5-2021

Augmenting the Site Analysis Phase of the Design Process Using Virtual Reality and Drones

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Recommended Citation

Blauer, Brandon, "Augmenting the Site Analysis Phase of the Design Process Using Virtual Reality and Drones" (2021). *All Graduate Plan B and other Reports*. 1547.
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AUGMENTING THE SITE ANALYSIS PHASE OF THE DESIGN PROCESS USING VIRTUAL REALITY AND DRONES

by

Brandon S. Blauer

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF LANDSCAPE ARCHITECTURE

(Plan B)

Approved:

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UTAH STATE UNIVERSITY
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2019

ABSTRACT

Augmenting the Site Analysis Phase of the Design Process
Using Virtual Reality

by

Brandon S. Blauer,Master of Landscape Architecture

Utah State University, 2019

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Department: Landscape Architecture and Environmental Planning

Virtual reality (VR) is a tool that has been utilized by designers for decades now. In most cases, VR has been utilized in the latter part of the design process. More specifically, VR has been used most commonly towards the design review phase of the design process where people are often looking for a final design suggestion. With regards to the design review phase, there have been many reports discussing the effectiveness of VR. However, there has been little to no research regarding the use of VR in the site analysis phase of the design process.

This thesis develops a methodology for generating a three-dimensional (3-D) terrain model using drones and photogrammetry software, then importing the 3-D terrain model to an immersive virtual reality program, along with GIS data and other online resources, to conduct a large-scale site analysis using VR.

This thesis uses the site Powder Mountain, Utah to explore ways of integrating VR into the site analysis phase design process. Powder Mountain includes 10,000 acres of rough terrain and steep slopes. The analysis focus was prioritized by existing program elements generated by Summit Powder Mountain.

The results of this study suggest that this methodology can enhance the site analysis process by increasing the connectivity of designers to existing site conditions, allowing designers to frequently reference site conditions as they proceed to later phases of the design process. VR also provides designers with a means to express their site analysis in a manner that is spatially connected to the site, rather than via abstracted 2-dimensional models and representations.

(62 pages)

PUBLIC ABSTRACT

Augmenting the Site Analysis Phase of the Design Process Using Virtual Reality

Brandon S. Blauer

For several decades, virtual reality (VR) has been explored as a tool for designers. However, in a large majority of cases, VR has been utilized as a visualization mechanism within the latter stages of the design process, more specifically, in the design review phase where designers often gather final design suggestions. However, there has been little research involving the use of VR during the site analysis phase of the design process.

This thesis develops a methodology for conducting a large-scale site analysis within VR by generating a three-dimensional (3-D) terrain model using unmanned aerial vehicles (commonly referred to as drones) and photogrammetry software. The 3-D terrain model was imported to an immersive VR program and then augmented with GIS data and other data sources in order to conduct an analysis of the site.

This thesis utilized the Powder Mountain Ski Area in Eden, Utah to assess ways of integrating VR into the analysis phase of the design process. Powder Mountain includes an immense 10,000 acres of rough terrain and steep slopes, making the site difficult to traverse and analyze using traditional site inventory and analysis approaches.

The results of this study suggest that this methodology can enhance the site analysis process by increasing the connectivity of designers to existing site conditions, thereby enabling designers to frequently reference site conditions as they proceed to the later phases of the design process. VR also provides designers with a means to express their site analysis in a manner that is spatially connected to the site rather than via abstracted two-dimensional models and representations.

ACKNOWLEDGMENTS

I just want to say thanks to everyone who has influenced me in my life. Thank you to all of the people who have made this thesis possible. I want to specifically thank my committee members— Ben George for encouraging me to be the best I can be, Dave Evans for his charismatic input, and Andreas Wesemann for his thoughtful advice. Thank you to all the faculty in the LAEP department for your contribution to this thesis. Lastly, I want to thank my family, friends, and my wife, Natalie. Thanks.

Brandon S. Blauer

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CHAPTER 1

INTRODUCTION

Background

Virtual reality (VR) has interested designers for several decades (Mazuryk, Gervautz, 1996). Until recently, the cost of VR has limited its use to research labs or unique applications. However, the recent advent of several consumer-level VR products now provides an opportunity to bring VR into the mainstream design process. This has the potential to be especially beneficial in the design fields because virtual reality provides designers with a powerful tool to visualize complex design concepts (Horne & Thompson, 2008). However, the large majority of the published research has only explored the use of VR as a visualization tool to be used in the latter stages of the design process. Research that has explored the use of VR earlier in the design process has demonstrated promising benefits that VR can provide. One of the primary identified benefits is an embodied sense of presence in a location, which is of particular interest to designers because it enables designers to naturally and immediately understand the spatial character of the existing conditions and impacts of their related design decisions (George, Sleipness, & Quebbeman, 2017).

Even less research has been conducted on the use of VR to conduct a site inventory or analysis, which occurs as one of the initial steps of the design process. How VR might be used during these early phases of design has not been adequately explored, and we can only hypothesize about how the identified benefits of VR might be applied to a site analysis.

This research examines the use of VR during the site analysis phase of the design process. Based on previous research using VR in other aspects of the design process, it is theorized that VR has the potential to contribute to the site analysis phase in several ways. First, VR can enable designers to virtually revisit a site, providing an opportunity to repeatedly reference site conditions in a way that may not otherwise be physically possible due to travel or cost limitations. This benefit may help the designer make more informed design decisions because they may retain a higher level of awareness of site conditions. Secondly, VR can also enable designers to more directly connect analysis data with the physical conditions of the site, as VR provides designers with a means of expressing their site analysis in a manner that is spatially connected to the site, rather than via abstracted 2-dimensional models and representations. Finally, it is further theorized that VR could alter the way designers approach site analysis and form conclusions, due to VR's strong spatial emphasis that keeps designers focused on the forms and conditions of the site. The integration of this spatial component may further enhance a designer's ability to understand and respond to site conditions and their implications during the site analysis phase.

Research Questions/Objectives

The primary goal of this research is to develop a methodology that augments the landscape architecture design process by combining contemporary technologies with common landscape architecture practices. Furthermore, it is hoped this research will contribute to a broader adoption of VR by designers through addressing missing data and enabling future researchers and developers to create immersive VR environments tailored to the needs of landscape architects.

This research will specifically seek to answer the following research questions:

1) Can VR be effectively utilized to conduct a site analysis?

2) How does VR enhance the user's connectivity to site conditions?

3) Can VR analysis be implemented in landscape architecture?

LITERATURE REVIEW

Site Analysis Process

The land planning and design process is a series of activities requiring the visualization, analysis, and application of site information. Graphic and verbal communication can help clients, consultants, and other individuals understand and participate in the different phases of the land planning and design process (LaGro, 2001). Documenting efforts to protect public health, safety, and welfare can also expedite the permitting and approval process of the construction phase (LaGro, 2001). This process can benefit the designer, developer, future site users, and the existing communities.

Within land planning and design, site inventory and analysis are iterative steps in the design process. During the site inventory phase, data is collected, informed by the project program, about the physical, biological, and cultural characteristics of a site. The analysis phase synthesizes the data gathered during inventory and aligns it with existing program elements to facilitate the generation of design concepts. In contrast to the inventory, a site analysis identifies—in a spatially explicit form—the site's opportunities and constraints for a specific land use program, and the inventory maps provide data needed for the site analysis (LaGro, 2001)

The output data from the site analysis process are often illustrated via 2-dimensional representations, either drawn on paper or represented on a computer screen. Data is typically represented in a series of overlapping layers, as pioneered by Ian

McHarg (1969). Booth (1990), in *Basic Elements of Landscape Architectural Design,* says, “Design concepts and proposals are prepared and studied as tracing paper overlays on top of the base sheet” (p. 4). This idea of representing site analysis on a 2-dimensional medium is similar across most site analysis practices and is by far the most common method taught in education and utilized in practice.

Virtual Reality

Humans live in a world in which they are continuously subjected to spatial sensation. The experience of space is a common and vital human experience, comparable to experiences such as food, sleep, clothing, or sex (Eckbo, 2002). The visual sense is the dominant component of human sensory perception (Bruce et al., 1996; Rose, 2012), and research on visualization suggests benefits from expanding visual representations across a variety of fields and disciplines (Hansen & Machin, 2013; Valiela, 2009; Ware, 2013).

Because of the importance of the visual sense to humans, our brains have become adept at processing spatial information (Gersmehl & Gersmehl, 2007). Virtual reality can use humans’ physiological preferences for visual and spatial thinking as a tool for spatial visualization and communication (de Freitas & Ruschel, 2013). Such an approach has been demonstrated to be beneficial in representing complex information, as the noted visualization expert Edward Tufte (1990) describes visualization as a method for clarifying complex data in a way that provides advantages over singular oral or written descriptions.

Castronovo, Nikolic, Liu & Messner (2013) define virtual reality as a computer environment that creates a “convincing illusion and sensation of being inside an artificial [digital] world.” (p. 23) Several researchers have explored the use of VR throughout the design process; however, the majority of the research conducted to date has focused on using VR to visualize completed, or nearly-completed, designs as a mechanism for sharing the design with others or gathering feedback.

Freitas & Ruschel (2013) assessed VR research in architecture and found that nearly all the instances of the use of VR occurred in the evaluation and review phase of the design process. Similarly, Portman, Natapov, & Fisher-Gewirtzman (2015) reviewed VR research and noted the majority of landscape architects used VR solely for visualizing landscapes. Bullinger, Bauer, Wenzel, & Blach (2010), Dunston, Arns, & McGlothlin (2011), and Castronovo et al. (2013) all demonstrated that VR was an effective design review tool.

Other researchers have begun to explore the application of VR in assessing the current state of a site. George (2016) had students view 360-degree video in VR to conduct a rudimentary site inventory of a residential site and found that students were able to successfully conduct an inventory that accurately responded to the site conditions. Zhang, Jeng, & Zhang (2018) describe how VR headsets can offer a high-quality immersive environment and serve as interactive tools for historical landscape analysis and preservation.

However, VR has yet to be fully incorporated in the landscape architectural design process. Chamberlain (2015) suggests that tools which aid the understanding of spatial landscape planning concepts will improve the capacity of planners and landscape architects to derive solutions in tandem with stakeholder engagement. Design tools and technologies which help improve the human decision-making process will also help us become more effective stewards of our planet (Goodchild, 2010).

Recent research has demonstrated that VR can be successfully used during the design development phase of the design process. Chamberlain (2015) utilized a video game platform to create urban landscapes to help students better understand urban design principles. George, Sleipness, & Quebbeman (2016a) demonstrated that virtual reality can be an effective means for producing design concepts on a small site during the early conceptual phase of design. George & Sleipness (2016b) found that students were able to rapidly prototype designs in VR more effectively than using computer-modeling software and that they were particularly aware of the spatial impacts of their decisions.

Drones

Another way VR can be utilized is through pairing VR with other technologies, such as drones, to create high-quality 3-dimensional digital models of a specific site, using a method known as photogrammetry. Kullmann's (2018) paper on the application of drones in the field of landscape architecture states that designers who use drones to facilitate direct, unfiltered on-site user engagement have a stronger connection to the site they are focusing on. However, most consumer-level drones are still relatively expensive and require a high degree of expertise to safely and legally operate. However, as the technology matures, it can be expected that drones will become less expensive, more readily available, and easier to fly. As a result, in the future, it can be expected that more landscape architects will be able to utilize drones in their site analysis and design process as both hardware and software advances become more tailored to the needs of landscape architects. This is evidenced by a recent survey of landscape architecture firms which indicated that drones are one of the top new technologies which firms plan to adopt (George & Summerlin, 2019).

METHODOLOGY

This research adopts a case study approach utilizing the action research method. According to Deming & Swaffield (2011), “Action research produces new knowledge based on the process of direct engagement” (p. 40). Kurt Lewin’s (1946) work at the Massachusetts Institute of Technology Center for Group Dynamics defines action research as a spiral of steps, each of which is composed of a circle of planning, action, and fact-finding about the result of the action. In order to successfully answer the research questions, there will be iterative cycles of planning, action, and fact finding about the result of the action. Following this cycle, there will then be a discussion section to assess what was found in the action and results sections. The iterative cycles that will be covered in this paper are:

- Site visits where drone missions were planned and executed to collect geolocated images to later generate a three-dimensional (3-D) base model. The 3-D model will be created using photogrammetry.

- Once the 3-D model is generated from the drone imagery, the model will then be placed into VR with maps generated from GIS data sets to conduct the site inventory and analysis. Information gathered from these efforts was utilized to create a set of suitability maps indicating terrain suitability for future design exploration.

This will be followed by a discussion of the aforementioned information to examine the use of drone photogrammetry and VR in the site analysis phase of the design process. The importance of this is to present the overall findings and conclusions of the research, to note possible implications in other areas of study, and to explore improvements that can be made to further this research track.

Study Site

The focus site for this project is the Summit Powder Mountain ski resort (SPM). SPM is located at 8,900 feet (2712m) above sea level (ASL), straddling Weber and Cache Counties, Utah. SPM is one of the largest skiable mountains in North America with over 8,464 skiable acres and thousands more acres of undeveloped wilderness. The vastness of the site has immense popular appeal and has led to an interest in developing a portion of the land atop the mountain as a resort community to increase access and accommodate more skiers. Figure 1 shows the property boundary of SPM and its expansive 10,000+ total acres in white. The two ridges, Bobcat and Gertsen Ridge, enclose the focus site of this thesis, otherwise known as the Phase 3 development. Phase 3 is where SPM would like to incorporate their defined program elements for this project.

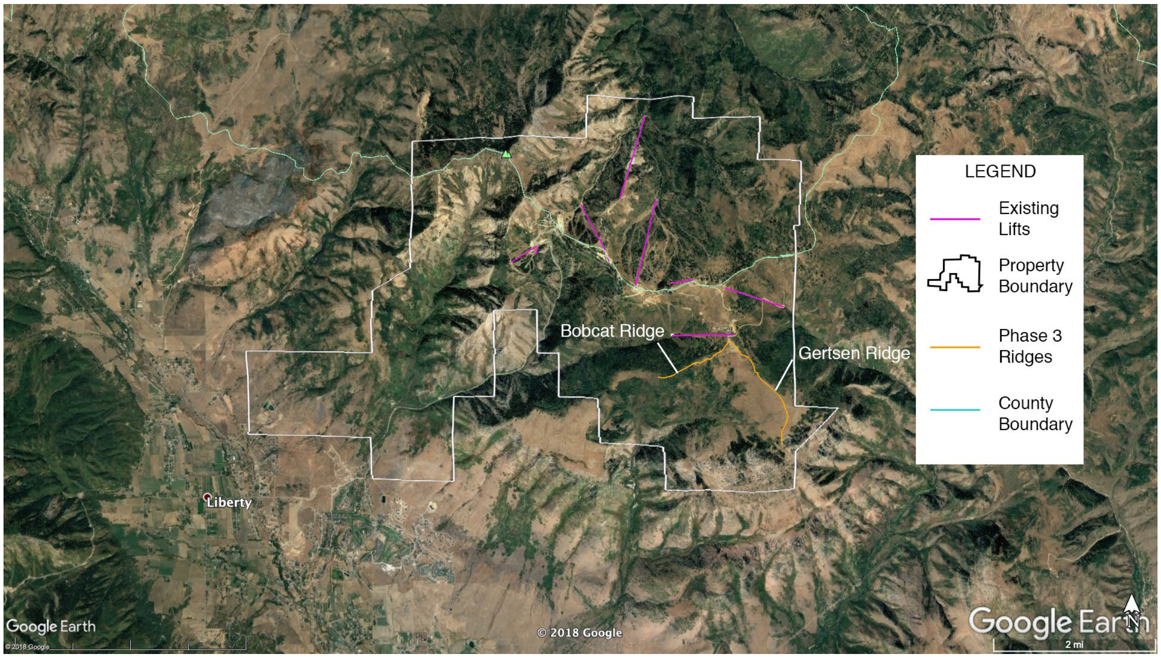


Figure 1. Powder Mountain Context

SPM partnered with Utah State University's (USU) Landscape Architecture and Environmental Planning (LAEP) program to develop concepts for a village development on the area highlighted in yellow in Figure 2. LAEP arranged a design charrette, a week-long event where students and faculty across the department participated in developing

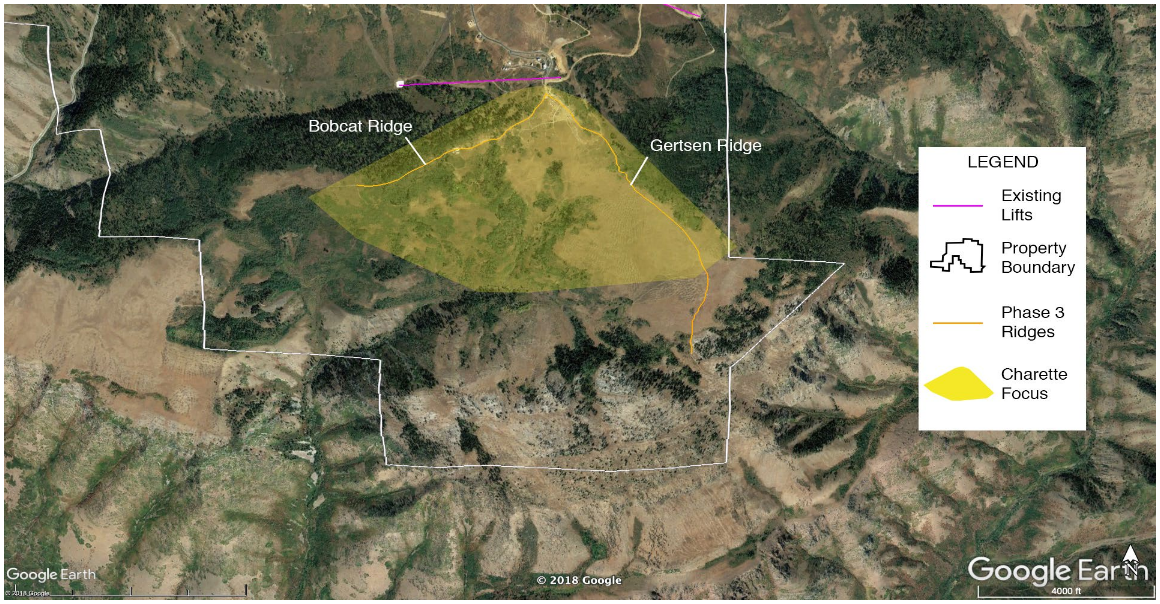


Figure 2. USU Design Charrette Focus in Yellow

potential future design concepts for SPM in order to generate ideas for the village development. The present thesis was implemented in the preliminary stages of the design charrette, specifically during the site inventory and analysis phase.

SPM is open year-round, but in recent years, SPM has opened for the ski season during the months of November and December. In order to collect accurate photo imagery, it was necessary to capture drone imagery before snow started to accumulate on the mountain, after which point it would be more difficult to generate an accurate terrain model of the site using photogrammetry because the snow would cover many of the visible details that the photogrammetry process uses to generate the model. The site visits and drone flights took place in late September through the end of October, with the intention of having the 3-D base model created and imported into VR for further exploration during the design charrette, which occurred at the end of January.

CHAPTER 3

DATA COLLECTION/ MODEL CREATION

Brief Drone Rules

There are many important regulations regarding the operation of drones. Several Federal Aviation Administration (FAA) and Utah regulations limit where one can and cannot operate drones. Fortunately, this project did not fall under any limiting rules and did not have to issue a Notice to Airmen (NOTAM), due to the fact that the property is privately owned and is not located in any competing airspace, such as airports or military operation areas. The stakeholders were informed and gave the researchers permission to fly at will across the site. Although there were no rules that impeded the drone flights, there are rules that all drone pilots must follow per FAA policies. Those general rules are:

1. Must fly below 400’ AGL (Above Ground Level).
2. Must fly in the line of sight of the drone.
3. Never fly near other aircraft, especially near airports.
4. Never fly over groups of people.
5. Never fly near emergency response efforts, such as wildfires.
6. Never fly under the influence.
7. Must have a minimum of 3 statute miles of visibility to operate unmanned aircraft system.

All of these regulations were adhered to during the operation of the drone on the SPM site. In addition to following government procedures, additional precautions were taken during drone flights. This included having an additional observer on-site to assist the operator in identifying any potential obstacles, ensuring the control for the drone remained in the operator’s hand even during times of autonomous flight, and maintaining an adequate supply of back up batteries and spare parts.

Action

For this project, the researcher partnered with Intel and Intel’s drone team. Intel’s drone team is based out of San Jose, California, which led to challenges in coordinating drone flights over SPM. The scheduled flights had to coordinate with Intel's schedule, the researcher’s schedule, and forecasted weather conditions in order to maximize the efficiency of the use of Intel’s drone each day. The scheduled flights were planned to take place in September and October for the following reasons:

1. This was when Intel’s drone pilot could fit the flight days into his schedule over a total of 4 days.
2. This was when Intel could ship their Sirius drone and other needed equipment.
3. This timeframe would enable project fruition prior to the USU design charrette.
4. The site location would most likely be snow-free.

The drones used to gather imagery were Intel’s Sirius UAS (Figure 3), Intel’s Falcon 8 (Figure 10), DJI Mavic Pro (Figure 6), and DJI Inspire 1 (Figure 7).

The Sirius UAS is a fixed-wing foam plane with a single propeller on the front. The Sirius takes aerial photos using a high-resolution 16mp Fujifilm X-M1 camera. The

Sirius has autonomous flight planning capability with high geo-location accuracy and global navigation satellite systems real-time kinematic (GNSS RTK) mapping that eliminates the need for ground control points. The Sirius uses MAVinci desktop software to program the flight path. Prior to the flight, the pilot sets the flight parameters of the mission on a laptop, and the MAVinci software automatically calculates the altitude and flight waypoints based on the amount of image overlap desired. The pilot then uploads the generated flight parameters to the Sirius drone. Once set up, the Sirius flies autonomously with minimal pilot intervention. The drone can operate for approximately 20 minutes, regardless of wind conditions, before needing to land in order to change batteries.

The research team wanted to gather as much drone imagery as possible in collaboration with the Intel drone team during the four days with the Sirius drone. Because it was not possible to fly the entire site while maintaining a relatively low elevation (below 400 feet, in keeping with FAA regulations), the pilot divided the site into multiple cells (geographic sections) that would be flown on individual missions. Additionally, the Sirius drone had to stay within the line of sight of the drone operator, and battery life also limited the length of flight, as the drone needed to return to land when the battery level reached 30%. Figure 5 shows a representation of what the drone missions were plotted to be.

Figure 3. Image of the Sirius Intel Drone by Topconpositioning.com

There were 16 missions planned by the MAVinci desktop mission planner. Each mission was planned to cover roughly 350 acres of land, which would take about 16 minutes per mission. The Sirius's altitude sensors told the drone to fly 300 feet above the ground level while following the terrain of the mountain ridges. At this height, the X-M1 camera on board is capable of capturing higher resolution images than the DJI Mavic Pro and Inspire 1 drones. The drone missions were assigned a priority level to determine which should be captured first, which was determined by how close a cell was to the development area of the site. Figure 4 shows a map illustrating the planned flight cells overlaid with the levels of importance of each mission to be flown, based on the proximity to the primary location of the development.

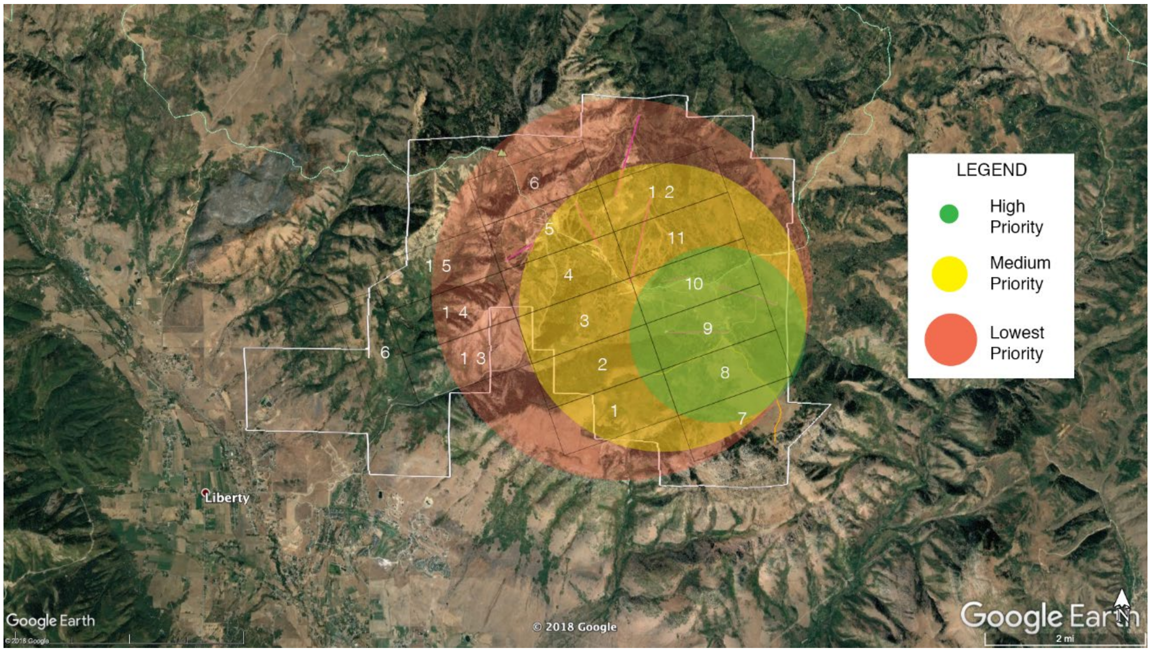


Figure 4. Drone Image Priority Map

Once the images are captured using the Sirius drone, the memory cards on board the Sirius are transferred to the laptop on-site, from which the photos are exported to the MAVinci software, which automatically adds the metadata holding the georectified coordinates assigned to each image taken by the drone so that the photogrammetry software can generate an accurate 3-D point cloud from the imagery.

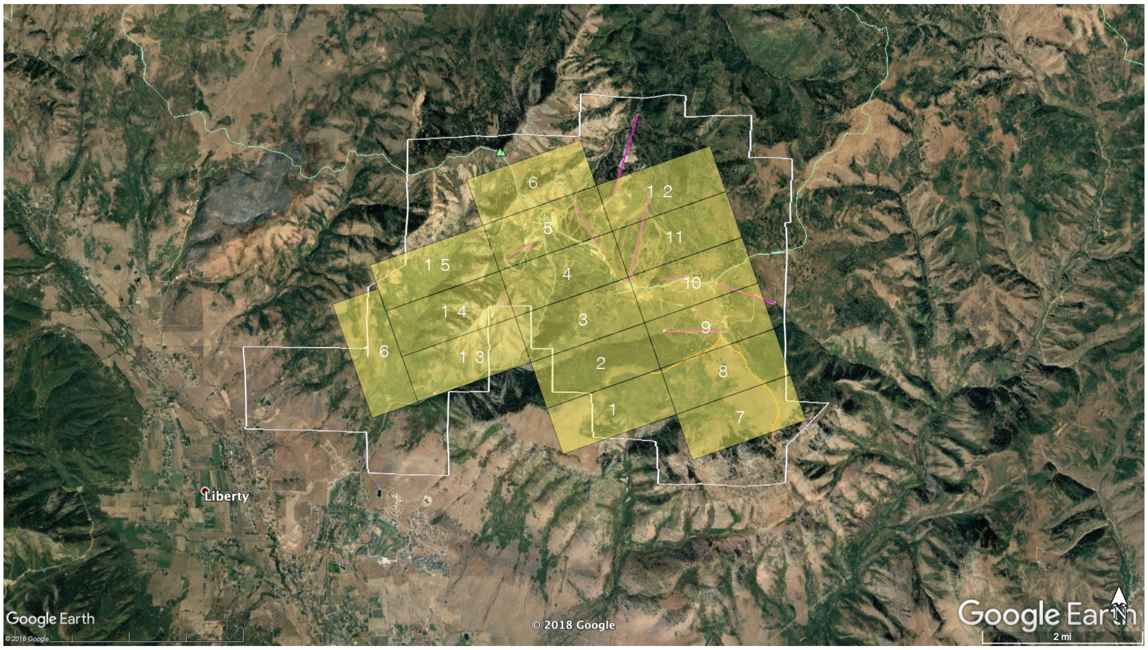


Figure 5. Representation of the Sirius Drone Mission Planner

Prior to the Intel Drone team's arrival at SPM to fly the site with the Sirius drone, flights were flown by the researcher using LAEP's DJI drones to gather preliminary imagery. The drones used for these flights were the DJI Mavic Pro and the DJI Inspire 1 (see Figures 6 and 7). Both drones carry 12-megapixel cameras and use Pix4D software to autonomously pilot the drone. Pix4D does not automatically choose flight altitude, image overlap, or flight path. The software allows for manual adjustment of these settings, which were set prior to each mission flown. The batteries on both drones provide an average of 16-20 minutes of flight time, depending on wind conditions. Like the Intel drones, the Pix4d mission planner allows the pilots to pause the mission and recall the drone to change batteries before continuing the mission from the location at which it was paused in order to complete the mission.

Figure 6. DJI Mavic Pro

Figure 7. DJI Inspire 1

Photogrammetry

Pix4d is the Photogrammetry software used to create the 3-D model. Pix4D has the ability to generate multiple file types, including a 3-D textured mesh (the primary function of Pix4D), which will be used for the 3-D base model in VR; and contour lines, which will be referenced during the site analysis phase of this research. The photogrammetry process will begin once all the images are taken by the drones and can be processed in the same project in Pix4D.

Results

Sirius Drone Flight

Unfortunately, the Sirius drone missions yielded disappointing results, as only a single mission of the 16 planned missions was flown, due to a malfunction in the drone's flight controls which caused the Sirius drone to crash into the trees on the mountainside.

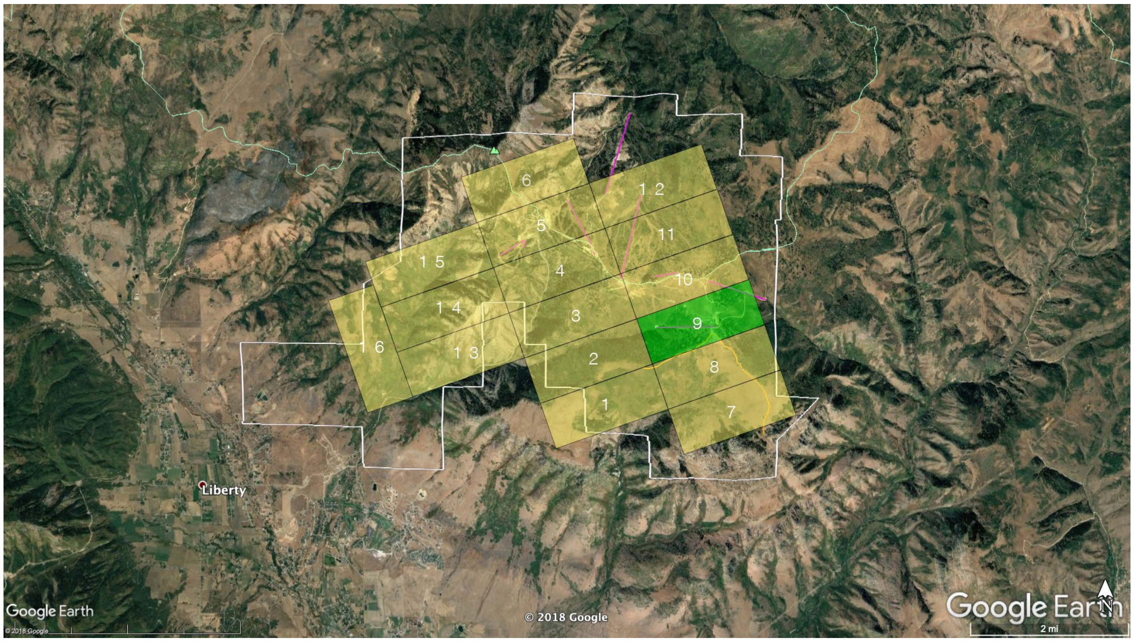


Figure 8. The green is the area that the Sirius drone flew

This resulted in serious structural damage which was unable to be repaired on-site, and the drone was deemed unusable for the rest of the project duration. As a result, cell 9 was the only mission completed using this capture method, during which the drone took a total of 850 images. Photos captured in cell 9 had exceptionally high-quality output due to the quality of the camera on board the Sirius drone. Figure 8 shows the 350 acres in cell 9 that were flown and captured with the Sirius drone. The flight was flown at 300' AGL. Mission 9 was chosen first to fly based on its level of priority (see Figure 4).

Figure 9. Complete model generated from Mission 9

Figure 9 shows the 350-acre site generated in Pix4D from the 850 geolocated images taken during the Sirius drone flight.

Due to unexpectedly early cold weather conditions, the site was covered in snow when the Sirius drone flew Mission 9. Fortunately, this had little to no effect on the drone mission or creation of the model, as the highly accurate geolocation of the images enabled Pix4D to still generate a very accurate model. Because of the early onset of winter, the weather conditions on SPM changed daily, and the process of scheduling flights became more complicated due to the variability and unpredictability of the xweather. Thus, the failure to capture the entire site with the Sirius drone due to the crash jeopardized the completion of the project in a timely manner. For the project to continue, the research team had to form a plan B approach to gather adequate data for the project to proceed in a timely manner.

Plan B

Intel's drone team was forced to temporarily leave the site, due to the inability to operate the damaged Sirius drone. At the time, the Sirius drone that crashed was the only fixed-winged drone available for use with this research. When the Intel Drone team returned for a second site visit, they brought an alternate drone called the Falcon 8. The Falcon 8 is a V-shaped octocopter that has 8 electrical, brushless motors and carries a precise 36 MP DSLM camera. The Falcon 8 uses AscTex Navigator flight planning software that automatically sets the flight path, altitude, and image overlap percentage.

Figure 10. Falcon 8

However, the Falcon 8 is not ideal for photographing large areas due to its relatively slow flight speed, short battery life, and heavy camera payload. The Falcon 8 is capable of carrying a heavier, higher quality camera similar to the Sirius drone, but since the Falcon 8 is limited by its short battery life and subsequent shorter flight capability, there is a smaller output of around 30-40 acres per flight, compared to the 350 acres that the fixed-winged Sirius drone could capture in a single flight. The Falcon 8 could fly higher and capture fewer images due to its higher resolution camera; however, the time it takes to fly at the higher altitude AGL to capture those images ended up draining additional battery life, resulting in relatively little impact on the overall area that could be captured.

Similar to the Sirius, the Falcon 8 required special expertise and training in order operate it. The Intel drone pilot was the only available operator of the drone and flew all of the missions. Unfortunately, even with the additional drone, it would not be possible to capture all of the originally intended terrain data of SPM, so the researcher communicated to the pilot which parts of the site were most critical to capture in order to adequately capture the images necessary to generate a 3-D model of the primary development area.

A total of 14 successful missions were flown with the Falcon 8. The missions were flown between 250’ and 300’ AGL. Each mission captured roughly 30-40 acres of images (See Figure 11, Box 2) per flight and captured between 115 and 196 geo-rectified images each. These georectified images were then exported from the Falcon 8 onto an external hard drive to later be imported onto the computer to generate the point cloud. While the Intel drone pilot was flying missions with the Falcon 8, the researcher was simultaneously flying DJI drones owned by the LAEP department to capture additional site imagery elsewhere on-site.

The DJI drones flew a total of 10 successful missions covering similar ground as the Falcon 8. Each mission encompassed roughly 30-40 (Figure 11, Box 3) acres of land with an average of 270 images per mission. There are significantly more images in the DJI drone missions, due to the fact that the DJI drone camera has a lower resolution and requires more imagery to adequately cover the site. The DJI drone was flown at an average elevation of 275 feet AGL. Similar to the Falcon 8, images taken during the autonomous drone missions were extracted from an SD card and transferred to an external hard drive for later processing on the computer.

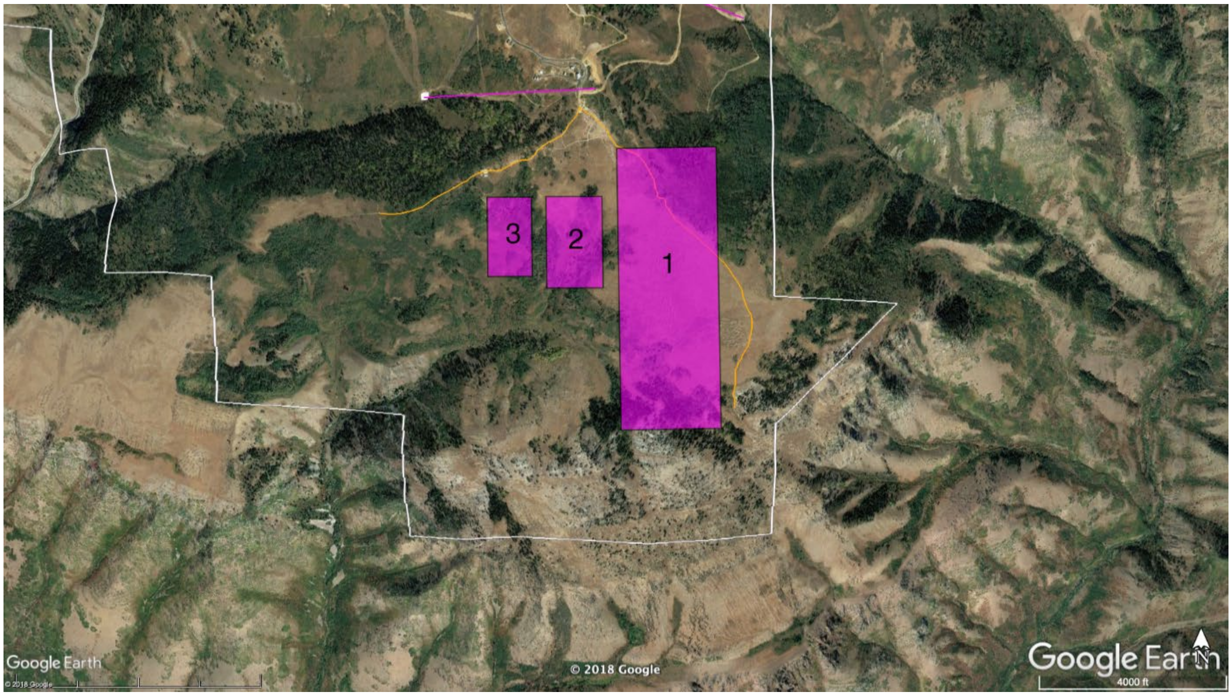


Figure 11. Box 1 is the land coverage of the Sirius Drone, Box 2 is the land coverage of the Falcon 8, Box 3 is the land coverage of the DJI drones

Figure 11 shows the relative sizes of the missions flown by each drone, with an 80% image overlap pattern for the photogrammetry software to adequately relate one mission to the next. Once the images were gathered from all drone missions, the images were placed into Pix4D and processed in order to generate the point cloud, 3-D object file, and contour data.

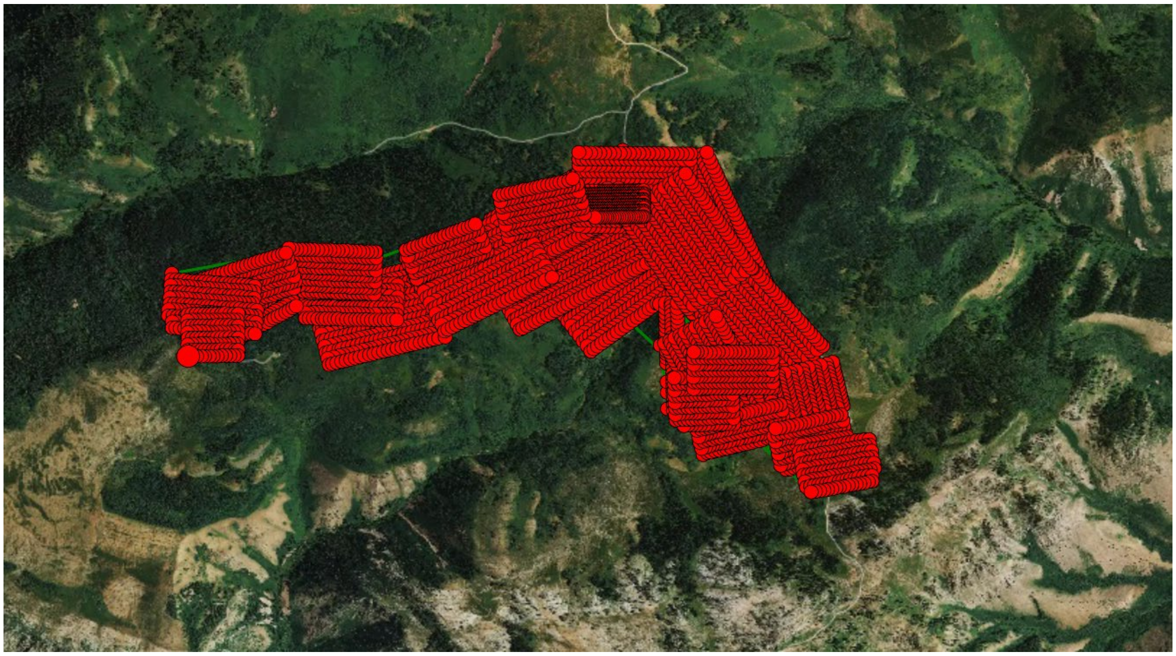


Figure 12. Image of all the drone missions overlapping

Figures 13 and 14 are screen captures of the Pix4D photogrammetry software. All the images captured by the drones were used to generate the 3-D point cloud in Pix4D. The software generated an object file that was imported into Tilt Brush for inventory and analysis.

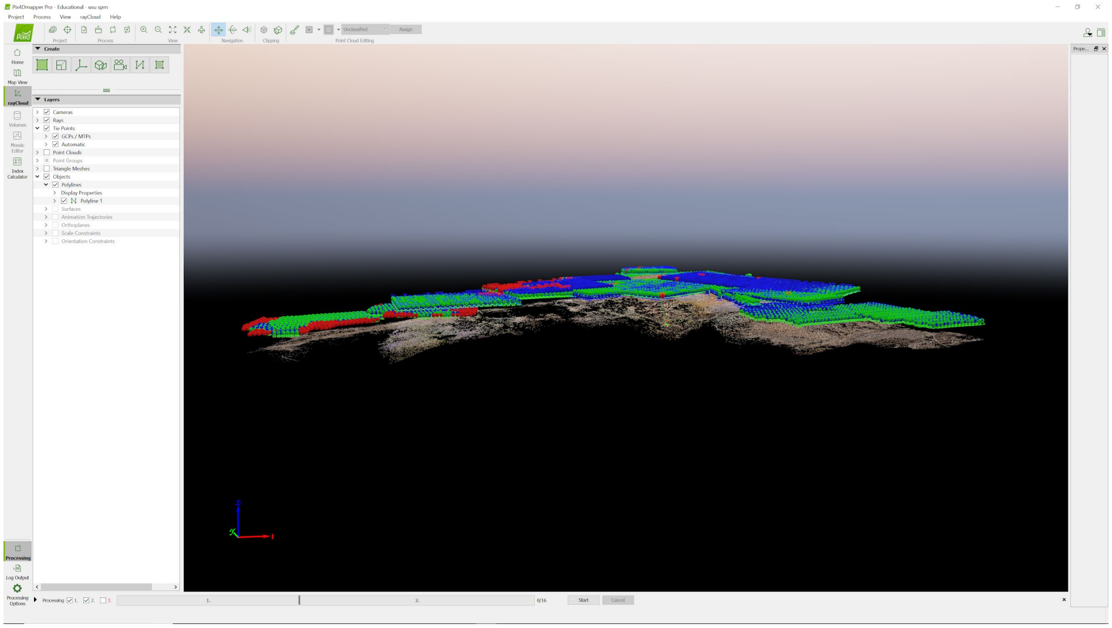


Figure 13. Screen capture from Pix4D

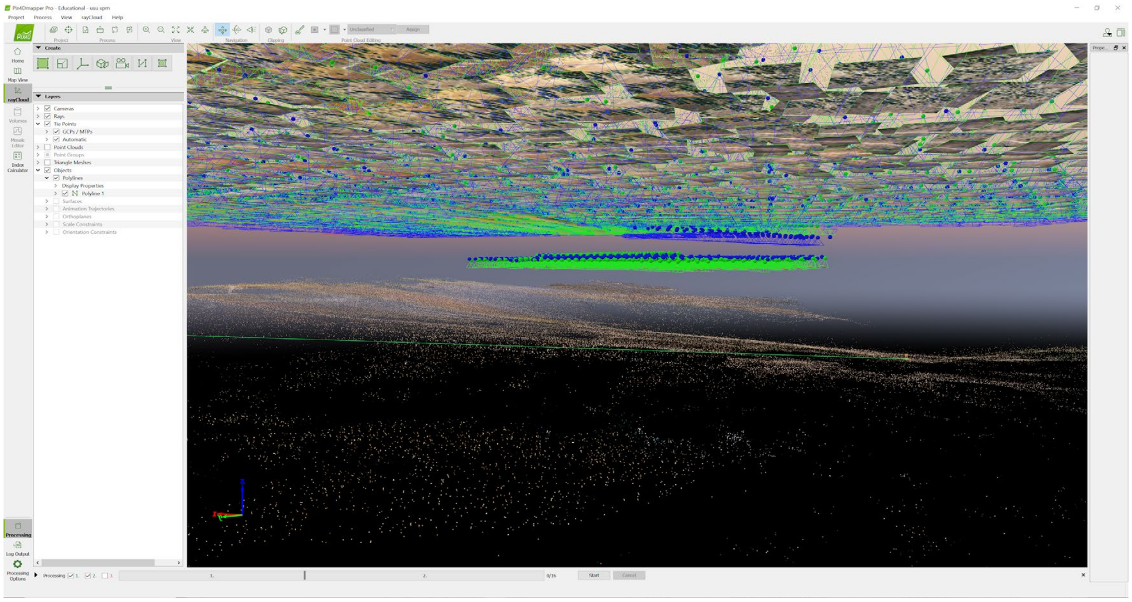


Figure 14. 2nd Screen capture from Pix4D

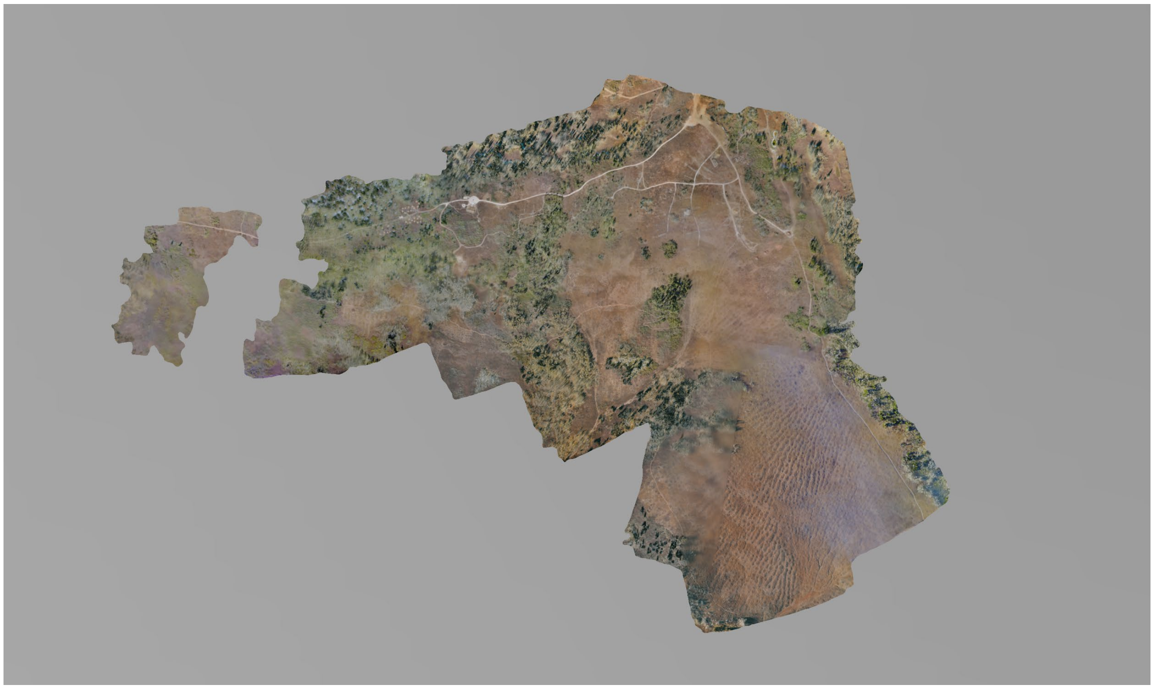


Figure 15. Complete mission from Falcon 8 drone and DJI drones

Figure 15 shows the final model that was generated using Pix4D's 3-D mesh creation function. The model adequately covered the focus site of the USU Design Charette at SPM, but is still much smaller than the initially expected results had the Sirius drone not crashed. The jigsaw shape of the model is due to the cells of each mission overlapping each other. Figure 12 shows the cell overlap causing the uneven edges of the model. The gap on the left side of the model is due to an insufficient number of images taken in that area, which resulted in a failure to generate a 3-D mesh in Pix4D. Unfortunately, weather and timing did not make it possible to re-fly this cell in order to capture additional imagery to repair this portion of the model.

Figure 16 shows the created drone model overlaid on a larger section generated from Google Earth to provide the larger site context. From this, it is apparent that there was only sufficient high-resolution imagery to encompass the focus site of the USU design charrette, rather than all the surrounding terrain to provide additional context, as originally anticipated.

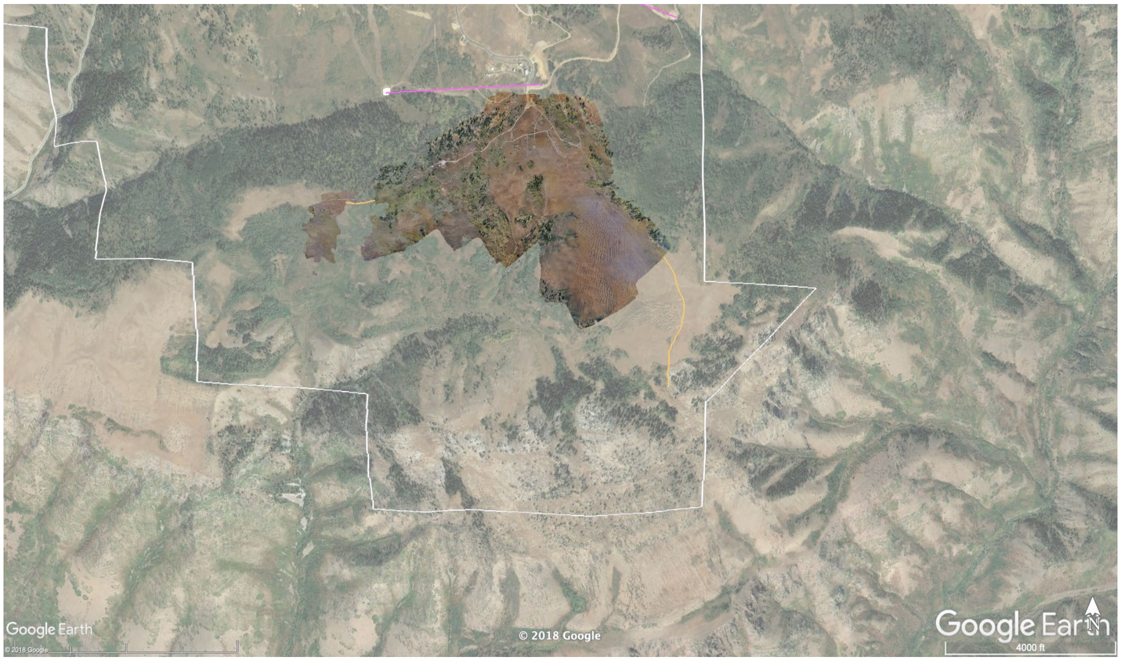


Figure 16. Complete mission from Falcon 8 drone and DJI drones in context to site

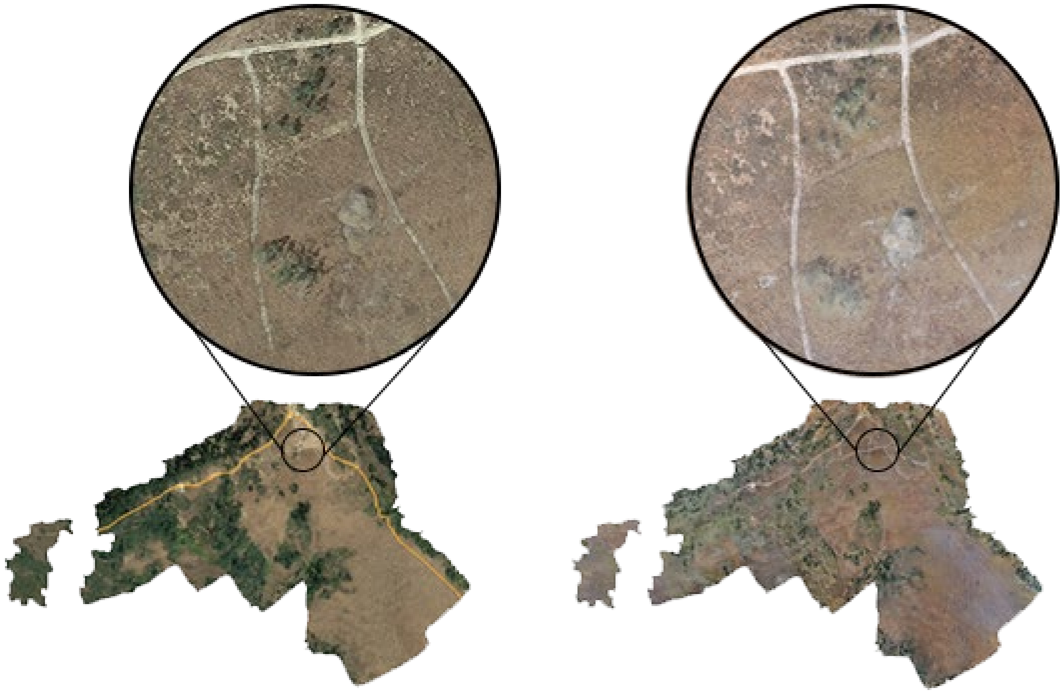


Figure 17. Comparison of Google Earth terrain model on left and the drone model on right

Although there was significantly less area flown by the drone than anticipated at the start of the research project, the benefits provided by the drones to the areas mapped were substantial, with a highly noticeable difference in the level of detail between the drone-created photogrammetry model and the Google Earth imagery (Figure 17). Additionally, Google Earth does not directly allow the user to export 3-D terrain files, meaning that it is necessary to use process work-arounds to acquire exportable Google Earth imagery mapped to the terrain data through third-party programs such as SketchUp Pro 3-D terrain function. However, this still yields lower-resolution imagery and data and is significantly less accurate than the drone model.

SITE INVENTORY AND ANALYSIS IN VR

Action

Every site is embedded within a larger landscape that provides context to a site and imbues it with meaning. The site inventory is an essential step in understanding these characteristics of a site and the physical, biological, and cultural linkages between a site and the surrounding landscape. The site analysis may entail several different kinds of evaluation, and the information contained in a site's physical, biological, and cultural attribute maps might be synthesized, for example, to create maps of the site's suitability for residential, commercial, or other land uses (Lagro, 2001).

This research will utilize Tilt Brush on an HTC Vive VR headset to conduct a site analysis utilizing the drone-generated terrain data as a primary input. Tilt Brush was used as the VR program to conduct the site analysis due to its spatial expansiveness and flexible drawing inputs. Some of the features and capabilities of Tilt Brush that resulted in its selection for the project include dynamic brush tips, export capabilities, ability to freely explore the space, and ease in importing models. At the time of this research, consumer-level VR headset and software were relatively new, and Tilt Brush was a premier example of a program that could have a loose 3-D drawing style with an array of dynamic brush tips to enable a designer to express their ideas effectively with relatively few limitations imposed by the technological tools.

In addition to its features, there were several practical reasons for choosing Tilt Brush, including its affordable price, simple interface that does not have a significant learning curve, availability on the HTC Vive, Oculus Rift, and Windows Mixed Reality, and its ease of use, in that it does not require a high-powered computer to run it. Additionally, users are able to import almost any size model object file. For the purpose of this research, the 3-D mesh exports from Pix4D will be imported into Tilt Brush as an .obj model file with an .mtl and .txt texture map.

Site Inventory Process

This thesis applies landscape architecture site analysis practices as established by James A. Lagro Jr. in his book *Site Analysis: Linking Program and Concept in Land Planning and Design* (2001) to the SPM terrain. The broad phases include developing detailed inventory maps of the site elements, both natural and man-made. To understand the landscape at SPM, the inventory data was gathered on-site and through online databases of GIS data, such as the ESRI or USGS databases. The inventory attributes that were gathered to be analyzed in Tilt Brush are:

Site Inventory: Physical Attributes

Topography

Topography is important for nearly all land planning decisions. In most cases, these efforts are gathered by a licensed land surveyor, but in this research, they will be completed using GIS data and the topographical information gathered by the drone flights, which are capable of producing topographic accuracy to 2cm. The three fundamental landform components are elevation, slope, and aspect, which will all have a uniform effect on future development patterns for SPM.

Geology

Geology also has a significant impact on the development of a site. The geology of a site is complex and includes features at the surface level, subsurface level, and even hundreds or thousands of feet below the site surface, all of which can significantly affect design decisions. Particularly important to consider are landforms and seismic hazards, such as fault lines.

Hydrology

The hydrology of a site is critical to consider during a site analysis, due to the many influences it has on the planning process. Water circulates in the Earth's environment through precipitation, overland flow, infiltration, storage, and evapotranspiration. These different types of hydrology functions, when paired with the elevation and terrain of SPM, can increase the risk of design failure if poorly managed.

Soils

Attributes of soils that are typically considered during a site inventory and analysis may include acidity/alkalinity, permeability, erosion potential, depth to the seasonal-high of the water table, and depth to bedrock. Buildings and other structures require foundations that must be constructed to a depth below the frost level. Difficult subsurface conditions affect not only the complexity of excavation and construction, but also the design of new structures. (Lagro, 2001)

Climate

The last attribute in the Physical section to consider is climate. The climate of SPM will significantly influence design decisions, as aspects to consider when planning on top of a mountain are solar access and orientation, solar radiation, wind patterns, snowfall, rainfall, inversion level, temperature, wind, humidity, temperature, and potential natural hazards.

Site Inventory: Biological Attributes

Biological attributes account for the large contiguous natural areas and should be given the highest priority for protection from future development. However, simply leaving the natural area untouched may not be sufficient to ensure their continued function. One of the primary functions of the site analysis process is to identify areas that require active steps to ensure the preservation (or expansion) of these areas. Examples of biological attributes to consider are:

Vegetation

Vegetation encompasses all things related to flora, including communities (wetlands, meadow, montane), plant provenience (native and exotic species), or noteworthy specimen trees. These components require an expert eye and a detailed survey to understand the character and expanse of the existing vegetation of the site.

Wildlife

Wildlife encompasses the fauna on the site and additional factors related to fauna lifecycles. As the site is one of the most remote portions of SPM property from the main entrance to the ski resort, developing a village at this location on the mountain can be expected to have substantial impacts to wildlife and their natural habitat. Examples of things that will be considered in this attribute are the species of wildlife on the site, wildlife corridors, and food sources.

Site Inventory: Cultural Attributes

Lastly, the extent of the cultural context refers to the historical, legal, aesthetic, and other socially significant attributes associated with land and landscapes (Lagro, 2001). Some examples of cultural attributes include land use and ownership tenure, land use regulations, local regulations, circulation, utilities, buildings, historic resources, and perceptual qualities addressing visibility and visual quality.

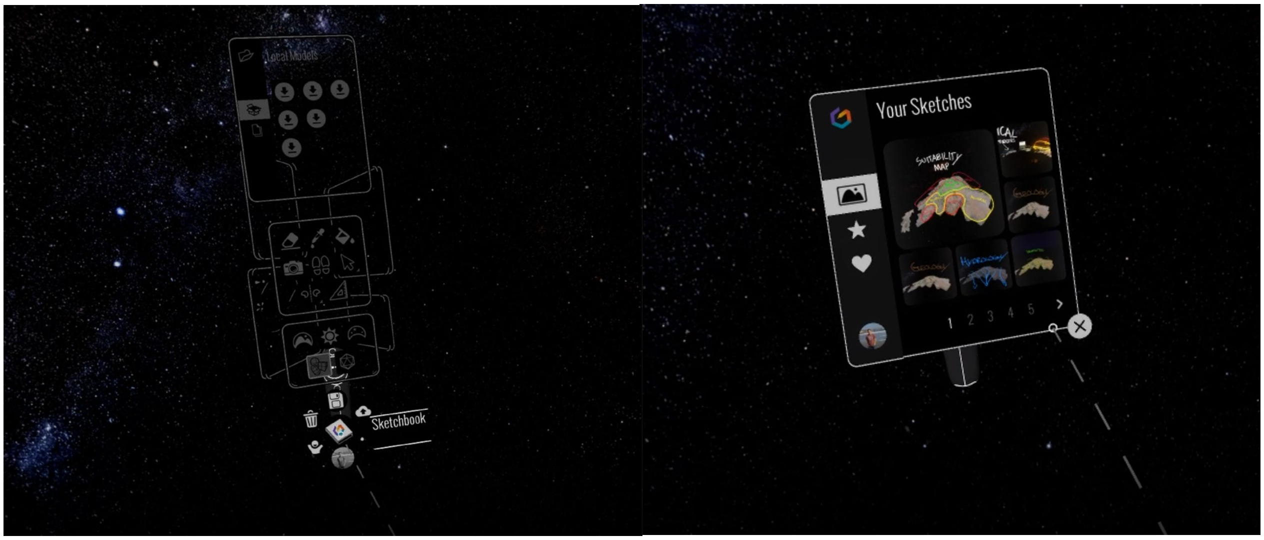
Site Analysis

The site analysis will result from the analysis of the accumulated physical, biological, and cultural inventory elements placed onto a suitability map developed from the information found. The suitability map will be created in VR and exported as a 3-D mesh that could be used and referenced for further design exploration during the conceptual development phase.

Results

Importing the Model

The model was imported into Tilt Brush through Tilt Brush's media library housed on the computer. The model was then opened within Tilt Brush via the media library tab on the settings pallet (see Figure 18). The model was then manually placed in the virtual work space within Tilt Brush.



Laying Out Inventory Attribute Maps

To facilitate the site analysis, the researcher found that it was most effective to import a series of models arranged in an array shown in the figures below (Figures 19 and 20). Similar to typical site analysis involving individual 2-D maps, the information could be difficult to decipher due to crowding of imagery if it were all on the same 3-D model. Additionally, a limitation of Tilt Brush is the lack of an option to turn layers on and off, therefore requiring all the information to be on a single layer, which would cause the inventory to become exceptionally cluttered and hard to read.

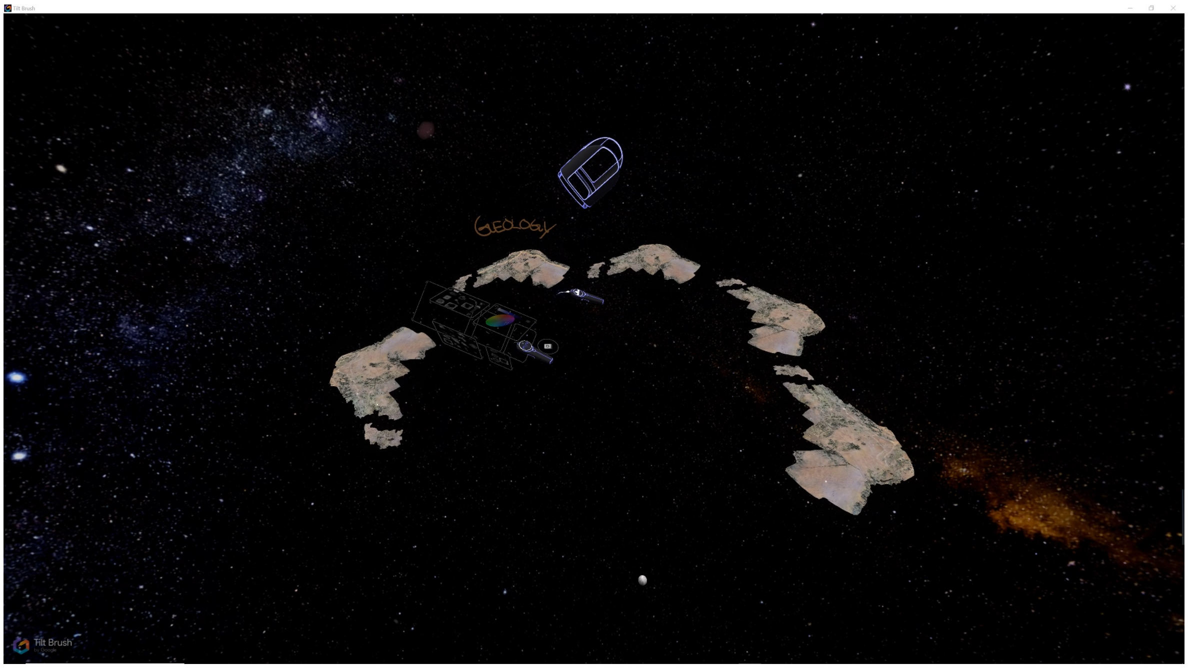


Figure 19. Array 1 of Models in Tilt Brush

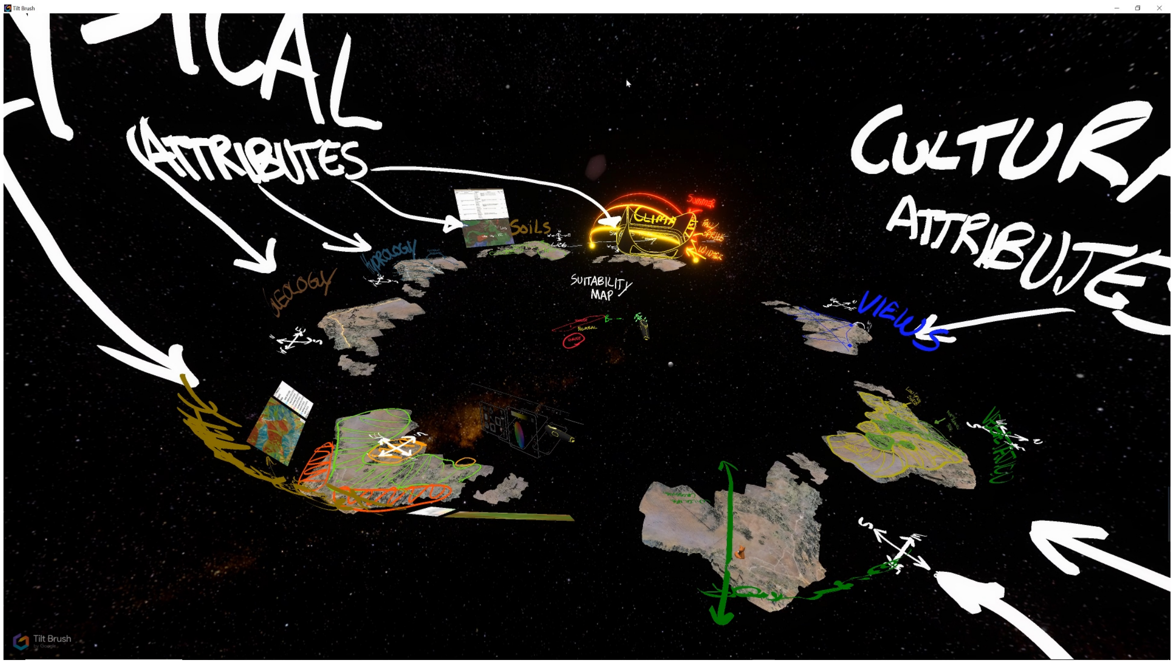


Figure 20. Array 2 of Models in Tilt Brush

Conducting the Site Inventory Maps

To conduct the site inventory in Tilt Brush, all external sources of data were imported into the virtual space as .jpg files and scaled within the virtual space. This was completed so the researcher could reference site conditions and transfer the data onto the map generated by the drones earlier in the research. Figure 21 shows an example of an external .jpg next to the model. It should be noted that this method is not ideal, as the researcher was not able to transfer all of the data as precisely as would occur using software such as GIS. Tilt Brush does not support geo-referenced datasets, and so it was not possible to import the data directly onto the model. However, a benefit of transferring the data by hand to the model was the discovery that it helped provide a stronger understanding of the connection of the data sets to the site, which then developed an increased awareness of all the aspects of different areas of the site.

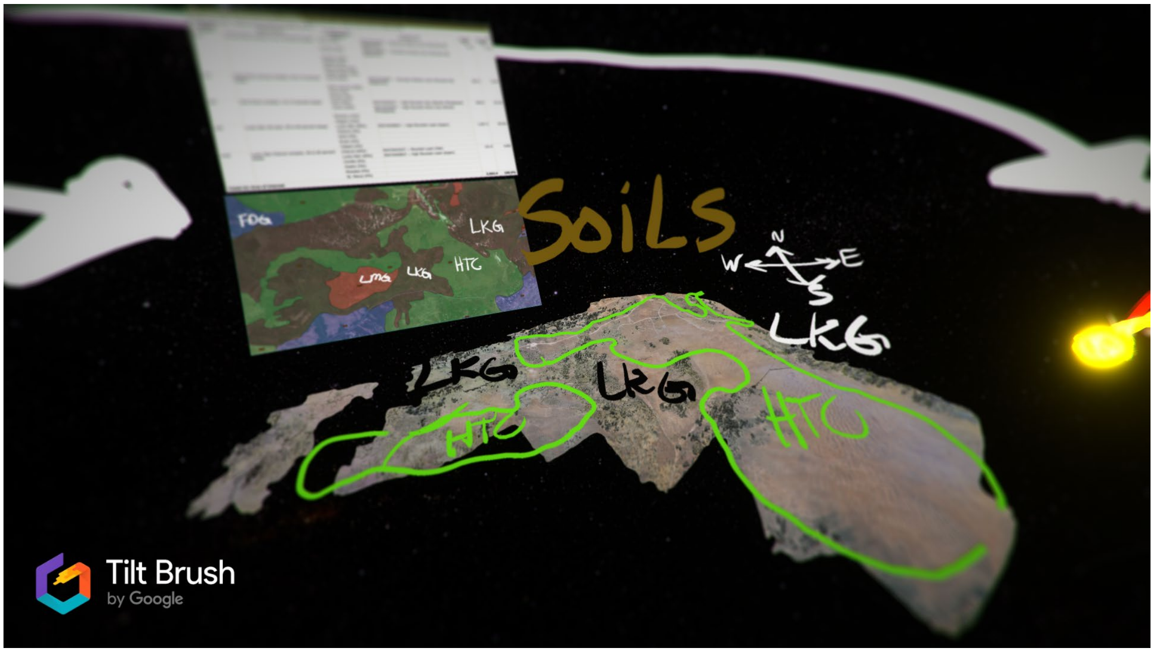


Figure 21. Image of an imported .jpg into Tilt Brush

Site Inventory: Physical Attributes

Topography

The topographic information was accessed through the website utah.gis.gov and through the use of the contour data generated by the drone surveys. In Figure 23, the slope was identified and labeled by color. Slopes in green ranged from 0-8% slope, slopes in yellow ranged from 9-30%, and red ranged from 30-90%+ slope. The areas with the least amount of slope are typically most suitable for development, as they will require the least cut and fill and stabilization. Other areas of steep slope would be more expensive and challenging to develop.

In general, the site as a whole is not as steep as the rest of SPM, which is one of the reasons why SPM has not yet installed a ski lift in this location. However, the shallow slopes may favor novice skiers or people skiing into the proposed village development. Another reason why this area does not have significant existing skiing infrastructure is because the site has a primarily south or southwest aspect. This produces a quality of snow that would be worse than slopes with a northern aspect because southern-facing slopes experience more pronounced melting and re-freezing. However, as winter at SPM is very cold, these southern-facing slopes are favorable for the proposed village development due to improved solar gain potential for structures. This would make the southern exposure favorable across the development.

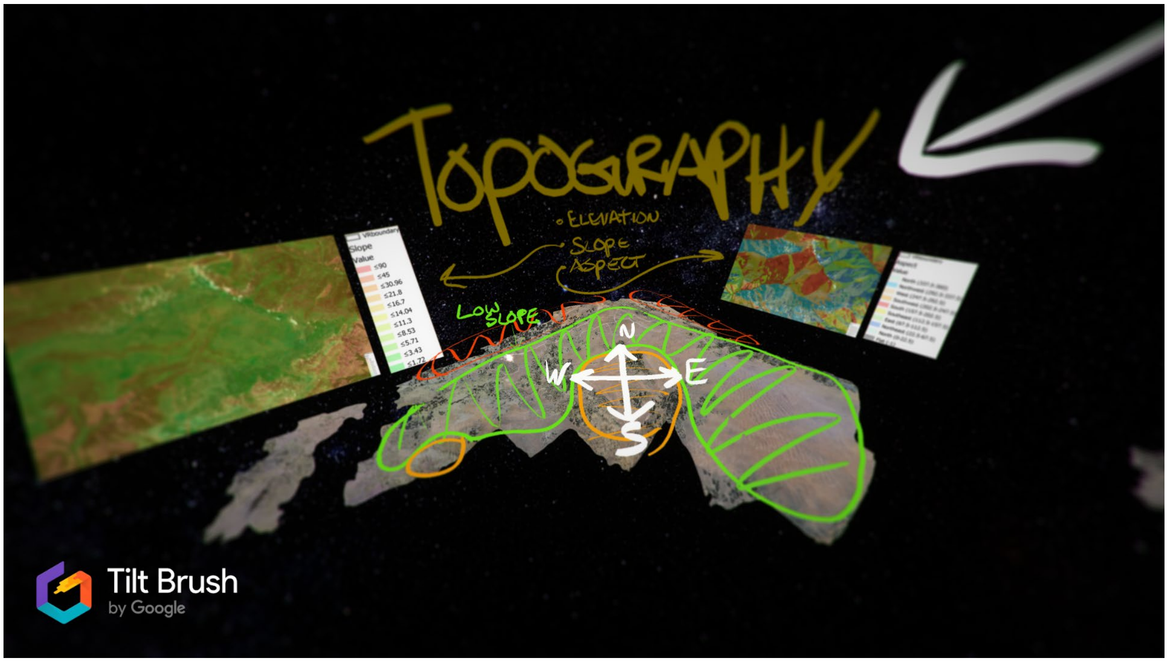


Figure 22. Topography Analysis image 1

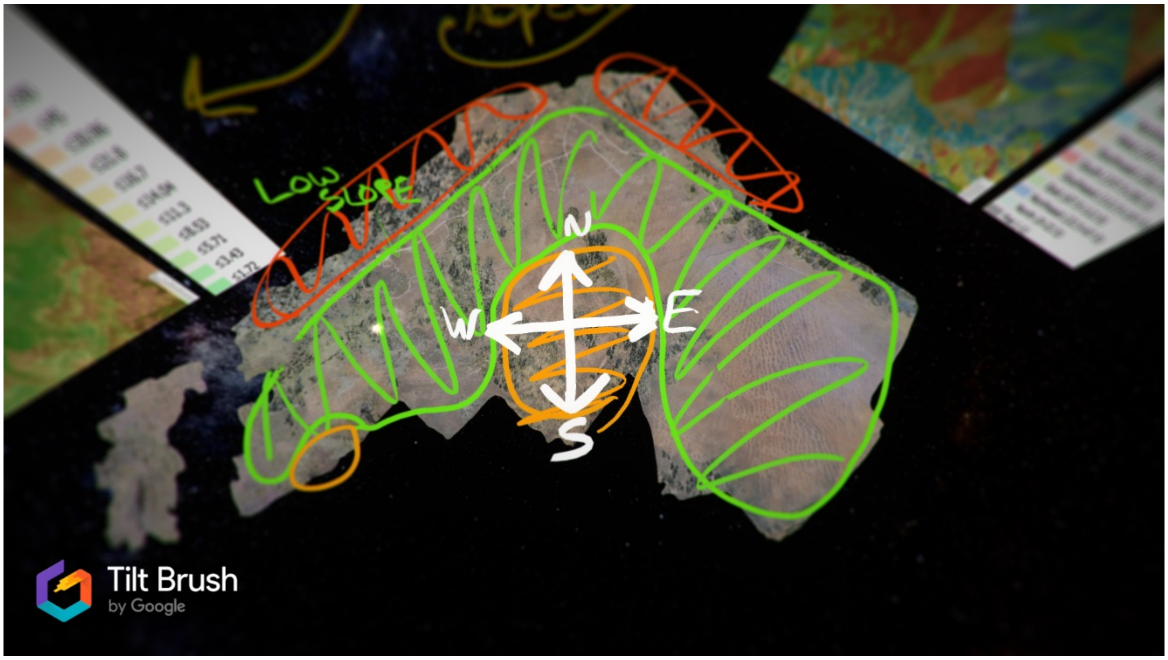


Figure 23. Topography Analysis image 2

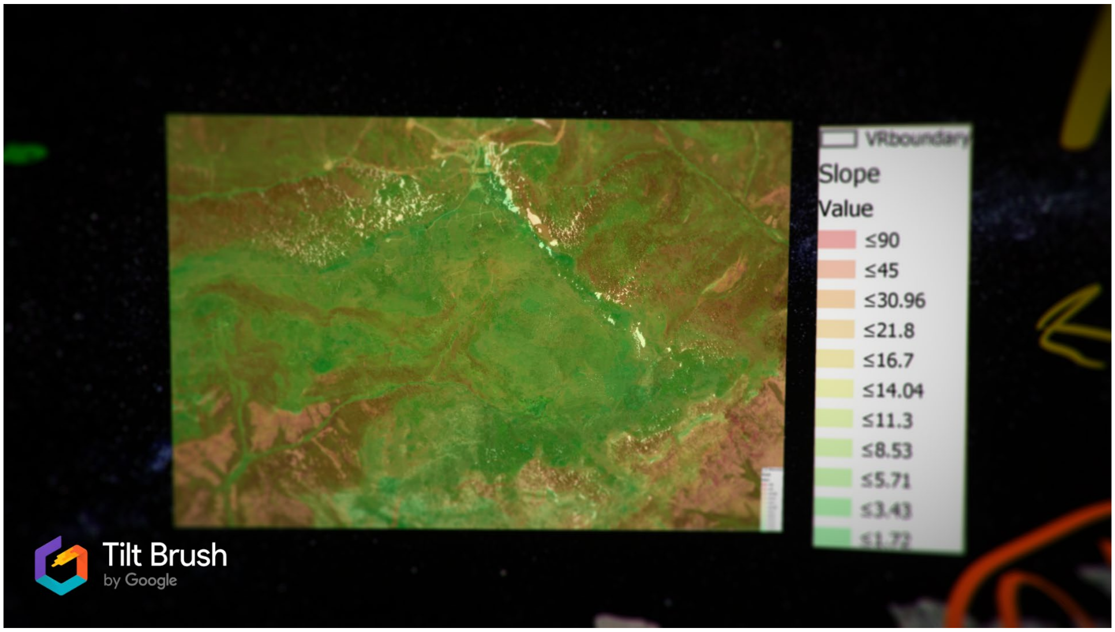


Figure 24. Topography Analysis: GIS Slope Data Import

Hydrology

Hydrologic information was found through various site visits and through scaling the site at micro and macro scales in order to understand water movement, infiltration, storage, and discharge, and was considered while representing the information on the 3-D map. Winter, spring, summer, and fall all have somewhat different effects on the hydrology, but for this research, the individual seasonal variations were not taken into account.

For the purpose of site development, it was particularly important to consider where the major and minor drainages were on the site. Blocking the major drainages with development may cause damage to new infrastructure and may cost SPM more money to regularly repair damage to the newly constructed infrastructure than it would if SPM were to build elsewhere. The major drainages were located near the southernmost part of the site referenced in Figure 25. Animated light blue lines were used in Tilt Brush to represent the overland flow and drainage patterns of water across the site. This was visually beneficial to aid in understanding and communicating how water is moving across the site and that it is an active and fluid process.

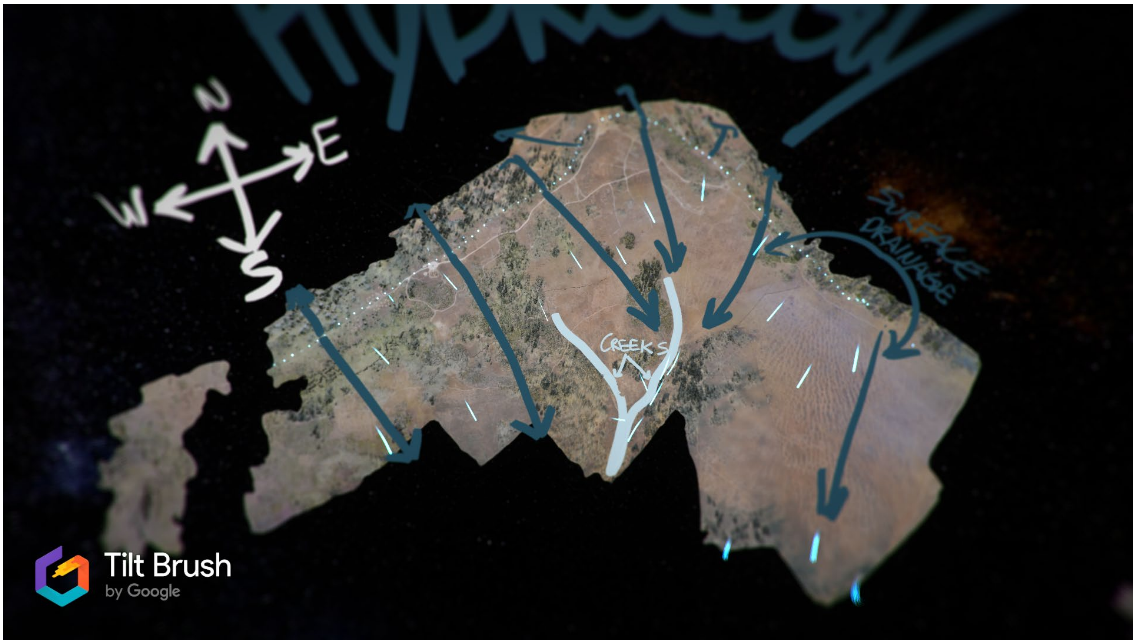


Figure 25. Hydrology Analysis

Soils

Soil data was gathered from the national soils online database (websoilsurvey.nrcs.usda.gov). The soils were similar across the site, containing three different types of soils. All soils showed positive potential to structurally support development and are referenced in the figures below.

The major soils found were first, Foxol-Rock outcrop complex, found on slopes around 40-70% and composed primarily of mountain shallow loam dominated by Mountain Big Sagebrush plant communities. Another soil type was Lucky Star silt loam, which is typically found on slopes ranging from 30-60%. Primary vegetation communities found in these areas include aspen and Gambel oak. The final primary soil type found in this area was Herd-Yence complex. This soil type was found on slopes ranging from 3-15% slopes. The primary vegetation found growing in this soil was slender wheatgrass. Herd-Yence complex was the most common soil found on-site.

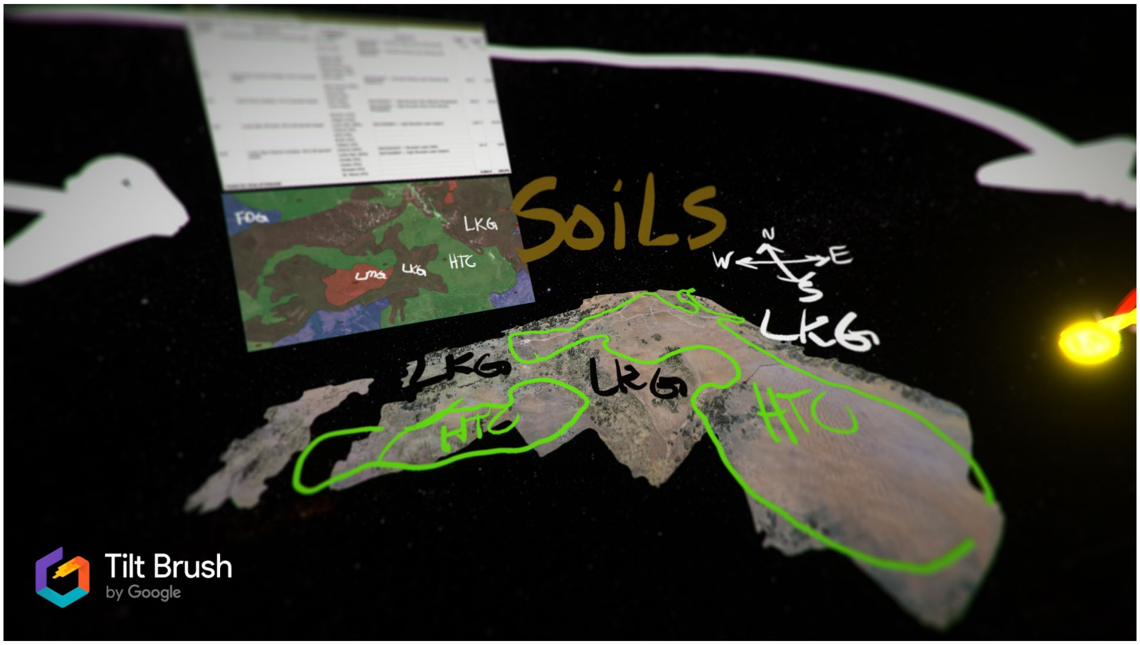


Figure26. Soil Data websoildsurvey.nrcs.usda.gov 3

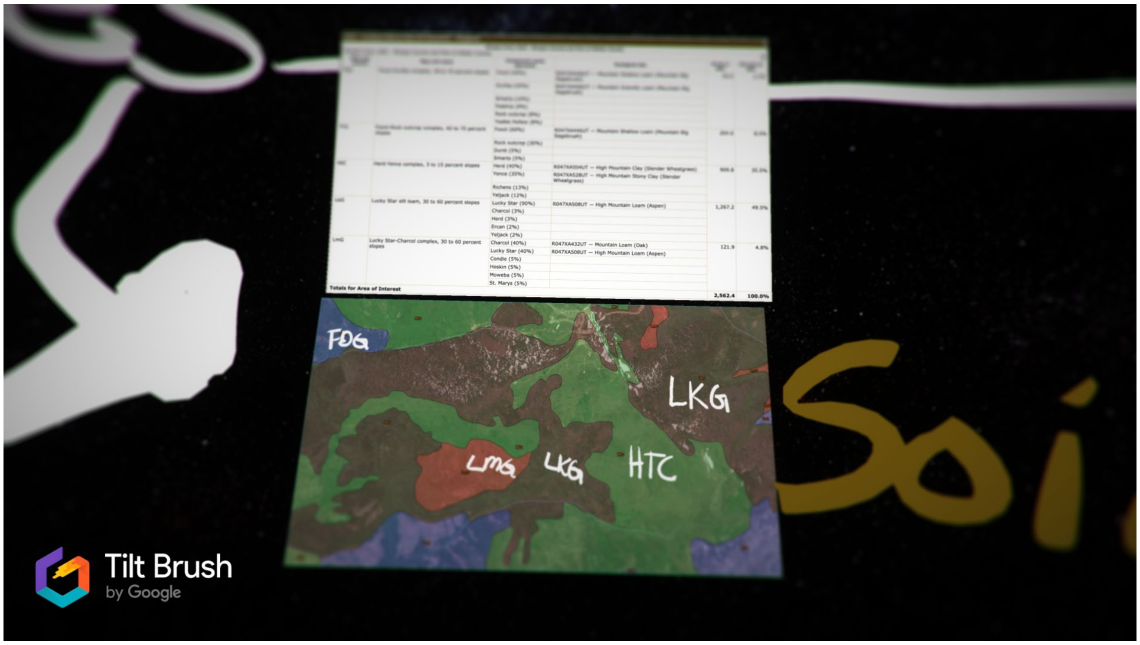


Figure 27. Soil Data websoilsurvey.nrcs.usda.gov

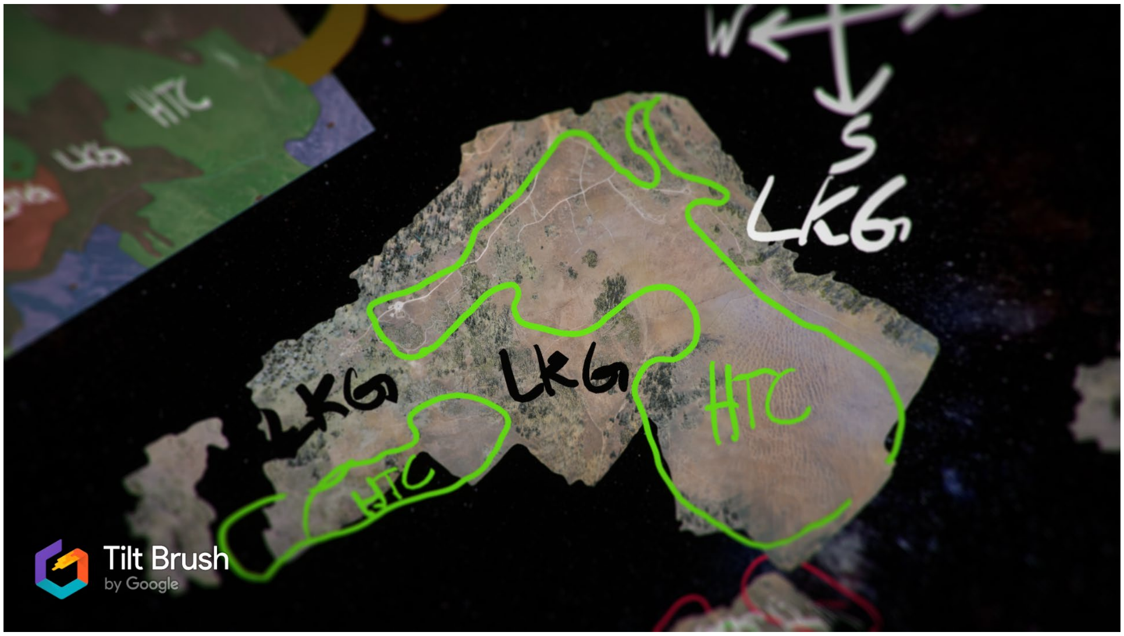


Figure 28. Soil Data websoilsurvey.nrcs.usda.gov 2

Climate

Climate data was gathered using the website US Climate Data, https://www.usclimatedata.com. This information allowed the researcher to apply data to the 3-D maps in VR such as sun paths, wind patterns, and snowpack within VR, and illustrated the capability of VR to powerfully visualize this type of spatial data.

The zenith angle showed that the summer solstice had an angle of 63 degrees from the horizon. In the fall and the spring, the sun sits around 40 degrees from the horizon. In the winter, the sun lies around 15 degrees. An important thing to note is that the site is exposed to the sun year-round, as there are few obstructions that would block sunlight from reaching the site. The only objects blocking the sun are stands of trees or new buildings. Future climate trends show an increase in average annual temperatures which may lead to a decrease in the amount of snow accumulated on the mountain each year, which could then affect future development patterns at SPM (EPA, 2016).

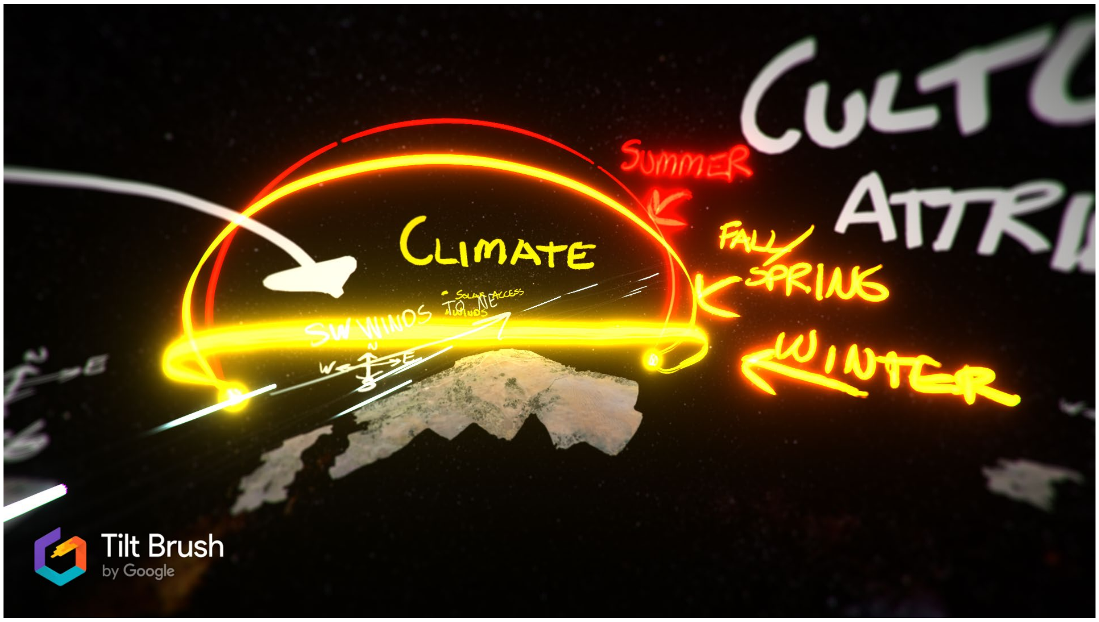


Figure 29. Climate Analysis 1

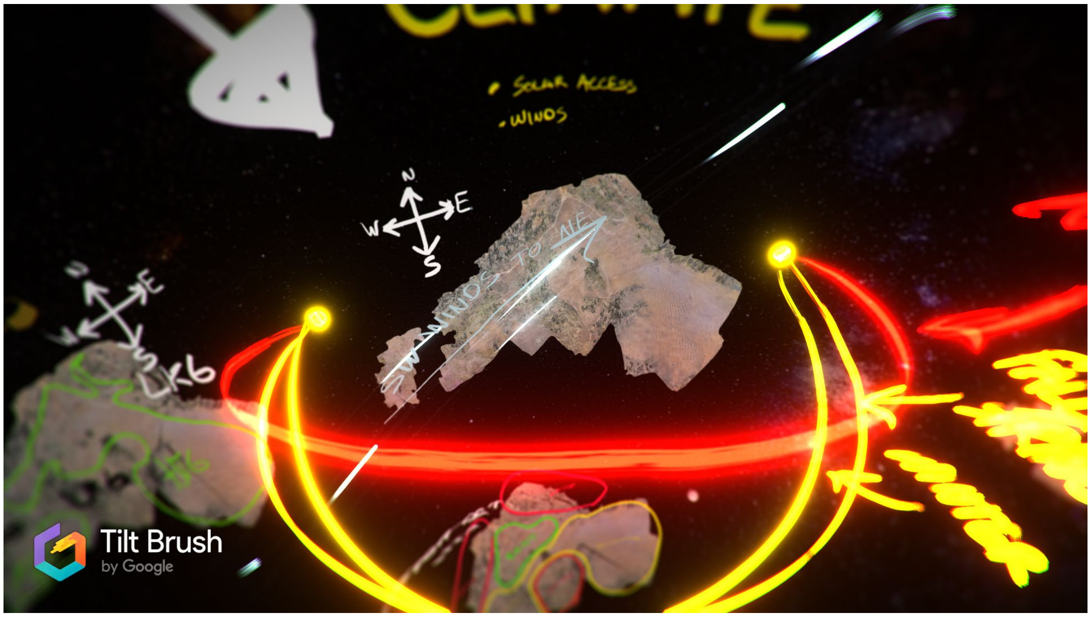


Figure 30. Climate Analysis 2

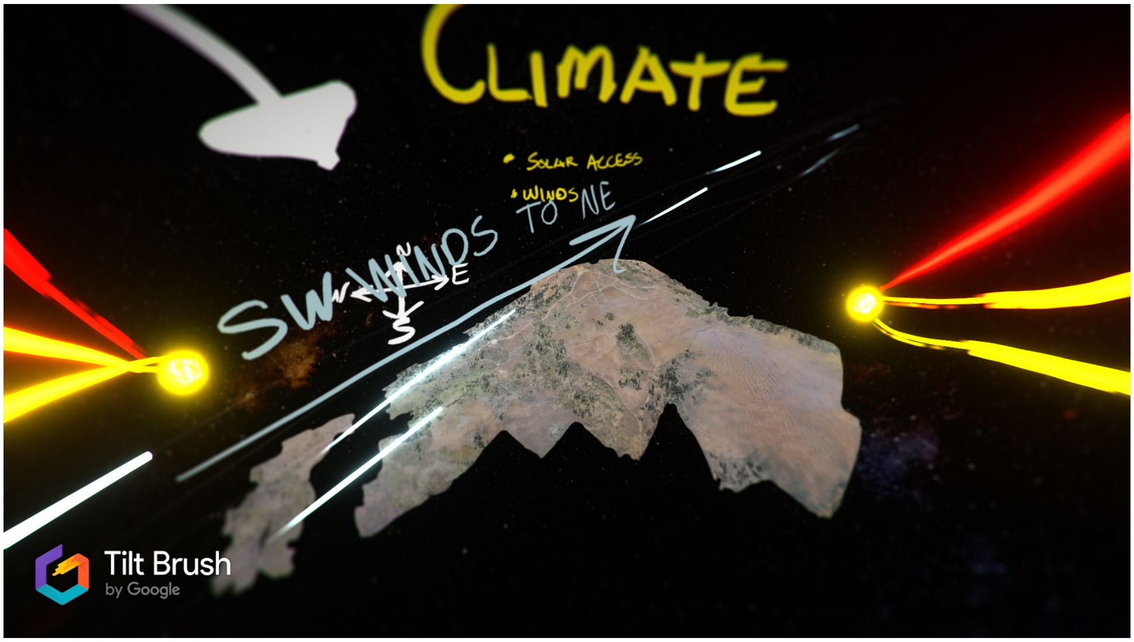


Figure 31. Climate Analysis 3

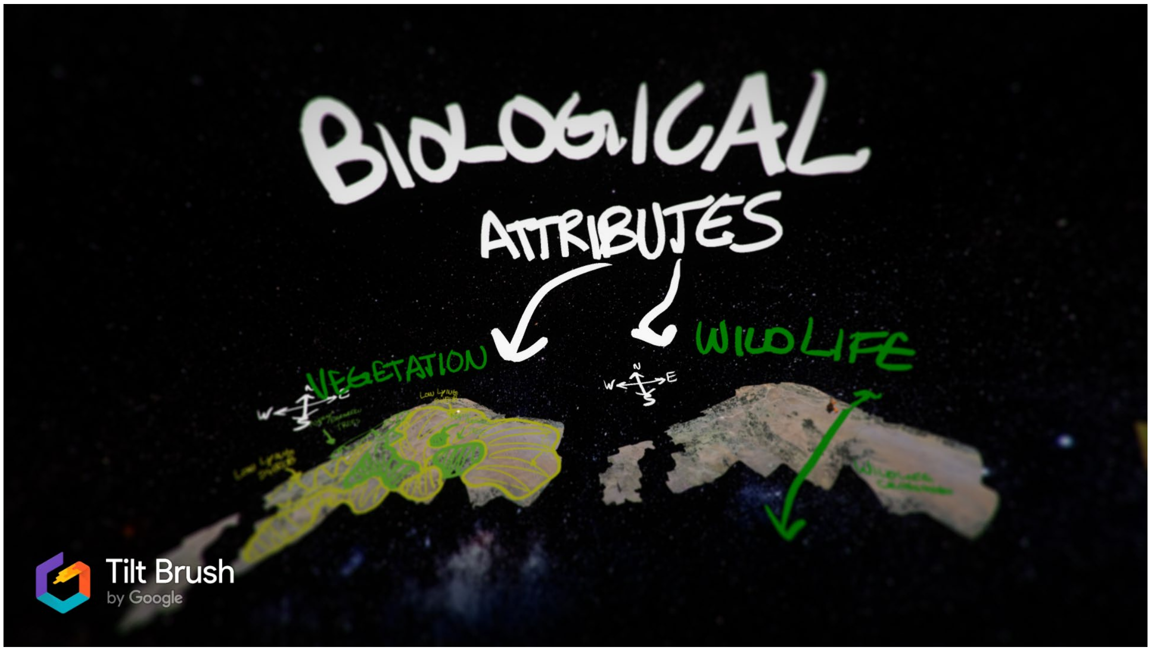


Figure 32. Biological Attributes

Site Inventory: Biological Attributes

Vegetation

The vegetation attributes were divided into two different categories: Low-lying shrubs and Aspen/Evergreen Clusters. The different categories were documented by visiting the site several times and then comparing the collected data to the site vegetation visibly represented via the 3-D model in VR. The researcher used multiple brush types to represent the various elements in the figures below (Figures 33, 34).

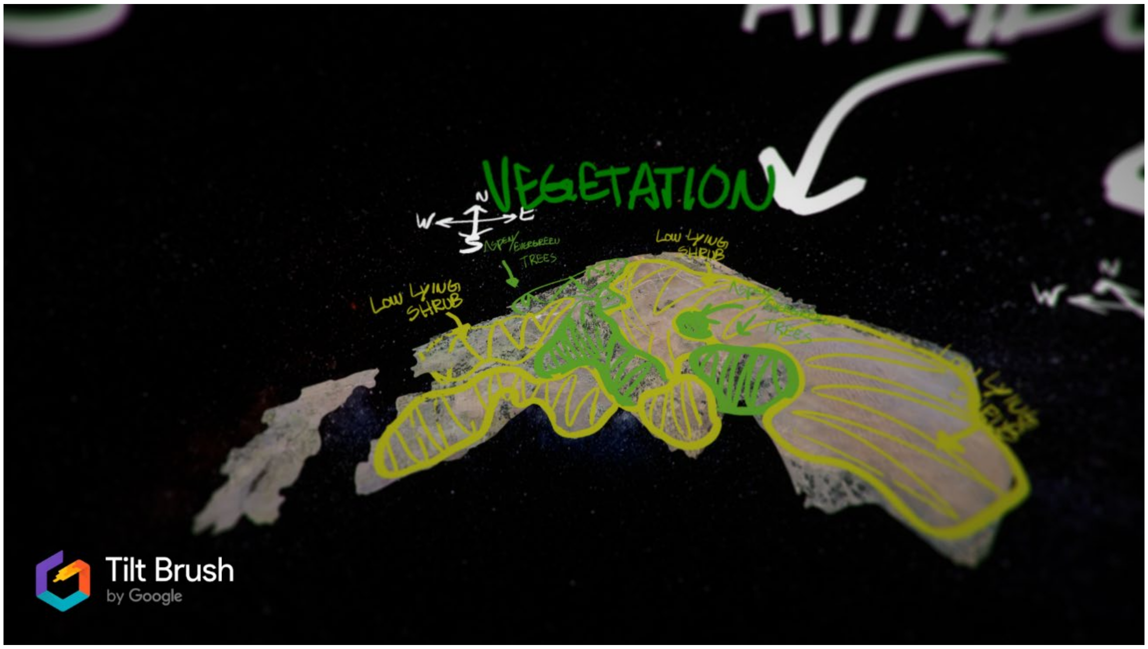


Figure 33. Vegetation Analysis 1

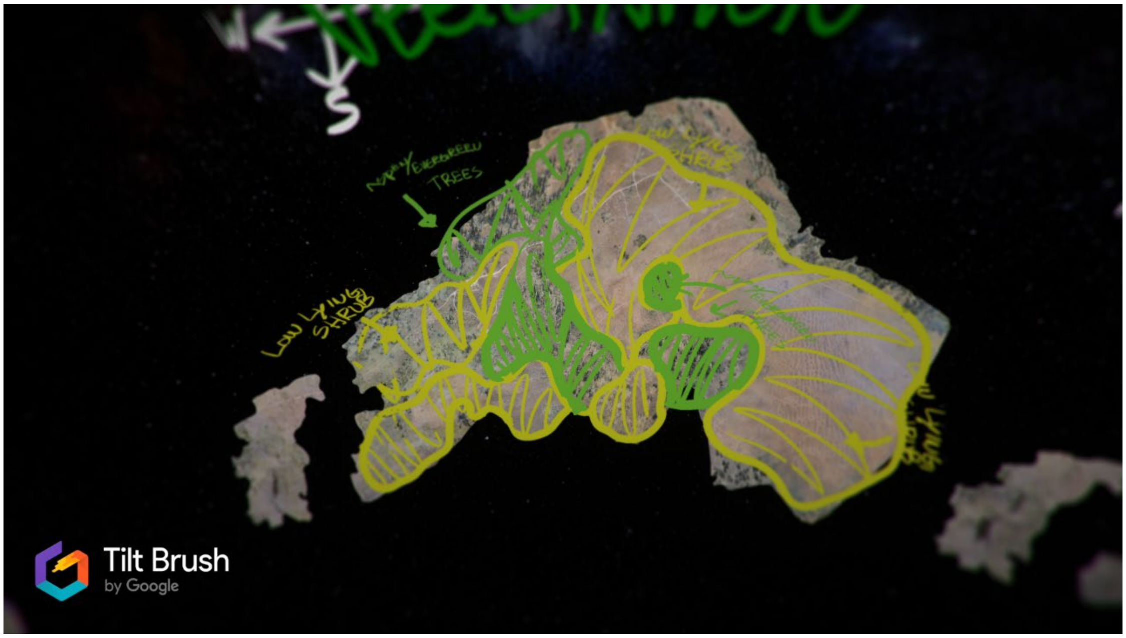


Figure 34. Vegetation analysis 2

Wildlife

Information found regarding wildlife patterns primarily came from a lengthy conversation had with the stakeholders involved with the project. One of the topics discussed was the identified wildlife corridors spanning from the northeast of the site to the southwest of the site. When on-site, there are distinct signs of wildlife migrating through this specific area. It is important to note that this portion of SPM is an important habitat to a large number of species, such as bear, elk, deer, mountain lions, beavers, and rabbits. It is important that the needs of existing wildlife are considered when planning the future development of Powder Mountain.

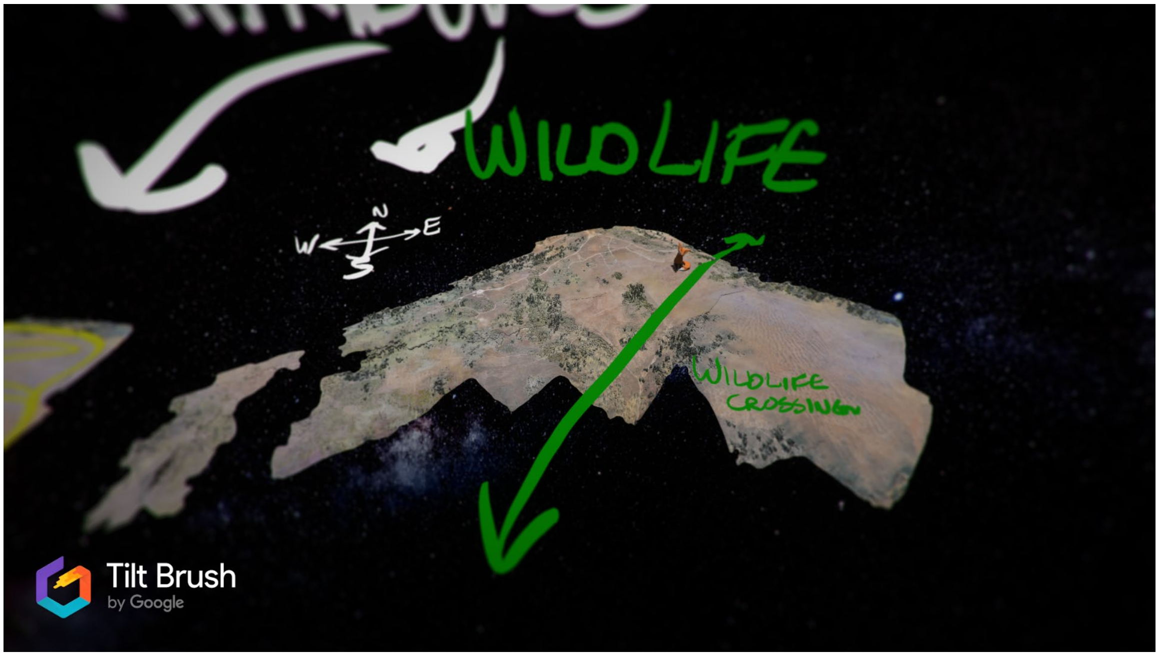


Figure 35. Wildlife analysis 1

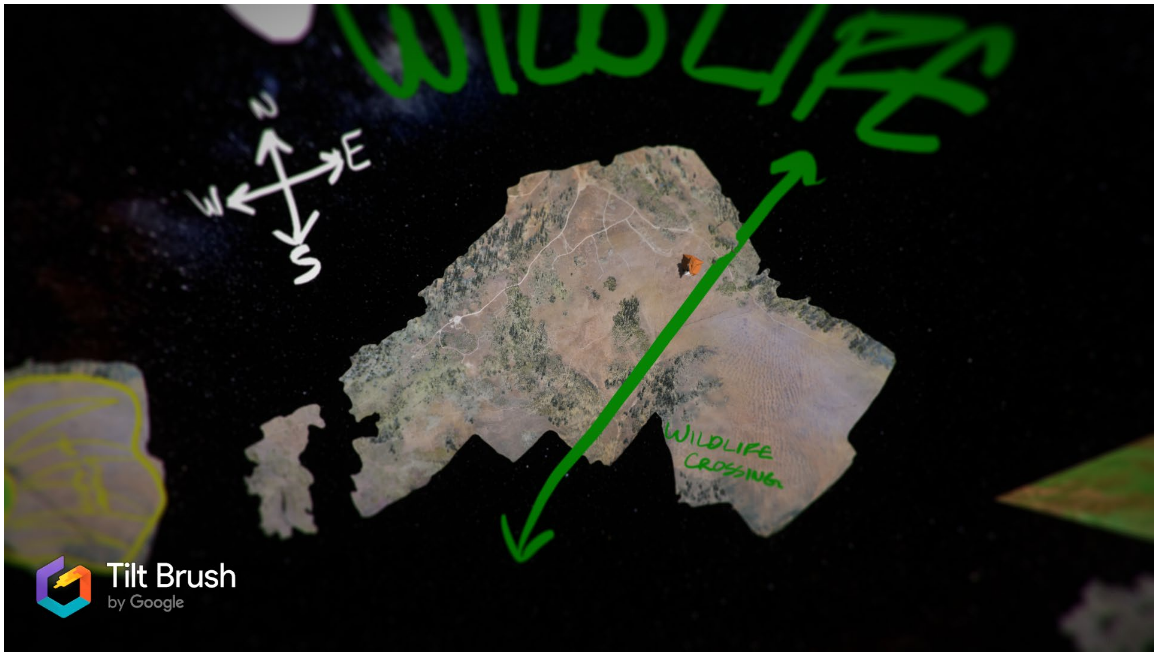


Figure 36. Wildlife analysis 2

Site Inventory: Cultural Attributes

Views

The figures below demonstrate that good views from the site are available virtually everywhere on-site. However, views from the top of the site facing the south are more open than views to the east and views to the west. The terrain is oriented so that you can see nearly every part of the site from any location. Primarily, the only obstructions of the viewsheds are the existing trees on-site. Because the photogrammetry model included most of the trees on the site, it was possible to use the VR headset to quickly identify where the trees (and landforms) would obstruct views from any particular location on the site. This was a powerful benefit that VR provided to the researcher and enabled fast and accurate identification of view corridors across the site, which would have been much more time-consuming to physically do on-site.

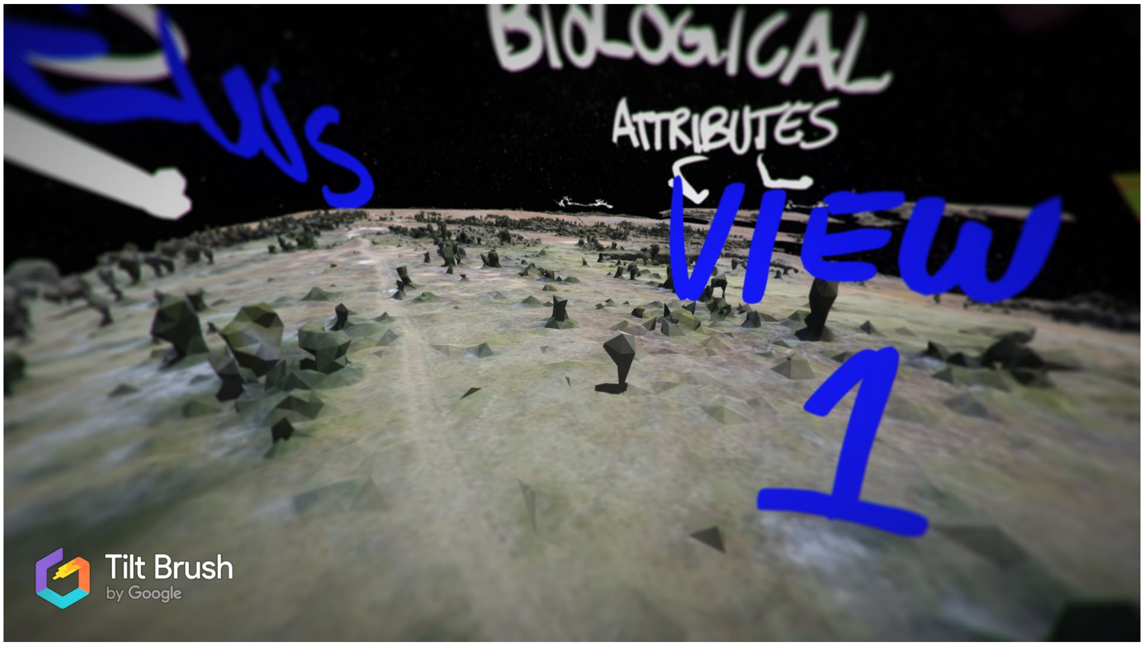


Figure 37. View 1 looking North West on Bobcat Ridge

Figure 38. View 2 looking South West on Bobcat Ridge

Figure 39. View 3 Looking South West on Bobcat Ridge

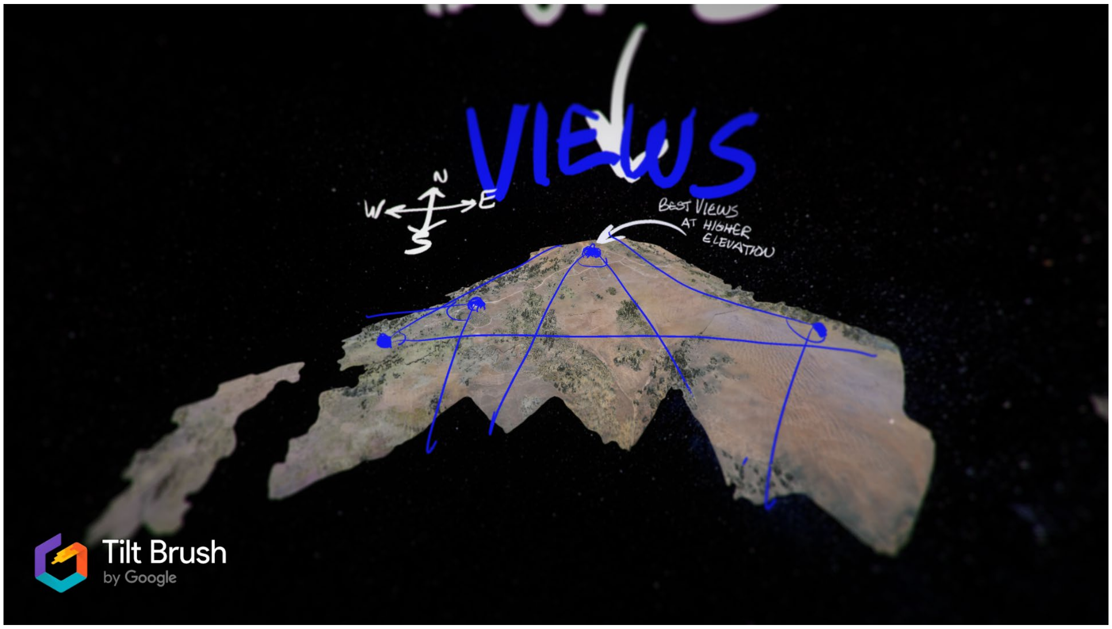


Figure 40. Viewshed analysis

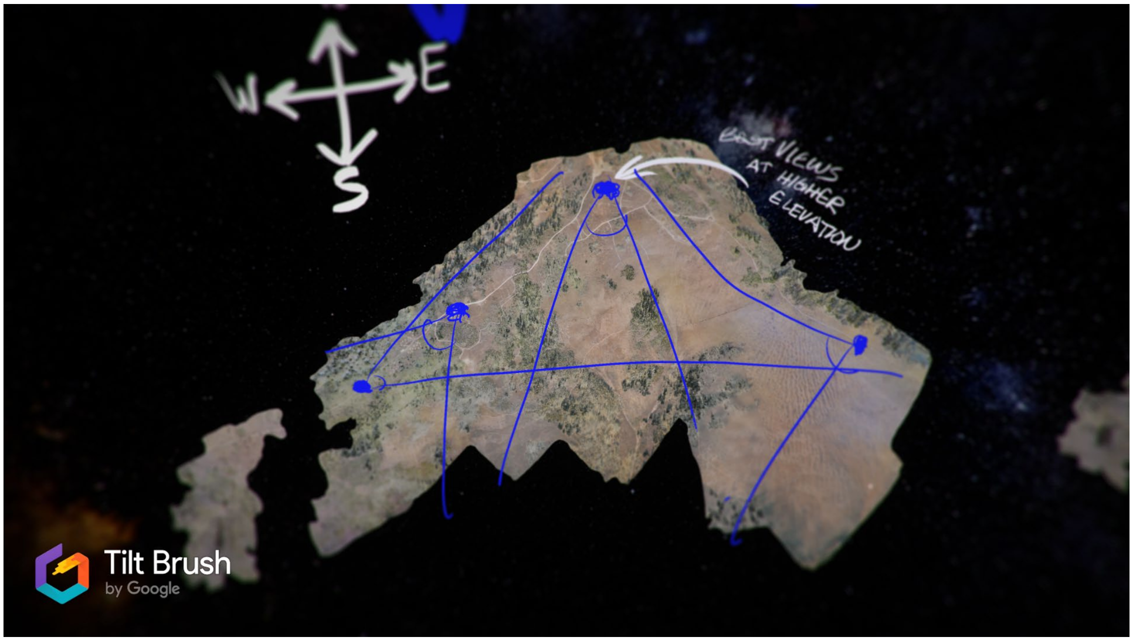


Fig. 41 Viewshed analysis from above

Site Analysis: Integration and Synthesis in Virtual Reality

Future Development Suitability Map

By considering all of the individual attributes and placing them onto the 3-D model, it was possible to create a suitability map for the site. The areas shown in green are areas most suitable for development due to their low slopes, small impact on animal migration patterns, and proximity to existing infrastructure. Areas shown in both green and red are areas that could be developed in the future, if approached with respect to the wildlife and viewsheds from the north end. The areas shown in red should not be developed, due to the potential impact on animal migration patterns, steep slopes, unstable soils, proximity to streams and drainages, and proximity to utilities. Lastly, the areas in dark red and green are unsuitable, due to the existing plant communities of deciduous and evergreen trees located here.

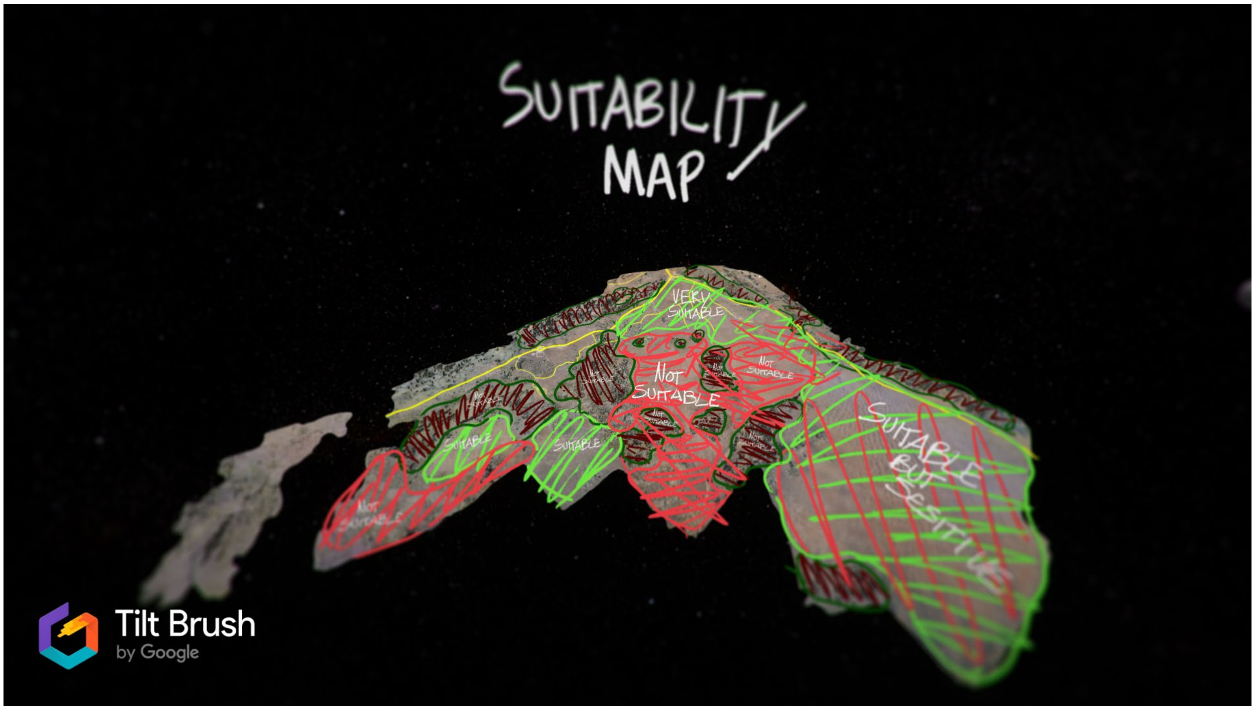


Figure 42. Suitability Map 1

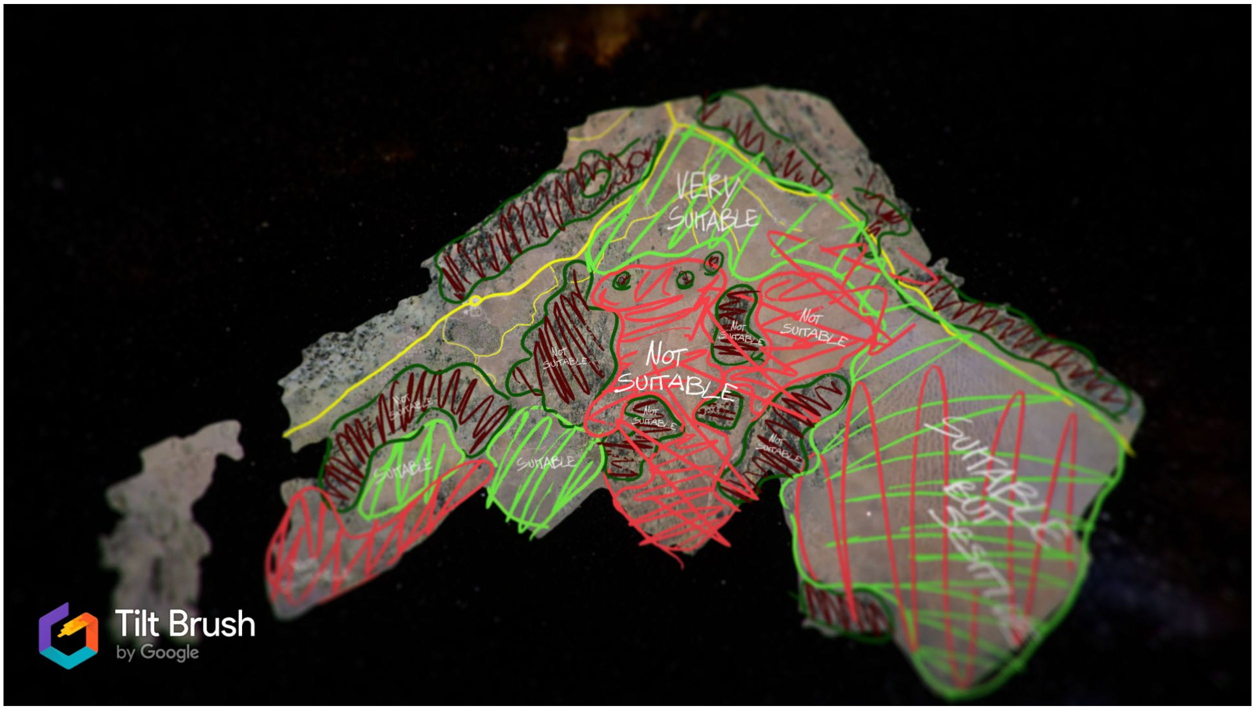
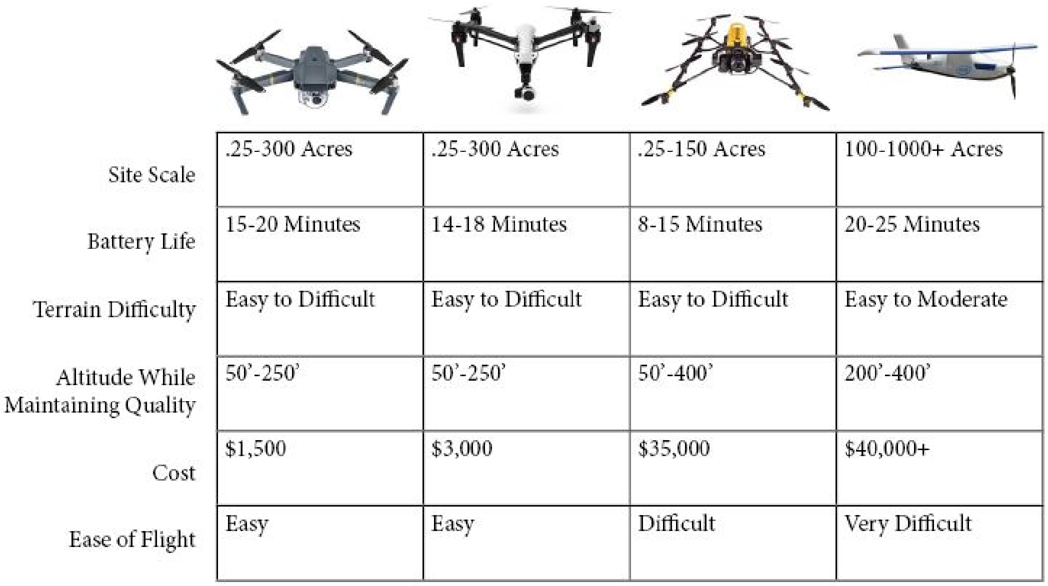


Figure 43. Suitability Map 2

DISCUSSION

This research has shown that VR can contribute to the site analysis phase of the design process and shows promise for the future use of VR to conduct a site analysis. The results show that designers can successfully reference observed and documented site conditions to the existing landscape via Tilt Brush; however, because of a lack of specialized programs to georeference GIS data, it is not ideal. The designer has the ability to constantly reference site conditions when proceeding forward with a project into the later phases of the design process. But there were some significant limitations and criticisms regarding the process overall.

First, it is important to note the challenges that arose from flying the site with vertical take-off and landing drones. These types of drones were not designed for capturing very large areas in a short amount of time. If the Sirius drone had not crashed, it would have enhanced this research by providing higher quality imagery and roughly 8 times the terrain data due to its ability to fly higher and faster with higher quality photos than the DJI drones created. The initial drone missions would have taken the Sirius fixed-winged drone an estimated 256 minutes of flight time without errors to capture 5,600 acres of Powder Mountain. Instead, it took the Falcon 8 and the DJI drones roughly 384 minutes to capture only 800 acres. Those 384 minutes do not include the amount of time needed to charge the batteries, set up the drone, and travel to and from the site multiple times. The figure below shows the types of drones that were used during this research.



Site Scale	.25-300 Acres	.25-300 Acres	.25-150 Acres	100-1000+ Acres
Battery Life	15-20 Minutes	14-18 Minutes	8-15 Minutes	20-25 Minutes
Terrain Difficulty	Easy to Difficult	Easy to Difficult	Easy to Difficult	Easy to Moderate
Altitude While Maintaining Quality	50'-250'	50'-250'	50'-400'	200'-400'
Cost	$1,500	$3,000	$35,000	$40,000+
Ease of Flight	Easy	Easy	Difficult	Very Difficult

Figure 44. Drone Types

In selecting the type of drone that should be used for this scale of a project, it is recommended that without access to a fixed-winged drone, future researchers may not choose to fly the site with the DJI Mavic Pro, DJI Inspire 1, or the Intel Falcon 8 drone. The drone's inability to quickly fly large areas effectively hinders the ability to create a large-scale model. It is difficult to fly large swaths of land with drones hindered by limited flying time. Additionally, there was a short timeframe in which the drone operations could take place, creating further pressure to quickly capture the site. From project initiation to the analysis deliverable date, which was the USU design charrette, there was less than a two-month window to conduct the flights to capture the data.

Because this research was conducted in the months of September and October, there was also a limited amount of daylight available to fly the drones. The photogrammetry software is sensitive to harsh shadows cast by the angled winter sun in relation to the angle of the mountain side. Because of this, the drone flights could only take place during a short window of time during the day, typically between 11am and 4pm. If there had been additional advanced knowledge of the project in which to plan the capture process, perhaps this research would have been able to fly during months with more daylight and fewer extreme angles of sunlight, or perhaps it would have been possible to wait for the damaged Sirius drone to be repaired and utilized to fully capture the initially intended scope of work.

It was found that pairing the 3-D model acquisition process with the site visits also allowed for a broader understanding of the landscape. It was beneficial to be able to see various parts of the large site through the drone's perspective. This process encourages the designer to explore the site in a different way than they could before, allowing for a stronger understanding of the site's condition. This may be especially beneficial to the designer in areas of a site that are impossible to access by vehicle or foot. Also, this view helps the designer to remember the broader context of the site while conducting the analysis, thereby reminding them that all of the factors on the site are tied together.

As discussed above, having access to drone imagery produced a much higher-quality model than is possible when using satellite imagery. Thus, to use this method to its highest potential will require the use of a drone, and this requirement may limit the method to smaller sites or sites wherein the researcher has spent more time planning flights. The alternative to drone use would be using low-quality satellite imagery or a manned aircraft, such as a small plane, to capture photography of the site, which can cost over $3,000 per flight.

Once the drone imagery, modeling, and the inventory data were gathered, the researcher was able to quickly and effectively identify the following major features of the site using Tilt Brush: relationships between elements on the site, design opportunities and constraints, views and natural desire lines, boundaries, and poor terrain. As a result of having the site model and site data available in VR, it was not necessary for the researcher to go back to the site, although doing so certainly could provide additional levels of detail. This was an important benefit, as SPM is quite far away from USU. Due to the ability to reconstruct the natural features of the site, even at a lower resolution than actually being on- site, researchers can virtually revisit the site by using the virtual environment created with the drones. This could be very useful for a firm that is working on a project remotely, where it is not feasible to regularly visit the site.

Conducting site analysis using VR may also benefit the non-designer, such as members of the public who attend a presentation and learn/see what was done during the site analysis. It may also benefit a student who is learning both how to conduct a site analysis and how their analysis connects to the site they are studying. It can be difficult to understand the connection of the analysis using traditional 2-D maps or similar resources. Using VR enables the designer to communicate with the public more effectively.

An unexpected finding from this research is the effectiveness of being able to arrange the generated 3-D analysis maps in a 360° array (Figures 19, 20) within the VR workspace around the designer. This feature further enhances the designer's ability to quickly reference existing site conditions in a very spatial and graphic manner, similar to what is possible in a physical studio with wall pin-up space, but with the added benefit of an essentially infinite pin-up area. While this is was a valuable benefit, it should be noted that this was necessary because Tilt Brush does not support an effective way of layering the site data in a manner similar to what happens in GIS software.

Another benefit for designers within Tilt Brush is the ability to freely scale the model within VR, allowing the designer to see their inventory and analysis of the site at a human scale. This can be a powerful tool when considering that nearly all current site analysis approaches and plans are viewed 2-dimensionally via printed paper or computer screen, and do not allow the user to experience the site as if they were there standing on it. Tilt Brush allows designers to gain a more natural feel for the site, which also yields a stronger connection to the site, and should enable the designer to make more informed decisions.

The combination of VR with other online resources and GIS data proved to be beneficial, despite the aforementioned constraints. When used together, the designer is able to interpret geographic data that can serve as guidance throughout the design process. However, without the external sources of data (other than contour data extracted by the photogrammetry process), there would be no way of finding the data form within Tilt Brush. At that point, Tilt Brush would only be a conceptual drawing medium. Hopefully in the future, design software for VR will be available that will support the import of GIS data.

Another notable limitation to Tilt Brush is that the user is not able to edit the 3-D base map directly in the program. If there is data that the designer wants removed from the drone model, the user would need to do so outside of Tilt Brush in a program capable of editing 3-D object files, such as Rhinoceros or Pix4d, where the model was originally created. While this may not be a significant problem during the site analysis, it becomes important later in the design process when a designer may want to shape the landforms of the site.

A criticism of this research is that the researcher's expertise in using drones and Tilt Brush is taken for granted, and that many designers will not possess this level of expertise. There is a learning curve for these technologies, and it is important to note that these technologies take time and practice to be able to utilize them fully and effectively in future research. It is theorized that, once competent in the software, this and similar workflows will be beneficial to students and designers practicing landscape architecture, especially as these technologies become more widespread.

FUTURE RESEARCH

Much research still needs to be done in this area. This includes testing subjects, such as students, faculty, and practicing landscape architects, with the intent to quantify the various results that would come from the studies. If VR is utilized in a future USU design charrette, it may be beneficial to the department to further study its impact.

Additionally, there are several functions that future developers should focus on in VR design software. These include the ability to toggle brush strokes on and off in layers within Tilt Brush. Another function that future developers should consider is the capability of simulating various types of natural occurrences, such as water falling on the spaces depicted in the map to assess where it would it flow and accumulate, a depiction of the current trees 20 years into the future, and/or what an altered climate could do to the site.

CONCLUSION

The techniques developed through this thesis demonstrated promising potential. VR and drone technologies are advancing at a fast and energetic pace. Since this research was begun, there have been advances in consumer-level mapping drones and in VR software. The decreasing cost trends of the technology, paired with easier user interfaces, will encourage more landscape architects who have little to no prior experience to utilize the technology within their design process.

In the past, VR has been integrated into various stages of the design process. More specifically it has been implemented into the latter phases of the design process, known as the design review phase, where designers often share the final representation of their design before actually building the project. This research, however, focuses on the site analysis phase of the design process. It was theorized that VR could enhance the user's relationship to the site while being able to reference site conditions continually through the analysis process.

In this research, it was demonstrated that VR could enhance the site analysis phase of the design process. The workflow of this process included site selection, which in this case was Powder Mountain, and model creation, which involved traveling to the site multiple times with drones capable of taking landscape images from the sky to create a three-dimensional model used for the purpose of importing a high-resolution base map into virtual reality. Once the model was generated, it was then imported into Tilt Brush, along with imports of GIS data and other sources of online data. Once imported into Tilt

Brush, the researcher found that it was effective to conduct a site analysis within VR for various reasons, including an opportunity to connect to the site with deeper emotion and awareness of the existing site elements.

Furthermore, due to the rough terrain and the inability to access certain parts of the site, the researcher was able to acknowledge site elements that might have been out of reach of vehicles or feet. This research uncovered unexpected findings that only enhanced the site analysis portion of the design process. When considering the future of site analysis in VR, there is potential for growth more tailored to landscape architects and planners.

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