield. Collaboration is naturally difficult in this environment because interactors need to stand up from their desks and walk to the desks of other relevant interactors or to shout across the room to coordinate such troop movements. In practice, interactors frequently find this to be too much trouble, and therefore fail to coordinate their actions correctly.

4.2 Military Planning Using OrMiS

OrMiS (Orchestrating Military Simulation) is a military planning and war-gaming application based around a digital tabletop. We created OrMiS to address the two main issues we identified with the traditional paradigm of conducting military simulations using interactors. First, the interactors must use cumbersome user interfaces on complicated simulation desktop applications that are difficult to learn. This leads to repetitive and expensive training. Second, interactors are not able to communicate and collaborate easily and effectively.
4.2.1 Simple Touch-based Interaction

In OrMiS, we achieved a simple touch-based interface to improve usability and scalability of map based tasks. We strongly emphasized the ease-of-use of the interface as opposed to existing PC based simulation systems, which are complex and difficult to learn. For example, users can create, modify, or delete routes for units using single finger gestures. OrMiS supports two types of routes: permanent routes and one-time routes. Users create permanent routes from the map and can direct multiple units to use the route at the same time. Units using permanent routes can travel in any direction. Users create one-time routes from the individual unit. The route disappears when the associated unit reaches the endpoint.

Simple pinch gestures for zooming and drag gestures for panning control the navigation of the map in OrMiS. As with standard map applications (e.g. Google Maps), the resolution of the map display automatically increases with the zoom level, showing details that are not visible on the overview. The map can also be zoomed using bifocal lenses and personal viewports, as described in the following section.

![Figure 4.3. The OrMiS user interface and system.](image)

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10 Created by Christophe Bortolaso. Used with permission.
Users of OrMiS can drag, tap, or long press (i.e. touch and hold) elements to see the effects directly on the display. For example, a simple drag gesture originating from a unit icon automatically creates a one-time avenue of approach (or route) for the associated unit (Figure 4.4A). Tapping on the first or last waypoints can extend the current route. Users can tap on a unit to display a pie menu that enables route creation, movement control, or display visibility information. Users can move existing waypoints to different locations while a unit is traveling along a route. In this case, the unit will adapt its course in real-time to the new position of the nearest next waypoint. This technique allows simple and easy movement of units on the map. Interactors can efficiently react to situations where time is an issue, such as escaping from an enemy.

Similarly, a user can display a viewshed around a unit by simply tapping its icon (Figure 4.4B). A circular widget surrounding the viewshed modifies the heading of the unit (Figure 4.4B). To hide the viewshed and circular control, users simply tap the unit again.

To limit the number of controls and reduce clutter, OrMiS displays various feedback indicators automatically and only as needed. For example, as a user touches the map, OrMiS displays a small label indicating the terrain type (e.g. forest, road, water, land) near the touch point. This feature supports terrain exploration and provides information without the need of any additional control. During route planning, portions of the route that intersect with any non-drivable terrain (e.g. water) blink in red.
Figure 4.4. A) A user creates avenues of approach by simple touch and drag gestures. B) Units display their visibility of the surrounding area. This feature is accessible through a touch-based pie menu.\textsuperscript{11}

In contrast to the existing simulation interfaces, all of the controls described above are located directly in the context of the elements with which they are associated (e.g. unit, map, route) rather than on separated controls or external windows. Unlike, for example, ABACUS (see Figure 4.5), users do not need to switch between controls and the map, but can directly apply their actions to the units themselves.

\textsuperscript{11} Created by Christophe Bortolaso. Used with permission.
4.2.2 Naturally Supported Collaboration

With OrMiS, we aimed to improve communication and collaboration between interactors. Since OrMiS is based around a digital tabletop, it naturally supports face-to-face collaboration and awareness between users [58]. Research in group collaboration has shown that tools should support both explicit and consequential communication [2]. Explicit communication involves planned, intentional behavior, such as verbal expression, or non-verbal actions such as pointing or gesturing. OrMiS supports explicit communication by the physical configuration of the group around a shared workspace. Consequential communication occurs when a person does not

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12 Used with permission from the Army Simulation Centre
necessarily intend to communicate with others, but the person still conveys information to an observer. The tabletop allows consequential communication between users through peripheral vision. Interactors engage in consequential communication through their common understanding of military tactics. For example, an interactor positioning units in a specific formation may communicate the intent to attack.

A single shared tabletop with an interactive map is not sufficient for all activities interactors need to perform in their simulation exercises. Interactors may need to work at different levels on different parts of the map at different times. OrMiS allows interactors to work collaboratively in a strong group focus, individually on different areas of the table, or to switch between these configurations simply and easily. Collaboration that involves shifts between individual and group focus is called mixed-focus collaboration [25].

For example, two interactors may plan routes for different types of units on different sections of the map. In both cases, they require a detailed view of their part of the map; this would be a form of loosely-coupled coordination, as they are working to the same global objective, but separately. In this example, interactors may not communicate explicitly, instead using consequential communication to retain awareness of the locations of units.

Conversely, two interactors may plan routes through the same area and one interactor may be responsible for protecting the other’s units. They will now want to see the same part of the map in detail, each controlling the units for which they are responsible. This latter scenario is an example of tightly-coupled coordination, where the interactors are working closely together and attending carefully to other interactors’ actions. In this scenario, both explicit and consequential communication is important.

Multiple features in OrMiS support small group collaboration and facilitate explicit and consequential communication. We implemented a set of interaction techniques in OrMiS that tailor to different situations:
1. The *main map* on the table provides a common space for interactors to communicate and plan (Figure 4.6A). The interactive map can be zoomed and panned by using simple touch gestures. It supports both explicit and consequential communication by being visible to all interactors and providing awareness to the current state of the scenario. The main map supports tightly-coupled coordination because it can be zoomed to a common level of detail that is suitable for all users. However, interactors need a different technique to work at different levels of detail. In addition, as the map is zoomed in, any events that occur outside the zoom level (e.g., an enemy attacks a friendly unit) will be hidden to the interactors.

2. *Bifocal lenses* provide a circular area that can be zoomed and moved independently of the map itself by simple touch gestures (Figure 4.6B). A user places the bifocal lens over a part of the map to magnify that area into a higher level of detail. As the lens is zoomed-in, more of the underlying map is occluded, which has the potential to hinder awareness. The bifocal lens consequentially communicates the part of the map that each interactor is using. Bifocal lenses support loosely-coupled coordination because users can work independently at their own level of detail.
Figure 4.6. A) The main map. B) Users display two bifocal lenses on the map. C) Users show two personal viewports on different parts of the map. D) Users have tablets on the edge of the table and use the main map as a common planning area. Each images shows the radar view on the right.\textsuperscript{13}

3. *Personal viewports* are rectangular and can be moved to any location and zoomed in and out to any level of detail (Figure 4.6C). As the name implies, a single user usually controls personal viewports. Viewports provide support for explicit communication by enabling face-to-face communication. However, consequential communication is limited since OrMiS decouples the personal viewports from the main map. Therefore, it can be difficult for people to infer what part of the map a viewport is showing. The disadvantage of personal viewports is that they occlude the main map. They may hide important information such as routes and/or units. Similar to bifocal lenses, personal viewports support loosely coupled coordination since interactors can work simultaneously on different areas of the map with different levels of detail.

\textsuperscript{13} Created by Christophe Bortolaso. Used with permission.
4. **Tablets** provide an interface similar to the personal viewport but separate from the tabletop on a handheld device (Figure 4.6D). Therefore, tablets allow interactors to work independently and separately from the tabletop on a private workspace. In addition, the tablets are separated from the main map and do not occlude areas that would be covered by lenses or personal viewports. All tablets synchronize and reflect the actions performed on other tablets or the tabletop in real time, such as route creation and movement. Tablets provide poor awareness of others’ actions, since it may not be easy to see what other people are working on. Tablets are best for individual work requiring a low level of awareness.

5. The **radar view** provides an overview of the battlefield on a separate vertical display (see the vertical display on the right of each technique in Figure 4.6). It shows the positions of all units and routes as well showing which part of the map that other users are working in. The radar view displays the position of all lenses, viewports, and tablets on the main map. The radar view also indicates the zoom levels of these techniques by which users can infer areas of the map that are occluded by lenses and viewports (Figure 4.7). This view provides general awareness for interactors throughout the simulated exercise. The radar view synchronizes over the network to display up-to-date information and show changes in real time.

The combination of above techniques supports multiple scenarios with different types of communication and collaboration. With OrMiS, interactors can choose whichever interaction technique best suits the current collaborative scenario, and as a result provides the level of support for consequential and explicit communication required by the given situation.
Figure 4.7. The radar view. A blue rectangle indicates the area of the map displayed on the tabletop. The red circles are bifocal lenses and the radius of the inner circle indicates their zoom level. The red shaded areas indicate the area of the map the lens occludes.

4.2.3 Evaluation

The evaluation of OrMiS is not the focus of this thesis and thus we provide only a brief summary of the studies performed with the system. For further details on the development of OrMiS and the user studies we conducted please refer to the following publications [8,9,10].

We conducted two user studies evaluating the interactive techniques in OrMiS and observing how participants collaborate using the system. In the first study, we evaluated the view techniques in different spatial scenarios using an abstract task. We allowed participants to work on tightly-coupled and loosely-coupled tasks either with the bifocal lenses or with the zoom technique on the map. We learned that the global zoom technique better supports tightly-coupled tasks and that participants completed loosely-coupled tasks faster with the bifocal lenses.

In the second study, we observed participants from the Royal Military College performing a simple but realistic military scenario. Participants in the study held the Basic Military Officer Qualification – Land and thus were considered experts in their field. They had knowledge of the
topographical standards used in military maps, as well as basic troop deployment strategies. Participants were able to complete the task without any barriers to the system and with minimal training. Participants collaborated successfully, taking advantage of the different interaction techniques to split their work.

4.3 Terrain Analysis in OrMiS

Users can perform terrain analysis in a number of ways using OrMiS. The terrain displays contour lines showing elevation; a virtual light source provides hill shading of the terrain, and each unit can display a viewshed showing the surrounding visibility. The terrain in OrMiS is a 3D model shown from a top-down view. However, even with the tools provided, OrMiS does not fully support the terrain analysis needed for complicated military scenarios and procedures. Our experience with OrMiS motivated us to design a simple terrain analysis system based around an interactive tabletop in a multi-surface environment.

4.4 Conclusion

In this chapter, we described the use of military simulations for training and the issues associated with it. We detailed our tabletop system, OrMiS, designed to support collaboration in military simulation and planning scenarios using simple interaction techniques. Interactors need to perform terrain analysis when conducting simulations, yet OrMiS only partially supports the terrain analysis required for military scenarios. In the next chapter, we will describe a novel multi-surface environment for terrain analysis called TerraGuide. TerraGuide combines many of the techniques outlined in Chapter 3 and was inspired by our work with OrMiS to create a real-time fluid system for geospatial exploration and analysis.
Chapter 5

**TerraGuide: A Multi-Surface Environment for Visibility Analysis**

Existing digital tools for visibility analysis have made considerable advances over traditional paper-based approaches, allowing easier manipulation of maps using panning and zooming and by aiding analysis through visualizations such as viewsheds and panoramic views. However, existing systems fall short in integrating these tools in a fluid and fast experience allowing real-time exploration of terrains. As we have previously seen, our own OrMiS system allows interactors to collaborate around an interactive tabletop to plan simple military simulations. However, these tools fall short of allowing OrMiS to support terrain analysis in complex military scenarios. To address these issues, we have developed a system for visibility analysis in a multi-surface environment based around an interactive tabletop. This system, called TerraGuide, strives to provide users with simple interaction techniques, which people can use fluidly in concert, to perform visibility analysis. We also developed TerraGuide to investigate terrain analysis tools integrated into a multi-surface environment and explore how people use multi-surface environments in general.

As shown in Figure 5.1, TerraGuide is composed of three surfaces: a large interactive tabletop, a large vertical display, and a multi-touch tablet. TerraGuide supports exploratory visualization of terrain by combining 2D maps and 3D representations of the terrain in a multi-surface environment. The tabletop displays a top-down (planimetric) 2D map. The user can move and rotate a number of viewshed widgets on the tabletop. The vertical display is located across from the user, and shows a panoramic view from a first-person perspective. A tablet displays a *helicopter view*, showing parts of the terrain in a 3D view. In this chapter, we describe the design and functionality of each visualization technique in TerraGuide.
Figure 5.1. The three main interfaces of TerraGuide include the interactive tabletop, tablet, and panoramic view shown on the vertical display in front of the user.

5.1 Real-Time Viewshed

TerraGuide includes a touch-based interactive widget implementing the viewshed visualization (Figure 5.3). The user places a viewshed anywhere on the terrain simply by touching and dragging a widget to the desired location on the 2D map (Figure 5.2). The user changes the orientation of viewshed by using a touch-based interactive disk, located around the widget. Users can hide viewsheds (to reduce clutter) or show them by tapping on the widget. Figure 5.2 shows a user interacting with the viewshed and moving it to another location.
Figure 5.2. A user interacts with the viewshed widget. Users can move the viewshed anywhere on the map by touching and dragging the center dot. When moving the widget from A to C TerraGuide displays the viewshed at a low-resolution (B). When the user removes their finger from the widget, TerraGuide displays the high-resolution (C). The user can rotate the viewshed to any angle by dragging on the outer circle (D).

Similar to existing viewshed tools, the coloured areas of the viewshed represent a section of terrain that is visible to the observer (the blue dot in Figure 5.3). The dark non-coloured regions of the viewshed are invisible to the observer from the current location. In addition to visibility information, the viewshed displays elevation using a hypsometrically tinted colour gradient (see Chapter 3.3.3). As in traditional terrain analysis applications, the gradient scale for elevation maps blue to low, green to medium, and red to high. The gradient maps elevation colours between the minimum and maximum heights of the terrain (Figure 5.3).
Figure 5.3. TerraGuide displays the viewshed widget with elevation information. The blue area is a low section and the colour gradient shows the change in elevation. A hill is shown on the bottom left of the viewshed by red colours.

TerraGuide computes the viewshed in real-time as the widget is moved along the terrain. As opposed to other viewshed tools in traditional GIS applications, this allows users to explore the terrain in real-time. The user does not have to invoke menus or input parameters, nor do they need to wait for the computation of the viewshed to occur. TerraGuide’s real-time viewshed uses two different levels of resolution to keep the exploration and analysis fluid and uninterrupted. TerraGuide displays a low-resolution viewshed on the widget while the user is manipulating it (i.e. moving or rotating). The lower resolution allows for faster computation and thus, the movement and display of the viewshed remains real-time. The low resolution is set to the highest resolution that can compute the viewshed in real-time. However, due to the lower fidelity of the resolution, this low-resolution state compromises the accuracy of the viewshed. When the user stops manipulating the widget, TerraGuide computes the high-resolution viewshed and displays it on the widget (see Figure 5.8). Section 5.5.1 explains this process in detail.
5.2 Panoramic View

In TerraGuide, the panoramic view is located on a secondary display in front of the table (Figure 5.4). It displays a 3D representation of the viewshed from a first-person perspective. TerraGuide links the panoramic view to the last used viewshed on the tabletop. It shows the terrain from the origin of the viewshed, in the direction in which the viewshed is pointing. When a user moves or rotates the viewshed, the panoramic view updates in real-time. The panoramic view limits the range of the observation with a grey fog. The maximum range of the panoramic view is based on the range of the viewshed. Reasons for a limited range of visibility could be due to limits of human sight or transmission distance of a cellular tower.

We designed the panoramic view help the user look at the terrain from a different perspective. For example, the reason for a gap in visibility displayed on a viewshed could have multiple reasons. Perhaps a large rock or hill is obstructing the view, or a gorge lies between the observer and target. Analysts can interpret the elevation information around the gap to determine its cause and a possible strategy to attain visibility. However, when using the panoramic view, users can look to the vertical screen to see a 3D rendered area of terrain that corresponds exactly to the viewshed they are working with. The cause of the obstruction is often immediately apparent. For example, in Figure 5.5A a gap in visibility is found directly in front of the observation point. By consulting the panoramic view, it is obvious that a hill lies in front of the observer. The analyst can adjust the viewshed by moving it around the hill to gain visibility of the area behind the hill.
TerraGuide continuously updates the panoramic view and provides real-time information to the user. Unlike traditional panoramic views, TerraGuide’s appears on a separate dedicated display. Thus, our system does not occlude reference information, such as the map, by an overlaid window (see Figure 3.6) and users can immediately consult the panoramic view without interrupting their workflow.
Figure 5.5. a) A viewshed. b) The corresponding panoramic view showing that a hill in front of the viewshed is obstructing the view.

5.3 Tablet-Based ‘Helicopter’ View

In TerraGuide, a hand-held tablet shows an augmented 3D view of the terrain in the style of a Magic Lens [5] (Figure 5.6). Users can move the tablet over the table and see the terrain as it appears from the perspective of the tablet’s position and orientation (see the user holding the tablet in Figure 5.1). Moving and rotating the tablet changes the point of view of the 3D visualization that it displays. Intuitively, the tablet acts as a helicopter view, which the user can move around to view the terrain from different angles. The tablet view acts as a window that reveals a 3D model of the terrain directly overlaid on the tabletop. The view reacts in real-time to the tablet’s physical position and orientation in 3D space with no perceptible lag. This technique supports quick exploration of terrain features by physical movement and rotation.
Figure 5.6. The tablet ‘helicopter’ view shows the terrain from a low angle above the tabletop. The reflective markers are attached to the outside of the tablet. As the user moves the tablet above the tabletop the view to the terrain changes in real time.

Our implementation of this view renders the terrain based on the orientation and position of the tablet in space above the tabletop. Thus, viewers will see a realistic representation of the terrain when viewed through the tablet. Ishii et al. discovered issues when observing users of the metaDESK system. Users found the spatial information from the active lens (arm-mounted tablet) hard to perceive since it always rendered from a perspective perpendicular to the tablet, not from the users eyes. Our implementation allows users to align the tablet in front of their eyes. The tablet can be rotated on its side or upside down and it will still render the terrain properly.

We designed the tablet view to allow users of TerraGuide to obtain a quick overview of the terrain. By stepping back from the table, a user can see more of the terrain through the tablet, providing a bigger view. The tablet must remain within one foot from the edge of the table for the
cameras to continue tracking. A user can also lean in over the table, moving the tablet towards an area of interest to increase the level of detail displayed. Chapter 7 discusses a user study where we observed participants using this interaction technique with the tablet. This navigation mechanic allows a tangible terrain-exploration technique with multiple levels of detail.

A user can easily place the tablet on the edge of the table when it is not in use, and it is readily available when the user needs it again. The small size of the tablet also allows most users to interact with the tabletop while simultaneously holding and/or viewing the landscape through the lens. This attribute of the tablet supports the goal of easy rapid exploration.

5.4 Design Principles: Rapid, Coupled Operation with Ease of Switching

The design of TerraGuide as a multi-surface environment follows three principles: TerraGuide computes views in real-time; TerraGuide couples views on different surfaces tightly, and users can easily switch between different views.

1. TerraGuide computes views in real-time to allow rapid exploration of the terrain without complex dialogues or noticeable rendering times. In TerraGuide, all views are updated in real-time using simple interactions based on touch and hand motion. The viewshed widget’s adaptive algorithm allows users to get information about the terrain as they move their widget from one location to another. Furthermore, simple touch gestures control the widget, and it does not use menus or dialogues. The panoramic view also does not use menus and is always accessible to the user on the secondary display, keeping the map area free from extra windows and clutter. The panoramic view updates in real-time, as the user moves and rotates the viewshed widget. We designed the tablet view for fast and fluid exploration and navigation. It has no perceptible latency and is always available to the user.
2. We designed the system to tightly link views on different surfaces. As we have discussed, TerraGuide links techniques in two notable ways. First, the panoramic view is slaved to the last-used viewshed widget. When a user moves the viewshed widget, TerraGuide automatically updates the panoramic view. Therefore, a user controls both displays with a single touch interaction. This control scheme is significantly different from existing approaches where panoramic views are invoked explicitly using dialogues. Second, TerraGuide directly couples the tablet-based helicopter view to the map on the table, displaying a 3D landscape of the 2D terrain on the table.

3. TerraGuide supports the ease of switching between views. This is achieved by tightly coupling the views, helping users retain context when switching. The panoramic view is located directly in front of the table on a large screen readily visible to the user. The physical affordance of the tablet makes it easy to set aside when not in use, and pick up when needed.

Fjeld et al. proposed similar guidelines for designing tangible interactive surface environments [18] based around their implementation of the BUILD-IT system. They found that, depending on familiarity with virtual environments, users explore with different directives and styles. For example, some users explore virtual environments with a clear goal in mind and work at high detail. Others use a low detail approach to get an overview of the environment. Thus, it is necessary to design a system that supports different points of view and fluid navigation between them [33]. Specifically, Fjeld et al. proposed designing systems to support fluid navigation methods to explore 3D virtual worlds. Our third design guideline in combination with the implementation of the tablet view reflects the previous findings in designing systems for exploration of virtual environments.
5.5 Technologies Enabling TerraGuide

Each view technique relies on a specialized technology enabling TerraGuide to run smoothly. To compute the viewshed in TerraGuide, we modified Shapira’s discrete viewshed algorithm [63]. Our version allows resolution adaptive computation and operation in the Unity 3D game engine.

5.5.1 Algorithm for Viewshed

Shapira used the discrete viewshed method for calculating the visibility of viewpoint $v$ on an area of terrain [19,63]. This area of terrain is comprised of a set of points arranged in a matrix $P$ that corresponds to the elevation values stored in the digital elevation model of the terrain (see Chapter 3.2.2 for information on digital elevation models). The viewshed information is stored in another matrix, $V$, with the same size as $P$. To calculate the visibility of the area of the terrain, the algorithm checks the line of sight between $v$ and every point in $P$. If the line of sight intersects the terrain, then that point is not visible to $v$ and is stored in $V$ with a value of zero; otherwise, the point is visible and it is stored with a value of one. The algorithm renders all points that have a value of one in $V$ in one colour (e.g. red), while the points that have a value of zero are invisible. A GIS program displays the resulting image on a map overlaying the area of interest. The red area of the map represents the viewshed and shows the section of terrain that is visible to $v$.

Terrains in Unity have properties that allow us to enhance this process. Terrains, like digital elevation models, are stored as elevation values arranged in a matrix. It is possible to query elevation values from any position on the terrain using the API of the Unity Engine. If this position falls in between values in the grid of the terrain, Unity uses interpolation to return a value based on the sampled elevation information. This allows for more flexibility when choosing a viewpoint or an area of terrain to analyze since these points do not have to fall exactly on a point within the digital elevation model. Unity also contains built-in ray casting functionality. Ray
Casting involves sending a line in a given direction from a given point to determine the surface that intersects with the line.

We implemented the discrete viewshed algorithm in Unity, aided by the built-in ray casting functionality and the terrain system. The modified algorithm uses a predetermined resolution to create a square grid and a blank texture of size $N \times N$. Using the algorithm, we can configure the size of the square grid, $d$, to any value, where $d$ represents the maximum distance that the observer can see. The algorithm places the grid around the viewpoint, $v$, on the terrain and performs a ray cast from $v$ to every point in the grid. If the ray intersects with the terrain, the point is not visible to $v$ and the algorithm fills the corresponding pixel in the texture with the invisible colour (black with 50% transparency). If the ray casting determines no intersection, then the point is visible and the algorithm fills the pixel in the texture with a colour from a gradient based on the point's elevation.

![Figure 5.7. A 6 by 6 grid with a set of points. Ray casting from $v$ to each point determines the viewshed.](image)
Figure 5.8. A) A low-resolution viewshed of 36x36 pixels. B) The high-resolution viewshed at 200x200 pixels. Note that the high-resolution visibility (B) differs from the estimate (A) in the lower left corner of the viewshed.

Unlike viewsheds in existing tools which take significant time to render [21], TerraGuide’s viewshed is rendered in real-time as it is dragged across the table. This is due to the adaptive resolution implemented in Shapira’s discrete viewshed computation algorithm [44]. While the user is moving the widget, the resolution is set so the algorithm can compute a viewshed in real-time, allowing fluid movement and exploration. When the user stops touching the widget, TerraGuide computes and displays a higher resolution, and thus more accurate, viewshed. The calculation of the high-resolution viewshed takes approximately 500 milliseconds on a 2.6-gigahertz i5 laptop with 8 gigabytes of random access memory.

Our implementation of the modified algorithm transforms how the viewshed can be used, allowing exploration of the terrain visibility with the simple movement of a finger, as opposed to the traditional use of carefully planning where a viewshed should be shown.

5.5.2 Optical Tracking System for Tablet

TerraGuide precisely displays the terrain on the tablet view using optical tracking to locate the tablet’s position and orientation above the tabletop. The tablet uses five reflective markers attached in an asymmetrical pattern around the device. In order for TerraGuide to track the tablet, at least two cameras must be able to view at least three of the markers attached to the tablet. Thus,
we mounted four OptiTrack cameras to the ceiling and positioned them so they had overlapping fields of view (Figure 5.9). OptiTrack is the designer of motion capture cameras and software which we used for TerraGuide [42]. OptiTrack’s Motive software [41] allows us to calibrate the system and create a rigid body representing the tablet. A rigid body is a group of markers that defines an object tracked by the system. Motive streams information about a rigid body, such as its position and orientation, over the network to TerraGuide. Using optical tracking with proper calibration and low network traffic, we can achieve highly precise tracking with error less than one millimeter and no perceptible lag.

The OptiTrack system used in the EQUIS Lab is more expensive than consumer-grade depth cameras such as the Microsoft Kinect v2 [67]. The Kinect has been used for tracking objects, such as tablets [11], and is used as an input method for motion games [67]. We have hands-on experience with a Kinect-based tracking system [1] and have used the Kinect in past projects. Through our experience, we deemed the Kinect v2 unsuited to precise tasks such as visibility analysis, due to the Kinect’s latency and error while tracking objects. One of our goals when designing TerraGuide was to avoid user frustration and provide an effortless and fluent user experience. An inaccurate display of the map on the tablet may be jarring to the user and interrupt the flow of the task. Thus, we chose to rely on optical tracking using OptiTrack cameras to achieve our goals.
5.5.3 Janus Networking System and Architecture

Each device in TerraGuide is part of a distributed system. We use the Janus Networking Toolkit [56], developed in the EQUIS Lab, for sending messages to and from the clients. Janus allows developers to easily configure and synchronize variables across a set of clients. For example, we use Janus to synchronize the positions of the viewsheds on the terrain. Thus, the panoramic view, tablet view, and tabletop all display the viewshed in the same location on the map. When a user changes the position of a viewshed, TerraGuide automatically reflects the changes on all other clients.

5.6 Conclusion

In this chapter, we introduced a multi-surface environment called TerraGuide that we designed to support visibility analysis on an interactive tabletop using easy and fluid exploration techniques. TerraGuide consists of three different view techniques for visibility analysis: a real-time viewshed, a 3D panoramic view, and tablet-based ‘helicopter’ view. We developed
TerraGuide using three design principles: TerraGuide should compute views in real-time, TerraGuide should tightly link views on different surfaces, and it should be easy to switch between different views. Finally, we outlined the technical details behind the technologies within TerraGuide. In the next chapters, we describe a user study evaluating TerraGuide. The study is presented in two parts. The next chapter describes the first part, an abstract task used to directly compare and evaluate the view techniques.
Chapter 6

Effectiveness of TerraGuide Techniques

In the previous chapter, we described the TerraGuide system and introduced the visualization techniques developed for this multi-surface environment. In this chapter, we report the first part of a user study designed to evaluate the use of TerraGuide; we report the second half in Chapter 7. The first part of the study compared the three visualization techniques using several measures including task completion time, accuracy and cognitive load. The second part of the study allowed participants to complete a realistic terrain analysis task using all three visualization techniques at the same time.

The first part of the study compares the efficacy and usability of the techniques in TerraGuide when performing simple terrain analysis. We instructed participants to find the highest and lowest points on a digital terrain using TerraGuide. Interestingly, we found that it was more difficult to find the low points using TerraGuide than finding and comparing the high points. In addition, we found that participants’ confidence increased when using the panoramic view, yet their performance did not. At the end of the chapter, we discuss our findings, provide quotes from a semi-structured interview, and show our results.

6.1 Motivation

The first part of the study directly compared the three terrain visualization techniques: the interactive real-time viewshed, the panoramic view, and the tablet view. The first part provided us with quantitative results. We used these results to test the usability and effectiveness of the TerraGuide system.
6.2 Participants

We recruited participants from Queen’s University and the Kingston area. Recruited participants were regular users of touch devices, using a phone or tablet at least once a day. We recruited participants through email sent to Queen’s University computer science students and faculty and through a post on the ‘Kingston Summer Group’ Facebook group, used by people (mainly students) to share activities around Kingston, Ontario (see Appendix C). Participants were required to be over the age of 18 and tall enough to be able to touch all areas of the tabletop. Twenty-six participants (sixteen male, ten female) completed the study at the EQUIS Lab on the Queen’s University campus. Upon completion of the study, participants received a $20 honorarium. The General Research Ethics Board at Queen’s University approved this study (see Appendix F for letter of approval). To ensure anonymity, we reference participants in this thesis using an identification number.

6.3 Method

Participants used three technique sets that we created to compare the techniques in TerraGuide. These included (1) the viewshed alone, (2) the viewshed and the panoramic view, and (3) the viewshed and the tablet. Since the viewshed is a common tool for terrain analysis, we included it in all three technique sets. In addition, the functionality of the panoramic view relies on the use of a viewshed widget. The panoramic and tablet views act as supplementary visualization tools for the viewshed, providing an alternative, 3D perspective of the problem space (terrain). We expected that participants would not be able to complete the task using the panoramic or tablet views alone because they do not provide enough precise information.

These technique sets allow us to compare the tablet and panoramic view. In addition we can determine the impact of using one of these supplementary techniques with the viewshed versus
using the viewshed alone. To make these comparisons we designed an abstract task that would produce quantitative results allowing us to measure performance and user experience.

6.3.1 Task: Finding the Lowest and Highest Points

Participants were asked to find the highest and lowest points on a given terrain. We designed the task to be simple enough for non-experts with minimal training. Terrain analysts often need to compare elevations of land and thus, this task reflects real terrain analysis problems. For example, a section of land higher than another may have line of sight to that area (assuming there are no obstructions), and may provide an advantage of observation and field of fire.

Participants completed the task by exploring the terrain using TerraGuide equipped with one of three technique sets. After analyzing the terrain, participants dragged a red flag to the point of the terrain they believed to be the highest, and a blue flag to the point they believed to be the lowest. Once satisfied with the placement of their flags, participants ended each trial by pressing a button on the table, which moved them to the next trial.

![Figure 6.1. A terrain from the first part of the study. Participants used the viewshed to find the highest and lowest points on the map, which they indicated using the red and blue flags.](image_url)
6.3.2 Measures

TerraGuide recorded events in an activity log as the participant completed the task. The events and measures recorded in the task for each condition included:

- **Completion time:** The time from the start of a trial until the participant specified that he or she had found the highest and the lowest points. Completion time may be an indication of how easy a technique set is to use.

- **Error:** The difference between the chosen highest point and the actual highest point on the map, and the difference in heights between the chosen lowest point and the actual lowest point on the map. This measure captures the user’s accuracy in performing the task.

- **User confidence:** A user-entered value indicating their confidence in the chosen highest and lowest points. We measured user confidence using a Likert scale ranging from one (no confidence) to five (fully confident). The participant answered the question, “Indicate the degree of confidence you have on the placement of your flags” after each trial. The confidence scores indicate how the participant judged their performance using the technique set.

- **Cognitive load:** the subjective workload exerted by the participant in completing the task.

We measured cognitive load using the NASA Task Load Index (NASA-TLX) [27].

The NASA-TLX is a subjective workload assessment tool for tasks involving human-computer interactions. It uses a multi-dimensional rating procedure to quantify cognitive workload based on a weighted average of ratings on six subscales. The subscales used to rate workload include mental demands, physical demands, temporal demands, performance, effort, and frustration. Each subscale has a description that the participants read before rating each category on a 21-point scale, with increments for high, medium, and low. Appendix E contains
the paper version of the NASA-TLX. Participants completed the NASA-TLX questionnaire using a computer application which stored and calculated the results [64]. The computer program averages the scores from the six subscales and provides a rating from 0-100, where the higher number means a higher workload.

6.3.3 Terrain

The terrains used in the task were generated by a Terrain Toolkit script [39] used to create realistic terrains in Unity 3D. The script uses Perlin noise [48] implemented by Daniel Greenheck to randomize the hills and valleys in the terrain. Perlin noise is a type of gradient noise invented by Ken Perlin in 1983, which developers have used to create natural looking terrains [47]. The terrains were generated using the same values for the frequency and amplitude of the hills and valleys. Thus, all terrains had similar numbers of hills with similar heights. We generated the terrains with the aim of having the same aesthetics and difficulty. The resolution of the height map used on the terrain was 1025 by 576 pixels (see Figure 6.2).

We textured the terrains with sand, dirt, grass, and rock. These textures were simply for aesthetic purposes and were randomly distributed throughout the terrain. There was no connection between the textures and the elevation of the terrain.

We chose not to display contour lines on the terrain for this study. A participant may be familiar with using contour lines and thus, need not use the other techniques we wished to compare. For this reason contour lines were omitted from this study.

6.3.4 Techniques

We tailored each technique from TerraGuide for the study. The bounding box of the viewshed widget used a low resolution of 36 by 36 pixels and a high resolution of 200 by 200 pixels. As mentioned in Chapter 5, we based these resolutions on a balance between
responsiveness of the interaction technique and visual fidelity of the viewshed. The viewshed was computed at a simulated height of six feet. This provided the panoramic view with a perspective of the terrain as seen through the eyes of a person.

Through preliminary pilots of the study, we chose distances and angles for the viewshed and panoramic view that provided the user with enough information to complete the task, while remaining challenging. The field of view used by the viewshed and panoramic view was $90^\circ$ horizontal (Figure 6.2). This angle was chosen because it provided a field of view that simulated the natural binocular field of view of a person [30].

In terrain analysis tasks, there is usually a factor limiting visibility, such as the maximum range of a soldier’s weapon, the range of a telecommunications tower, or the weather. Thus, we chose to limit the distance of the viewshed and panoramic view. The visibility limit of the viewshed was 13” (distance on the tabletop), and thus the maximum area shown on the viewshed was 10% of the area of the terrain.

The tablet view, however, had no limit on the maximum visibility and thus could display the entire map. We wanted to retain the property of the tablet of allowing participants to gain an overview of the entire terrain.
Figure 6.2. Diagram showing the relative sizes of the viewshed and terrain in Unity.

6.3.5 Apparatus

The interactive tabletop used for the study consists of a 55” Sony television with a PQ Labs G4S infrared frame, mounted in a custom-built wooden table. Participants were able to freely walk around the table. The external vertical display used for the panoramic view was a Sony 46” television located directly across from the user (see Figure 6.3). Four V100:R2 OptiTrack cameras tracked a Microsoft Surface 2 providing the tablet view. Each device (the table, panoramic view, and tablet) ran its own instance of TerraGuide. The devices communicated through a wireless local area network.
Figure 6.3. The setup for the study of TerraGuide. The arrows indicate the size of the screens used in the study.

6.4 Procedure

Before starting the study, participants read over a letter of information (Appendix B) and signed a consent form (Appendix A) allowing the study to be video recorded. Optionally, participants could decline to have their pictures/video used in research talks or publicity videos.

A researcher then introduced the TerraGuide system to the participant. The researcher clearly explained and demonstrated how to use each technique, starting with the viewshed, then the panoramic view, and finally the tablet. The participant then completed a single trial of the training task of finding the highest and lowest points on the map using each technique. They
moved on to the next training session only once they felt comfortable enough using the technique and were satisfied they could complete the task again. After completing three training tasks (one for each technique), the participant started the study.

Participants completed the task of finding the highest and lowest points of a given terrain (see 6.3.1) three times with each technique set, each time using a different terrain. The order in which they received the technique sets was counter-balanced to account for learning effects. The order of the maps remained consistent throughout the study.

After participants completed a task, they were asked to respond to the question, “Indicate the degree of confidence you have in the placement of your flags” using a 5 point Likert-scale ranging from 1 (no confidence) to 5 (fully confident). TerraGuide displayed the question on the tabletop and users tapped a number to indicate their confidence. At the completion of each task, TerraGuide recorded information into a log file describing the completion time and error. We did not tell participants that we were measuring the time it took them to complete the task. This was to prevent participants from rushing through the task and haphazardly placing their flags.

Once participants had completed this part of the study, they had completed the task nine times, three times with each technique, on nine different terrains. On average, this took 25 minutes to complete. We then asked participants to complete the NASA-TLX questionnaire for each technique set to measure their cognitive workload while completing the task.

After the completion of this task, participants completed a second task (described in Chapter 7) and we conducted a semi-structured interview with each participant. During the interview, the experimenter asked questions about the participants’ use of techniques and general questions about TerraGuide.
6.5 Results

Our results compare the three conditions sets: viewshed alone (*ViewshedAlone*), viewshed and panoramic view (*ViewshedPano*), and viewshed and tablet (*ViewshedTab*). We now summarize these results in terms of task completion time, error, confidence, and cognitive load.

6.5.1 Analysis Methods

For the first part of the study, we collected data from four sources; the 5-point Likert scale confidence question, the NASA-TLX questionnaire, the data recorded by TerraGuide, and the interviews conducted after the study.

We compared the task completion time, error, and cognitive load (NASA-TLX scores) for each technique set across all participants using a one-way within-subjects analysis of variance (ANOVA). We conducted follow up pairwise t-tests with a Bonferroni adjustment to test for significance between technique sets.

To compare confidence, we summed the results of the 5-point Likert-scale question for each technique set, creating a scale from 3-15. We then used the Friedman statistical test to compare these results across technique sets. We used Kendall’s coefficient of concordance to normalize the Friedman test. Researchers use the Friedman test for assessing agreement among respondents, values range from zero (no agreement) to one (complete agreement). We also performed post-hoc pairwise Wilcoxon signed-rank tests using an alpha value of 0.05.

We measured effect size using Cohen’s $d$ where applicable. A higher $d$ value suggests a stronger effect on the phenomenon [4]. Cohen defined effect sizes as “small, $d = .2$”, “medium, $d = .5$”, and “large, $d = .8$” [4].
Task Completion Time

We define completion time as the time it took for a user to complete the task measured in seconds. Participants using ViewshedPano took significantly longer to complete the task than any other technique set (Figure 6.4). The results indicate a significant effect on completion time, Wilk’s Lambda=.68, $F(2,24)=5.76$, $p<.01$, multivariate $\eta^2=.32$. The mean completion time for ViewshedPano ($M=441.6$, $SD=231$) was significantly longer than ViewshedTab ($M=362.3$, $SD=164.2$, $d=.4$), $p<.03$, and ViewshedAlone ($M=353.1$, $SD=175.5$, $d=.4$), $p<.01$. Cohen’s $d$ of 0.4 suggests a moderate effect size on this slow-down. The mean completion times for ViewshedAlone and ViewshedTab were not significantly different ($p = .7$). That is, adding the tablet did not influence the task completion time.

6.5.2 Error for Highest Point

We define error as the difference between the participant’s red flag and the actual highest point on the terrain. The results indicated a significant effect on error, Wilk’s Lambda=.42, $F(2,24)=16.4$, $p<.01$, multivariate $\eta^2=.58$. The mean difference in error when using ViewshedTab
The Cohen’s $d$ of 1.4 and 0.71 shows a strong and medium effect, respectively. That is, when using the tablet view together with the viewshed, participants were able to find the highest point with significantly less error than when using the viewshed and panoramic view or the viewshed alone.

When participants were locating the lowest point on the terrain, we found no significant difference between the different technique sets. The difference in heights for the ViewshedAlone ($M=0.07$, $SD=0.04$) were not significantly different from ViewshedPano ($M=0.09$, $SD=0.16$), $p=.7$ or ViewshedTab ($M=0.09$, $SD=0.08$), $p=.3$.

6.5.3 Confidence

We determined participants’ confidence based on their response to, “Indicate the degree of confidence you have in the placement of your flags”. Participants rated their confidence on a scale of one (no confidence) to five (full confidence). The participants rated their confidence level three times for each technique set, one for every trial. We then summed the confidence levels to create
a scale from 3-15. Participants were more confident when using the panoramic view and viewshed than when using the viewshed alone, and further confident when using the tablet and viewshed (Figure 6.6).

Results showed a significant difference in the medians of participants’ confidence levels when using ViewshedAlone (MD=10), ViewshedPano (MD=11.5), and ViewshedTab (MD=13); ($\chi^2=18.24, p<.01$). The Kendal coefficient of concordance was .351, indicating moderate differences in ratings between the three conditions. The median confidence level for ViewshedTab was significantly higher than for ViewshedPano ($p<.02$) and ViewshedAlone, ($p<.01$). Also, participants were significantly more confident using ViewshedPano than ViewshedAlone ($p<.01$).

Cognitive Load

We measure cognitive load using NASA-TLX scores collected for each of the technique sets. Results showed that when participants used the viewshed and tablet ($M=30.97, SD=13.3$) to complete the task their cognitive load was significantly lower than when using the viewshed and the panoramic view ($M=39.53, SD=14.5, d=0.6$), $p<.01$ and viewshed alone ($M=39.38, SD=14.1$, $p<.01$).
A significant effect was found on cognitive load, Wilk’s Lambda = 0.4, $F(2,24) = 17.74$, $p < .01$, multivariate $\eta^2 = .6$. Further, the Cohen’s $d$ of 0.6 shows a moderate effect on cognitive load.

6.6 Discussion

We now discuss our findings about the three techniques, and reflect on the difference between the tasks of finding the highest and lowest points in the terrain.

6.6.1 Strategy

We observed a common strategy for finding the highest and lowest points in the terrain. The strategy can be broken down into three stages. The first is the exploration stage, where participants use the techniques to locate possible high and low points on the terrain. The second stage involves comparing the elevations of the areas defined in stage one and determining the highest and lowest points on the terrain. The user may need to go back to stage one to find more points to compare. The final (third) stage involves the placement of the flags on the peak of the mountain and the deepest part of the valley.
6.6.2 Viewshed

With the viewshed alone, participants were able to complete the task as quickly as (or quicker than) with other technique sets, despite having received only three trials of training. This implies that the viewshed is usable by non-experts. The colour gradients allowed participants to infer the shape of the terrain; however, some participants found the colours hard to distinguish. Participant 0 said, “It frustrated me a little having areas that were both blue, and it being hard to tell whether one is more blue than the other with just the viewshed, causing me to take a little bit longer to finally decide where I wanted to put things.” Participant 1 suggested that the viewshed output numbers with the colours so it would be easier to make comparisons, “I wish the colours were numbers because they were so close it was hard to know which one was the lowest. Then you have to move from your spot where you were to find what you think was the lowest, but you cannot compare the two.” Since the task only provided the user with a single viewshed, it was difficult for participants to compare the elevation of points if they were far apart.

6.6.3 Panoramic View

The presence of the panoramic view did not enhance participants’ performance. Compared to the viewshed alone, adding the panoramic view offered no improvement to error or cognitive load. We observed two interesting characteristics about the panoramic view: task completion time increased and, compared to using the viewshed alone, the participants’ confidence in their results improved.

During stage two of the strategy described in Section 6.6.1, participants need to take the time to switch their attention to a separate display to observe the panoramic view. Once participants compare the high/low points they must then switch their focus back to the table to either complete stage one again (find more points) or complete stage three. This may have taken longer compared to the viewshed only technique set, where participants use the table alone to complete the three
stages and do not need to move their focus from the table. During the tablet only condition participants use the tablet to complete stages one and two at the same time. We will discuss this in the next section.

When using the panoramic view, participants felt more confident in the placement of their flags compared to the viewshed-only technique set. The panoramic view may have acted as a reassurance for the participant. As stated above, some participants felt that the colours on the viewshed were difficult to compare, the panoramic view may have given participants another perspective to view the terrain, thus reinforcing their decision with the viewshed. Participant zero stated, “I would do a quick sweep with the viewshed, then I had a couple areas that I was interested in. Then I would place the flag, and I would use the panoramic view to look around, giving me an idea of what looked like the highest point. So it helped me determine not just based on colour, which narrowed things down for me.” Even though the panoramic view did not provide participants with any improvements on error, it allowed them to feel more confident in their initial placement of flags.

6.6.4 Tablet

The results clearly show that the tablet plus viewshed condition outperformed the other two conditions. The presence of the tablet increased participants’ confidence in their results, while reducing error and cognitive load. The use of the tablet had no effect on task completion time. This indicates that participants were able to interpret terrain data using the tablet’s “helicopter” view, and that the advantage the two views conferred outweighed any disadvantage in having to use two surfaces to solve the task. Participant 1 said, “The tablet was the easiest. You could instantly see what the highest points were, and you just went directly there and then just narrowed down with the viewshed too see what was exactly the highest point.”
Because the tablet view displays the entire terrain, participants can make comparisons while they scout out the landscape for areas of interest. Participant zero said, “I liked the tablet, because I could do a quick sweep of the terrain, and then I understood what I was looking at as a whole. It made finding the highest point very fast, since you could easily tell, usually, unless they were more similar in height.” This implies that participants completed stages one and two of the strategy at the same time.

6.6.5 Low Points Were Difficult to Identify

There was no significant difference between the errors of finding the low points when using any of the three technique sets. A reason for this may be that the low points on the terrain were harder to find and compare than the higher points on the terrain. When viewing the terrain through the tablet or panoramic view, the highest points stand out since the blue sky in the background provides contrast. However, the low points reside in between areas of terrain. Thus, no external queues, like the sky, set these areas apart, other than subtle hill shading. Participant 5 said, “You could really tell where the highest points were [when using the panoramic view], for the troughs it wasn't really helpful since you couldn't really tell how deep it is”. Also, Participant 10 commented on the panoramic view, “Of the three views, that was my least favourite, but it did help when you had two spots that were similar in height, you could look around and get a more accurate view of which is higher, but it didn't help with the minimum.” Some participants were able to find the low points but had trouble comparing them. Participant 11 stated, “I think just being able to pan with the camera was good. I think it definitely helped with finding the highest point because you could almost put it level with the table and just look straight to get an idea of which was the highest peak. You could definitely tell which areas were of least elevation, but maybe just differentiating which was less than the other was hard.” Perhaps 3D visualization techniques like the panoramic view and tablet view are not as useful for identifying low points in
digital terrains. It may be advantageous for users to spend more time consulting the viewshed when searching for and comparing low points of elevation in a digital terrain.

6.7 Conclusion

In this chapter, we presented the results of the first task of our user study. This task allowed us to compare terrain analysis techniques based on task completion time, error, confidence, and cognitive load. We found that the tablet technique allowed participants to find the highest point on the terrain with less error, more confidence, and with a lower cognitive load than using the viewshed alone. Similarly, the panoramic view gave participants more confidence in the placement of their points but did not actually improve their error, and in fact, took longer than using the viewshed alone. The novel techniques conferred no advantage for finding the lowest points on the terrain. We learned that the TerraGuide system was usable by novice participants to find high and low points on a terrain. Users felt comfortable using and interpreting the viewshed tool with only a small amount of training. In the next chapter, we will discuss the second part of the study, which provided participants with all the techniques and allowed them to complete a realistic visibility analysis task.
Chapter 7

Using TerraGuide for a Realistic Terrain Analysis Task

In this chapter, we describe the second part of our user study. Participants completed this part of the study immediately after the part described in Chapter 6, and thus, the experimental design was similar. We outline the realistic visibility analysis task that participants performed and discuss observations about how participants used the techniques in combinations.

7.1 Motivation

We conducted the second part to observe participants’ use of the different view techniques in combination. We wanted to collect qualitative data about the usability of the system during a realistic task. We conducted this part of the study to discover the usefulness of the view techniques (and combinations of them) when used in specific situations and whether there was a particular order in which participants used the techniques to solve the task.

7.2 Participants

The participants were the same as part one of the study. For a detailed description of the participants, please refer to section 6.2.

7.3 Task: Watchtower Positioning

We instructed participants to place three watchtowers (represented by viewsheds) around a terrain to cover six points of interest. This task required them to synthesize information over the entire map. As seen in Figure 7.1, a viewshed widget represented a “watchtower” and a red circle on the terrain represented a “point of interest”. The point of interest changed colour from red to green when it was in line of sight of a watchtower. The goal of the participant was to place their
three watchtowers so they collectively have visibility of all 6 points of interest. A watchtower could cover as many or as few points needed to complete the task. Once the participant achieved six green points, they pressed a button on the table to take them to the next map. Each map shared a different terrain with a different arrangement of points of interest. This task shares attributes of other visibility analysis tasks, such as placing towers in an area for telecommunications and determining suitable areas for erecting skyscrapers in urban planning. These types of tasks involve analyzing visibility from multiple points in the terrain and synthesizing visibility information.

Participants had all three view techniques available to use. Participants used the viewshed (watchtower), panoramic view, and tablet view with the same parameters from part one of the study. Thus, these techniques were consistent and familiar to the participants.

7.4 Measures

A GoPro Hero 3 video camera, mounted on the ceiling, recorded a top-down view of the system during the second study. We used video coding to show quantitative results from qualitative videos.

7.4.1 Video Coding

Video coding is the process of extracting behavioural information from videos. Researchers use video coding to identify patterns and quantify results from experimental videos. Researchers develop codes to represent characteristics of the video. For example, the hypothetical video code completed task represents successful completion of the task. Using a computer program, researchers watch experimental videos and indicate the time a coded event occurred. These codes create a timeline of events that researchers use to visualize participants’ behaviour and extract quantitative information.
7.4.2 Video Coding of Part Two

Our detailed video coding followed the scheme shown in Table 1. We coded each action over three dimensions: technique used, action type, and the body part involved. Example events were Viewshed 2 macro-movement with left hand, or Panoramic View looked with head. The action type dimension specifies the type of manipulation executed by users. For example, Micro and Macro distinguish between small and large movements of a viewshed.

We video coded participants’ interaction using a single map from the visibility analysis task. We chose to code the participants using the fourth map they encountered during the task (see Procedure in section 7.6). The fourth map was late enough in the task to give participants a chance to develop a strategy. In addition, this map required analysis of the terrain to complete. Participants could not find a solution by randomly moving around the viewshed widgets.

<table>
<thead>
<tr>
<th>Technique Used</th>
<th>Viewshed (1,2,3), Panoramic View, Tablet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action Type</td>
<td>Micro, Macro, Rotate, Search, Still, Look</td>
</tr>
<tr>
<td>Body Part</td>
<td>Head, Left Hand, Right Hand</td>
</tr>
</tbody>
</table>

Table 1. Dimensions of coding scheme.

We did not use time as a measure during the second part of the study because we were interested in observing how participants used the system, not comparing performance between users.

We used an open coding process to analyze the videos and identify behaviours and events. Of the 26 participants, we collected 25 videos. Technical difficulties prevented us from recording one participant’s video. We randomly chose videos from 10 of the 26 participants for detailed coding, representing 22 minutes and 17 seconds of video. From these 10 videos, common strategies were determined. Two researchers performed less detailed video coding on the remaining 15 videos in order to identify instances of these common strategies. Disagreements between participants’ strategies were resolved through discussion between the researchers.
7.4.3 Terrain

We generated the digital terrain using the procedures described in Section 6.3.3. We arranged the red dots (points of interest) by hand. Multiple pilot studies allowed us to balance the difficulty of the maps and ensure that all the maps had a possible solution.

7.5 Apparatus

The apparatus for the second study was the same as the first with the addition of a GoPro video camera mounted above the tabletop. Please refer to Section 6.3.5 for a detailed description.

7.6 Procedure

We instructed participants on the task of part two after they had completed the first part of the study. A researcher verbally explained the goal of the task and allowed users to interact and practice with the table to complete one training map. Participants then completed the task six times on six different maps, with different arrangements of points. We video-recorded all trials. During one of the trials chosen by a researcher, each participant followed the think-aloud protocol [80], where they verbally explained their thought process of how they completed the task.

Following the session, participants completed a custom questionnaire to assess their preferences, and participated in a semi-structured interview (Appendix D). Part two took on average 15 minutes for participants to complete.
Figure 7.1. User placing a watchtower (viewshed) to cover the red points of interest. Note the green point on the left of the viewshed indicating the point is in line of sight of the tower.

7.7 Data Analysis

Our detailed video coding revealed that participants took on average 2 minutes and 13 seconds to complete the task ($SD=94$ seconds). They switched frequently between techniques, on average 13 times throughout the task ($SD=9$). The table was used on average 6.6 times during the task ($SD=4.3$), or 71% of total time; participants physically interacted with the viewshed widgets for on average 59 seconds per trial ($SD=41$), representing 57% of their total time. Participants used the tablet 5.4 times on average ($SD=3.9$), or 28% of total time. Finally, participants used the panoramic view 0.9 times on average ($SD=2$), representing 1% of total time.

Our results showed a dominant strategy of bi-manual use of viewshed and tablet. Minority uses involved first using the tablet for an extended period, or using the table first for an extended period, before switching to the combined viewshed/tablet strategy. We summarize the distribution of these strategies in Table 2. With both the viewshed and the tablet, participants frequently adopted a sweeping motion, allowing real-time exploration of the terrain. Questionnaires showed a clear preference for tablet over the panoramic view. In the next section, we detail the strategies we observed and report participants’ preferences.
<table>
<thead>
<tr>
<th>Strategy Name</th>
<th>Num. Users</th>
<th>Sweeping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-manual viewshed/tablet alone</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Table first then bi-manual viewshed/tablet</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Tablet first then bi-manual viewshed/tablet</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Number of participants using each strategy. *Two of eight participants put the tablet down to use the viewshed.

7.7.1 Bi- Manual Viewshed and Tablet

Twenty-three of twenty-five participants adopted a bi-manual strategy, where they used the viewshed with one hand, and the tablet with the other, shifting their view between them. Figure 7.3 shows an example of this strategy. Participants switched between attending to the viewshed and the tablet on average 12.1 times when performing the task. Participants used the table for intervals of 16.1 seconds on average and the tablet for intervals of 6.5 seconds on average. Figure 7.2 displays an example of the video-coded analysis of this strategy. The timeline displays the amount of time it took the participant to complete the task and which interaction technique each part of their body was working with. In Figure 7.2, the participant looks between the tablet and the tabletop intermittently. At the one-minute mark, the participant is holding the tablet in their left hand and interacting with the tablet in their right hand, while glancing between these view techniques.

![Timeline](image)

Figure 7.2. A timeline displaying bi-manual use of the viewshed and tablet.
The remaining two participants used a variant of the bi-manual strategy. Rather than holding the tablet in one hand while interacting with the viewshed, they instead placed the tablet on the wooden edge of the table. When working with the tablet, participants picked up and used it with both hands, then put it down to return to the viewshed. This variant moved back and forth between the interaction techniques, as with the truly bi-manual strategy.

The bi-manual approach allowed participants to see detailed visibility using the viewshed together with the 3D perspective of the tablet view. Participant 24 explained, “I started off with the tablet, seeing where the points were. Then I tried a couple points with the viewshed, I would see if I could actually see the points from where I thought I could with the tablet. If I couldn't, I'd either try fine-tuning it if I could, or I'd use the tablet again to see if there were any other points I could use.”

![Figure 7.3. Participant demonstrating bi-manual use of the tablet and viewshed.](image)
7.7.2 Table-First

Eight of 25 participants used a *Table-first* approach where they used the table for an extended period at the start of the task. On average, these participants used the table for 74 seconds before moving to the bi-manual strategy.

Some participants adopted this strategy in hope of completing the task without actually analyzing the terrain. Users swept the viewshed around, hoping to randomly find a solution. Participant 0 explained, “I decided the distribution of the points where I would put the viewsheds, and then by chance see if I could get it, then if I couldn't, I would use the tablet to see if there is a mountain close by it could go on top of, or see why they're hidden”. Our maps were sufficiently complex that this strategy did not work, forcing participants to change strategy. Six participants switched to bi-manual and two participants switched to the strategy of moving between tablet and viewshed, but holding the tablet in both hands when in use (see the timeline in Figure 7.4 for an example of this strategy). Participant 10 explained: “Initially I tried with just the viewshed, and then once I realized that it was really important to be able to see depth, I just started using the combination of the viewshed and the tablet.”

![Timeline of a participant using the table first technique.](image)

In Figure 7.4, the participant is fully concentrated on the tabletop for the first third of the task. The participant picks up the tablet view after trying to complete the task using exclusively the viewshed.
7.7.3 Tablet First

Six participants used a Tablet First strategy, involving an extended use of the tablet at the beginning of the task. These participants used the tablet for 15 seconds on average before switching to the bi-manual strategy. Figure 7.6 shows a participant walking around the table using the table first technique. Figure 7.5 shows a timeline of a participant using this technique. In the timeline the participant immediately picks up and uses the tablet with both hands. Even though the initial time of exclusivity is short relative to the table first technique shown in Figure 7.4, the participant gains enough information to attempt to solve the task.

![Tablet, Table, Panorama, Tablet Movement, Viewshed]

**Figure 7.5. The timeline of a participant using the tablet first technique.**

Participants reported that the tablet was easy to use and aided navigation through the terrain. Participant 0 stated, “I liked the tablet because I could do a quick sweep of the terrain, and then I understood what I was looking at as a whole.” Participant 16 said: “The motion tracking made it really intuitive to use.” Participant 11 commented on the tablet’s ease of use: “The tablet was the best. It's a lot easier to see when you can just move the tablet around.” These comments are consistent with our findings from the first part of the study and suggest that the use of the tablet view reduced users’ cognitive load.

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Participant four used the tablet first strategy. He walked around the table with the tablet looking at the terrain from multiple perspectives.

This strategy allowed users to get a big-picture view of the terrain. Participant 18 stated, “[I used it] for getting a general lay of the land. It really helps in an intuitive sense to figure out where you have hills or valleys, where you are going to have the most occlusion.” Similarly, Participant 14 said, “The tablet gave me a quick overall view of the terrain and exactly how it's levelled. It also gave me a good idea of where to place the towers initially.” Participants then moved to the bi-manual approach, having already identified potential locations for solutions and areas to avoid.

Participants found the tablet useful for planning where to move the watchtowers; however, some did not use it for planning precise changes to the placement of the watchtowers. Participant 8 stated, “The tablet was good when figuring out where I should put the watchtowers to start, but then for precision, it was easier to use the viewshed”. In addition, some participants found the tablet heavy and uncomfortable to use after a long period. Participant 0 said, “The one issue with the tablet though, it wasn't a big deal, but holding it and moving was a bit hard”.

Figure 7.6. Participant four used the tablet first strategy. He walked around the table with the tablet looking at the terrain from multiple perspectives.
7.7.4 Panoramic View

The three strategies discussed indicate users were able to fluidly use the table and tablet to solve terrain analysis tasks. The panoramic view, on the other hand, received minimal use, accounting for only 1% of the participants’ time. In interviews, participants complained about discomfort when using the panoramic view. Participant 9 commented, “I felt really dizzy” and, “It gave me a headache, and I felt that it was easier to see where I want to place my towers using the tablet”.

The panoramic view was located in front of the participant, showing the terrain from the perspective of the viewshed. Therefore, the orientation of the panoramic view did not always match the orientation of the participant, requiring the participant to reorient the view on the terrain mentally to the panoramic view.

Participants found that the tablet provided similar information to the panoramic view, but more effectively. Participant 16 stated that they felt the panoramic view was not useful when the tablet was available. Participant 8 said, “The tablet kind of made the panoramic view a little bit useless”. Participant 23 said, “I could get all the information provided by the panoramic view on the tablet, but faster”.

Some participants actually did find the panoramic view useful. Participants found it provided a different perspective on the terrain when the solution was not immediately clear on the tablet. Participant 19 stated, “Most of the time I would try to use the viewshed and the tablet. When those two didn’t work out I felt like it was because I was misinterpreting what I was seeing. I looked at the panoramic view to see if I was looking directly at a hill instead of over a hill, since the tablet would sometimes make it seem like I was on top of a hill, when I was really behind it.” Similarly, Participant 18 said, “I only used the panoramic view if I was placing one of the towers in a location where I thought it would work, but it wasn’t working and I wasn’t exactly sure why. The panoramic view provided an actual representation of the view, whereas the tablet view gave more
information than the towers would have alone.” In addition, Participant 17 noted, “the tablet was just for getting a starting point, placing the towers initially. If it didn't work right away, then I used the panoramic view to help.”

Participant 21 stated that they were not sure if they would be able to observe small details in the terrain using just the tablet. They suspected that these details may only be present when using the panoramic view, “When I placed the watch tower I would look at [the panoramic view] to get an idea of what kind on minor variations of terrain might block my view […] I don't know if [the tablet] would really capture a small bump [on the terrain] that was only really visible from the panoramic view or from the viewshed.”

Other participants used the panoramic view for precise adjustment to the viewshed. Participant 20 used it for a more detailed view and Participant 24 said, “I used it to see how far off I was from being able to see a different point of interest.”

Figure 7.7. Participant 7 uses the panoramic view to perform precise adjustments to his watchtower.
7.7.5 Viewsheed Sweeping

Nine participants displayed a sweeping behaviour with the viewsheed where they made large circular movements around an area of interest. Nine participants used sweeping an average of 3.2 times each ($SD=2.8$). As shown in Table 2, all eight participants that used the Table First strategy also used the viewsheed sweeping behaviour. One participant used sweeping during a Tablet First strategy. By taking advantage of the real-time nature of the viewsheed widget, participants were able to quickly sweep the terrain to get a general sense of its elevation. Participant 0 explained, “I would do a quick sweep with the viewsheed, then I had a couple areas that I was interested in.”

7.7.6 Participant Preferences

Participants indicated their preferences through questionnaires. The majority felt that the viewsheed alone would have been sufficient to carry out the task. When asked: “Do you think you could have completed part 2 with the viewsheed alone?” 5 of 26 participants answered, “Yes” and 21 answered, “Yes, but longer”.

Participants overwhelmingly preferred the tablet to the panoramic view. When asked; “If you had to choose one technique to use with the viewsheed, which would you choose?” Twenty-four participants chose the tablet and two chose the panoramic view. When asked, “Did you ever forget about a technique?” Thirteen of twenty-six participants said they forgot about the panoramic view, two forgot about the tablet view and eleven did not forget any techniques. When asked, “Was the panoramic view still useful when given the tablet to use?” Sixteen participants replied with “No”. These responses are consistent with the dominant adoption of the bi-manual use of the viewsheed and tablet, and low usage of the panoramic view.

Participants believed the tablet to be the most efficient way to get a sense of the general topography. When asked “To best understand the overall shape of the terrain I found it best to use…” Seventeen of the twenty-six participants specified the tablet, two chose the panoramic
view and seven stated they used all three techniques. Similarly, when asked, “Was there any technique that allowed you to perform the task quicker?” Seventeen participants chose the tablet while nine indicated “No.”

7.8 Conclusion

In this chapter, we have presented the second part of a user study where participants completed a realistic terrain analysis task with TerraGuide and had the freedom to use all provided terrain analysis tools. This study allowed us to discover how participants used the techniques in combination for terrain analysis. We identified three different strategies used to complete the task: a bi-manual use of the tablet and the table, and two variants where participants used either the table or tablet first. In the following chapter, we discuss how our design choices may have implications on future designers of multi-surface environments.
Chapter 8

Implications for Design and Conclusion

TerraGuide is one of few multi-surface environments designed around a concrete application domain. As such, our experience in designing TerraGuide is of interest to other designers of multi-surface environments. In this chapter, we describe the success and failures of TerraGuide, provide implications for design, and summarize our findings.

8.1 Where TerraGuide Succeeded and Failed

Previous implementations of multi surface environments for spatial navigation have encountered issues with exploration. For example, Ishii et al. discovered that users of their metaDESK had trouble navigating through the landscape. Users of metaDESK relied on the 2D desk map to orient themselves when navigating with the active lens (tablet arm) [73]. We found the opposite was true for our implementation of the helicopter view. Users navigated the terrain purely by moving the tablet above the tabletop. Users found this navigation mechanic helicopter easy to use, understand, and preferred it to the more static, table controlled panoramic view.

All users of TerraGuide effectively used the three interaction and view techniques to complete a simple visibility analysis task. Users switched between the different surfaces for different parts of the task, demonstrating the usefulness of the techniques in combination. Participants' comfort with attending to and manipulating multiple surfaces is convincingly demonstrated by the adoption of a bi-manual use of the tablet and viewshed by 23 of 25 participants (and where the other two participants used a variant on this strategy.) Participants moved fluidly and frequently between the tabletop and tablet. Rather than introducing a cognitive
barrier, NASA TLX scores showed that the combined use of these two surfaces had a lower
cognitive load than use of the viewshed alone.

Moreover, this combination of surfaces proved easy to learn. With only a few minutes of
training, participants were able to use all aspects of the system to complete complex analysis
tasks.

Our results also show that simply providing multiple surfaces supporting different
interaction techniques is not a guarantee of success. Our panoramic view, as seen in study part 1,
increased completion time with no commensurate decrease in error (although user confidence was
increased). Study part 2 showed that given the choice, users prefer the tablet to the panoramic
view because of its simplicity in navigation.

Overall, this indicates that systems based on optical tracking for movement and navigation
like the tablet can provide significant benefit to task performance, error, and confidence, and are
therefore worthy of consideration despite the complexity and cost of their implementation.

8.2 Revisiting TerraGuide’s Design Principles

We used TerraGuide to explore three design principles for systems supporting real-time
spatial analysis: TerraGuide computes views in real-time, TerraGuide couples views tightly, and
users can switch between surfaces easily. We now discuss insights from our experience with
TerraGuide.

8.2.1 TerraGuide Computes views in Real-Time

One of our key technical advances over existing GIS systems is that TerraGuide computes
views in real time. This allows rapid exploration of the terrain without complex dialogues or
noticeable rendering times. Participants used both the viewshed and the tablet to perform
*sweeping* actions over the terrain to gain a rapid overview of elevation and line of sight.
Thus, in addition to general streamlining of interaction, the real-time update of views enabled a new form of exploratory behaviour. Real-time updating was only possible because we implemented TerraGuide to compute the viewshed in low resolution while the viewshed was in motion. Participants must therefore balance the benefit of sweeping with the lower fidelity rendering of the viewshed.

8.2.2 TerraGuide Couples Views Tightly

We hypothesized that tightly coupling the views on different surfaces would simplify their use in combination. In TerraGuide, we find both a successful and unsuccessful example of this design choice.

Coupling the tablet’s view to its physical position over the tabletop allows users to move between the table and tablet views rapidly, frequently, and with low cognitive overhead. The near unanimous adoption of bi-manual interaction shows that participants were able to effectively work with both views in concert. Fjeld et al. proposed the incorporation of bi-manual interactions as part of their guidelines for designing tangible interactive surface environments [18]. Interestingly, we did not explicitly design TerraGuide for bi-manual use; this characteristic occurred as a by-product of the principles we employed during the development of the system.

Conversely, participants struggled to interpret and use the panoramic view, whose use increased task completion time. We coupled the panoramic display with the position and orientation of the viewshed on the table, requiring users to rotate the terrain mentally to match these differing perspectives. Perhaps the panoramic view would have been more successful if participants controlled it separately, rather than tightly coupled with the viewshed.
8.2.3 Users Can Easily Switch Between Views

As we have discussed, participants made on average 12 switches between tablet and viewshed over their three-minute trials. This allays the fear that in multi-surface environments, users will be overwhelmed with too much choice, and with the overhead of switching between different devices. Ease of switching in this case is primarily a consequence of the tight coupling of the views, allowing users to switch between devices without loss of context, combined with the ease of holding the tablet in one hand while manipulating the viewshed in the other.

In summary, TerraGuide illustrates how these three design principles can lead to an effective use of multiple surfaces that leads to improved performance together with enthusiastic reception from users.

8.3 Conclusion

In this thesis, we introduced a novel multi-surface environment consisting of three tools for visibility analysis: a real-time viewshed, a panoramic view, and a tablet-based helicopter view. The system exemplifies three design principles: display views in real-time, bind views tightly together, and allow easy switching between views.

Terrain analysis is a difficult process and current tools do not adequately support analysts. Current systems often offer cumbersome user interfaces that hinder the adoption of useful tools for terrain analysis. In this thesis, we proposed the development and evaluation of a novel multi-surface environment called TerraGuide. TerraGuide aims to provide analysts with real-time terrain information through simple touch interaction. TerraGuide was validated through a two-part user study that showed participants could successfully complete a terrain analysis task using new view techniques and adopted bimanual interactions with a multi-surface environment. We found that successful terrain analysis was achieved by displaying visibility information in real-time on multiple displays and allowing participants to easily switch between them.
We evaluated TerraGuide and its use as a multi-surface environment through a two-part user study. The first part of the study allowed participants to complete a simple task of finding the highest and lowest points on a digital terrain. Participants used combinations of the technique to solve the task and we received quantitative data to compare techniques. The results indicated that the tablet-based helicopter view allowed users to perform terrain analysis faster and with less error, while simultaneously lowering cognitive load and increasing confidence. The panoramic view, however, increased completion time with no improvement in error. In addition, we found that users had more difficulty locating and comparing the low points on a digital terrain.

In the second part of the study, participants completed a realistic visibility analysis task with all view techniques available to use. This part of the study provided us with qualitative video information about the usability of the techniques in different combinations. We saw four strategies emerge from participants, including a near-unanimous adoption of bi-manual use of the tablet and tabletop. Variants on this strategy involved the participants’ use of the table or tablet first. Participants using the tablet first gained a broad knowledge of the overview of the terrain, which narrowed down the possible locations to place their watchtowers.

Multi-surface environments are complex systems that enable powerful new interactions. Our three design principles led to the successful, effective use of multiple techniques that increased user performance. However, we discovered that simply presenting information on multiple interactive surfaces does not guarantee success.
References


Appendix A

Consent Form

Participant ID: ______________________________

Exploration of Terrain Visualization Techniques on an Interactive Tabletop

I have read the letter of information describing this study being conducted by Matthew Oskamp, Christophe Bortolaso and Nicholas Graham at Queen’s University. I understand that I will be participating in a research project that follows the procedures described in the attached letter of information. I have had the opportunity to ask questions related to this study, and have received satisfactory answers to any questions.

I am aware that my participation is voluntary and that I may withdraw my study participation at any time without penalty by advising the researcher.

I understand that I may address any questions about study participation to members of the research team: Matthew Oskamp (7mao@queensu.ca, 613-242-8433), Christophe Bortolaso (bortolaso@queensu.ca, 613-572-6083) or Nicholas Graham (graham@cs.queensu.ca, 613-533-6526), and that any ethical concerns about the study may be directed to the Chair of the General Research Ethics Board at chair.GREB@queensu.ca or 613-533-6081.

Please Circle One Please Initial Your Choice

I consent to the use of non-identifying quotations in publications, talks and promotions

YES NO __________
I consent to being video and audio taped while participating in this study for the purposes of permitting accurate analysis of my actions during this session.

I consent to the use of still images and short video recordings made during this study in academic publications, talks and promotions (for example, YouTube videos for the lab)

Participant Name:  ____________________________________________

Participant Signature  __________________________________________

Date  __________________________________________
Appendix B
Letter of Information

Exploration of Terrain Visualization Techniques on an Interactive Tabletop

You are invited to participate in a research project directed by Matthew Oskamp, Christophe Bortolaso and Nicholas Graham (EQUIS Laboratory, School of Computing) of Queen’s University. We will read through this letter of information with you, describe our experimental procedures in detail, and answer any questions you may have. The research is being funded by the NSERC SurfNet Strategic Network.

The study aims to explore different terrain visualization techniques on an interactive tabletop. The study will last approximately 1 hour. During the study, you will be asked to carry out several tasks individually.

In the first step of the study, you will be asked to find the maximum and minimum heights of several digital terrains. You will be provided with several different techniques and technologies for analyzing the terrain. Following this step, you will be asked to fill in a questionnaire giving your opinions on the previously tested techniques.

In next step, you will be asked to position units on a digital map in a more realistic scenario. You will be using the same techniques as before. Following this step you will be asked to fill in another questionnaire and to take part in a semi-structured interview.

You will receive $20 as thanks for your participation. Your participation is voluntary. You may stop at any time by alerting the experimenter. Should you choose to withdraw, you will still receive the $20 for your participation. Any data collected up to the point of withdrawal will be destroyed. If you wish to withdraw at a later date, you may contact the research team using the
contact information provided below, and all data collected during your session will be destroyed.

There are no known risks in participating in this study.

We will ask your permission to use still images or short videos of your use of the digital map in academic papers, presentations or publicity for the project (example: YouTube videos for the lab). Should you decline to offer permission, we will not use this material. All information provided is considered completely confidential. All collected data will remain accessible only by our research team at Queen’s University. Your name will not appear in any publication resulting from this study. Quotes from your interview may be used in publications or presentations about this work, but will be presented in anonymized form. Data will be stored in a locked cabinet or in encrypted form on password-protected computers in the EQUIS Laboratory at Queen’s University.

This study has been granted clearance according to the recommended principles of Canadian ethics guidelines, and Queen’s policies. This research has been approved by Queen’s University General Research Ethics Board. However, the final decision about participation is yours. Any questions about study participation may be directed to members of the research team: Matthew Oskamp (7mao@queensu.ca, 613-242-8433), Christophe Bortolaso (christophe.bortolaso@queensu.ca, 613-572-6083) or Nicholas Graham (graham@cs.queensu.ca, 613-533-6526). Any ethical concerns about the study may be directed to the Chair of the General Research Ethics Board at chair.GREB@queensu.ca or 613-533-6081.

*Please retain a copy of the letter of information and consent form.*
Appendix C

Recruitment Email

Subject: Help Evaluate the Future of Digital Tabletops

You are invited to participate in a study exploring terrain visualization on an interactive touch tabletop! Participants will use different techniques to make tactical decisions in real world scenarios. You will even use an augmented reality lens!

The session will approximately last 1 hour and you will receive $20 for helping us out!

Please contact Matt Oskamp at 7mao@queensu.ca for more information.
Appendix D

Questionnaire

Participant ID: _______________________

8.4 Part 1

1. To best understand the **overall** shape of the terrain I found it best to use ____
   a. Viewshed alone
   b. Viewshed and Perspective view
   c. Viewshed and Tablet
   d. Viewshed, Perspective view, and Tablet

2. To best perform **precise** adjustments when aligning my towers I found it best to use ____
   a. Viewshed alone
   b. Viewshed and Perspective view
   c. Viewshed and Tablet
   d. Viewshed, Perspective view, and Tablet

3. To best understand the layout of the terrain highlighted by the viewshed I found it best to use ____
   a. Viewshed alone (I didn’t need any other technique)
   b. Perspective view
   c. Tablet
   d. Perspective view and Tablet

4. When **finding a location** on the terrain to place my tower I found it best to use ____
   a. Viewshed alone
   b. Viewshed and Perspective view
   c. Viewshed and Tablet
   d. Viewshed, Perspective view, and Tablet

8.5 Part 2

1. Did you ever feel overwhelmed by a technique? Yes or No
   a. If yes, please state the technique(s) and describe:

2. Did you ever forget about a technique? Yes or No
   a. If yes, please state the technique(s) and describe:
3. Did you ever think a technique wasn’t needed in a certain scenario? Yes or No
   a. If yes, please state the technique(s) and describe:

4. Was the perspective view still useful even when given the tablet to use?

5. Was it unclear which technique to use in a specific situation?

6. Was there any technique that allowed you to perform the task quicker?

7. If you had to choose 1 technique to use with the viewshed, what would you choose?
   a. Perspective view
   b. Tablet view

   Explain:
8. Do you think you could have completed task 2 (placing the towers) with the viewshed alone?
   a. Yes
   b. No
   c. Yes, but the task would have taken longer.
Appendix E

NASA-TLX

Figure 8.6

**NASA Task Load Index**

Hart and Staveland’s NASA Task Load Index (TLX) method assesses workload on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

<table>
<thead>
<tr>
<th>Name</th>
<th>Task</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental Demand</td>
<td>How mentally demanding was the task?</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>Very High</td>
<td></td>
</tr>
<tr>
<td>Physical Demand</td>
<td>How physically demanding was the task?</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>Very High</td>
<td></td>
</tr>
<tr>
<td>Temporal Demand</td>
<td>How hurried or rushed was the pace of the task?</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>Very High</td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td>How successful were you in accomplishing what you were asked to do?</td>
<td></td>
</tr>
<tr>
<td>Perfect</td>
<td>Failure</td>
<td></td>
</tr>
<tr>
<td>Effort</td>
<td>How hard did you have to work to accomplish your level of performance?</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>Very High</td>
<td></td>
</tr>
<tr>
<td>Frustration</td>
<td>How insecure, discouraged, irritated, stressed, and annoyed were you?</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>Very High</td>
<td></td>
</tr>
</tbody>
</table>
Appendix F

GREB Approval

May 12, 2014

Mr. Matthew Oskamp
Master’s Student
School of Computing
Queen’s University
557 Goodwin Hall
Kingston, ON, K7L 3N6

GREB Ref #: G-CISCI-073-14; Romeo #: 601721
Title: "CSCC-073-14 Exploration of Terrain Visualization Techniques on an Interactive Tabletop"

Dear Mr. Oskamp:

The General Research Ethics Board (GREB), by means of a delegated board review, has cleared your proposal entitled "CSCC-073-14 Exploration of Terrain Visualization Techniques on an Interactive Tabletop" for ethical compliance with the Tri-Council Guidelines (TCPG) and Queen’s ethics policies. In accordance with the Tri-Council Guidelines (article D.1.6) and Senate Terms of Reference (article G), your project has been cleared for one year. At the end of each year, the GREB will ask if your project has been completed and if not, what changes have occurred or will occur in the next year.

You are reminded of your obligation to advise the GREB, with a copy to your unit REB, of any adverse event(s) that occur during this one year period (access this form at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Adverse Event Report). An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example you must report changes to the level of risk, applicant characteristics, and implementation of new procedures. To make an amendment, access the application at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Amendment to Approved Study Form. These changes will automatically be sent to the Ethics Coordinator, Gail Irving, at the Office of Research Services or jirving@queensu.ca for further review and clearance by the GREB or GREB Chair.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Yours sincerely,

[Signature]

Joan Stevenson, Ph.D.
Chair
General Research Ethics Board

C: Dr. Nicholas Graham, Faculty Supervisor
   Dr. Christopher Boroloso, Post-Doctoral Fellow, Co-investigator
Appendix G

CORE Certificate

Certificate of Completion

This document certifies that

Matthew Oskamp

has completed the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans Course on Research Ethics (TCPS 2: CORE)

Date of Issue: 21 February, 2013