Characterizing Sedimentary Outcrops with Laser Scanning

Applied to Cretaceous deep marine limestone-marl sequences in the Vocontian Basin, France

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by

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Cover figure: The primary sedimentary outcrop analyzed in this study, near La Charce, France, shown with the Leica C10 laser scanner positioned to collect data.
Abstract

The traditional approach to studying and characterizing exposed, sedimentary rock outcrops has depended on both the experience of the geologist involved and on the accessibility of the rock surfaces themselves. Morphological characterization of an outcrop, such as its layered rock orientation and thicknesses, are features that can be measured by hand using a measuring device, a compass and Jacob's Staff for example, or with 3D digital instrumentation such as a total station or GNSS. However, these methods can be time consuming when the scale of the outcrop is tens of meters large and outcrop height blocks GNSS signal. While characterizing outcrops has proved useful for reservoir mapping and exploration, identifying markers can also provide a point of comparison between various outcrops as the values further our understanding of subsurface processes and the drivers that formed the rocks themselves. Thus, the goal of this study is to first determine which morphological features of rock outcrops are characteristic, and then, how those features can be estimated efficiently and without a loss in accuracy to traditional measurements.

When considering efficiency, automation in the measurement and feature estimation processes was prioritized. A terrestrial laser scanner (TLS) is a close-range, data collection device that calculates line-of-sight distances to create a three dimensional point cloud representation of the target, an outcrop in this case. It can collect millions of points in just minutes with millimeter accuracy, and automated after scan parameters are input. This solution appeared to suit the needs of the project and was selected for outcrop data collection. The next challenge was selecting an region with sufficient data, or outcrops, to study. The Drôme department, primarily composed of the French Alpine foothills, contains numerous outcrops of varying formations, dimensions, and characteristics. The rocks in the region were formed ~100–150 million years ago from sediments in a deep sea that existed at that time. The distinct sedimentary rock layers also encourage data collection here as the morphological features protruded from the outcrop surfaces providing clear planar features and an opportunity to try out automated feature extraction. The week-long fieldwork survey in the region concluded with dense (sub-centimeter) TLS data for ten outcrops of varying features. The most distinct layering was found in an outcrop near the village of La Charce. From this 3D point cloud sample, quantifiable orientation and thicknesses values need to be estimated.

The characteristic feature estimation process was then developed through a semi-automatic work flow of efficiently extracting information from the 3D point cloud. The algorithms composing the work flow were developed in Matlab on a 5 x 5 m sample section of the La Charce outcrop. The local surface normals of the points in this section were calculated, grouped, and then filtered to extract points only belonging to the tops of bedding layers. Virtual planes were fit to these grouped ‘top’ points and estimated values for the dip and dip direction (layer orientation) and exposed layer thicknesses were calculated from the planes. Based on traditional compass measurements taken in the field of these same parameters, the algorithms estimated values fall within one standard deviation of orientation field measurements. In fact, the estimates may actually be more precise considering an average of the layering over a larger area (than compass measurements) was used in the algorithm calculations and compass measurements are subject to human (BSc student) error. Thickness estimates of layers within the formation varied greatly (20–300cm) from field staff data and are dependent on the layers that the measurements were taken from (algorithm estimates of layers within the La Charce sample fall within this range, regardless).

Close-range three dimensional measurement data from terrestrial laser scanning has proven to provide adequate information for estimating morphological features of rock outcrops. In addition, possibilities were explored for using laser intensity and surface roughness to derive rock composition, and this is recommended for future study. Thus, in addition to traditional field measurements, laser scanning can be used to both validate and gain possibly more accurate insight to the true geometry and characterization of a sedimentary outcrop. It is a relatively efficient method that ‘brings’ the outcrop back into the laboratory for repeatable, detailed analysis. This developed method, fully functional for the La Charce sample outcrop, demonstrates a viable road map for extracting morphological features from 3D point clouds of sedimentary rock outcrops.
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Software:

CloudCompare v2.7.0 (General Public Licence) is an open source software developed by Daniel Girardeau-Montaut at Telecom Paris (TSI/TII lab) and financed by EDF R&D (SINETICS Dept., CAD & Virtual Reality team).

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Acronyms

3D three dimensional
AESB Applied Earth Sciences Bachelor course
C/A coarse/acquisition
CiTG Civiele Techniek en Geowetenschappen faculty
DOM digital outcrop model
DSLR digital single-lens reflex
ECTS european credit transfer and accumulation system
EM electromagnetic
EOS electro-optical system
FWHH full width at the half-height
GLONASS globalnaya navigazionnaya sputnikovaya sistema
GNSS global navigation satellite system
GPS global positioning system
GRS Geoscience & Remote Sensing
LIDAR "light" radar
MPE maximum permissible exposure
MSc Master of Science
OLRS Optical & Laser Remote Sensing Laboratory
PCA principal component analysis
ppm parts per million
RADAR radio detection and ranging
RANSAC random sample consensus
RGB red-green-blue
RMS root mean square
RTK real time kinematic
SSD solid-state drive
TIN triangulated irregular network
TLS terrestrial laser scanning
TU Delft Technische Universiteit Delft
UAV unmanned aerial vehicle
USB universal serial bus
Terms

dip is the steepest angle of descent of a tilted bed or feature relative to a horizontal plane

eccentricity $e$ is a parameter that determines the amount by which Earth's orbit around the Sun deviates from a perfect circle

carbonates are rocks or minerals made of chiefly carbonate minerals that are dominated by the carbonate ion $CO_3^{2-}$

geometric the characterize-able properties of rock outcrops in this study, namely layer thickness, surface roughness, strike, and dip angle

induration is lithification or the hardening of rock by heat or pressure

obliquity $\epsilon$ is the angle between Earth's rotational axis and its orbital axis

outcrop is a visible exposure of bedrock or ancient superficial deposits on the surface of the Earth

ppm Parts per million (for GPS) are used to relate error magnitudes with baseline length (e.g. 1 ppm corresponds to a 1 mm error over 1 km and a 1 cm error over 10 km)

precession $\omega_p$ is a change in the orientation of the rotational axis of Earth

sedimentary rock are types of rock that are formed by the deposition and subsequent cementation of material on Earth's surface (and water)

strata or stratum (sing.) are layers of sedimentary rock with internally consistent characteristics that distinguish it from other layers

stratigraphy is a branch of geology which studies rock layers (strata) and layering (stratification)

strike is a line representing the intersection of that feature with a horizontal plane
Introduction

Sedimentary rock outcrops are traditionally studied with instruments such as the compass and clinometer to extract characteristics identifying each unique outcrop. These defining characteristics give clues to past climate cycles in the region from their cyclical layering and hint towards the structure of the subsurface in their surroundings. However, in recent years, remote sensing technology, specifically lidar, has developed into serving various fields in ways derived often after the technology itself was developed. Using lidar to characterize sedimentary outcrops has been demonstrated in many different applications (Anders et al. [2016], Bellian et al. [2005], Burton et al. [2011], Dewez et al. [2016], Olariu et al. [2008], Slob et al. [2002], Yeh et al. [2014]) and continues to grow as instruments become more precise, point cloud processing evolves, efficiency improves, and computing power increases. This project is one of the first studies that combines semi-automatic algorithms for point cloud analysis with the goal of extracting morphological features from virtual 3D sedimentary outcrops.

1.1. Sedimentary Outcrops and Laser Scanning

Rock outcrops are sections of bedrock that have been exposed either by natural processes, such as erosion, weathering, or tectonic uplift, or by human excavation work. Sedimentary rock outcrops are outcrops composed of rocks formed from the deposition and cementation of sediments, or small naturally occurring material particles (such as sand or silt), that settled to Earth’s surface in a body of water. Millions of years of cyclic climate change produce different types of sedimentary rocks based on the depositional environment at the time of their creation. In the Vocontian Basin of southeast France during the Cretaceous period (circa 100 million years ago), the depositional environment was considered to be marine, or sedimentary rocks were formed from sediments that sunk to the depths of a sea or lake that existed there at the time. As climate changed, the amount of water in the sea, the types of sediments, and currents affecting how sediments were transported also changed. In this particular region, limestone and marl sequences define this cyclic depositional environment. Limestone is generally formed in deep marine waters from organic sediments such as shells, corals, or algae and is composed of mostly calcium carbonate, CaCO$_3$ [King, 2016]. Marls are also composed of calcium carbonates, but contain mud stone as well. They form from clay and silt deposits in freshwater marine environments [Pettijohn, 1957]. Figure 1.1 clearly illustrates the alternating limestone (jutting out) and marl (set back) layers, or strata, that compose outcrops in the study region.

Sedimentary outcrops can provide insight to many fields aiding in understanding, modeling, visualizing, planning, and even teaching. Previous work on rock outcrops can be divided in four main categories: geological research, civil engineering, industrial development, and scientific analysis and/or modeling. Geologists study outcrops for a greater understanding of subsurface processes and hints toward the dating of geological events. Some of these studies have lead to important conclusions about the causes and effects of Earth’s changing climate through time, for example (Franceschi et al. [2011], Franceschi et al. [2015], Gréselle et al. [2011]). In civil engineering, outcrops can be analyzed for determining structural properties of the regional bedrock. This structural analysis is then used for infrastructure planning such as constructing tunnels, roads, buildings, dams, bridges, etc. (García-Sellés et al. [2011], Sturzenegger and Stead [2009]). A major source of
funding in many past sedimentary outcrop studies can be traced back to industry, specifically oil and gas companies. Outcrops provide direct access to geological features that can otherwise be very expensive to locate, drill, and analyze. Companies have used outcrops to enhance their oil recovery through reservoir modeling and seismics (Berger [1988], Hodgetts [2013], Jones et al. [2011], Lamarche et al. [2011]). Additionally, clues about mineral composition, coal content, fossil fuel presence, drinking water, and ore can all be tested. The last main category deals with the scientific or mathematical approach of outcrop research. These studies tend to model processes such as flow simulation, erosion, salination, or the potential for landslides. The models can additionally be used for better visualization and teaching (Buckley et al. [2008], Richet et al. [2011]). In this study, the primary focus is on both geological research and scientific analysis and modeling.

A variety of tools and techniques are used to study rock outcrops considering the many different applications mentioned above. Traditional geological approaches including locating sites with GNSS, taking samples with rock hammers and compasses, surveying, and analysis are irreplaceable in the field. However, outcrops can have heights ranging from 10's to 100's of meters making these measurements dangerous or even unattainable in certain cases. In this sense, remote sensing, or data acquisition without direct contact, can aid in filling the gaps of geological sampling, quantifying estimated parameters, and giving a greater insight to rock properties invisible to the human eye.

In terms of remote sensing techniques, satellites platforms, photogrammetry, hyperspectral imagery (both VNIR-SWIR and MIR-TIR), ground-penetrating radar, and lidar have all been used to study and characterize rock outcrops. Each have advantages and disadvantages depending on the specific aim of the study.

- **Satellite** platform instruments are good at capturing large-scale features, as many outcrops are, but the spatial resolution and top-down looking angle of the instruments are often not sufficient for studying the individual features or layers of the outcrop.

- **Photogrammetry**, or using photographs to make measurements, solves the spatial resolution issue (if done at low altitude, close-range) but must have a clear line-of-sight view and usually requires tens to hundreds of images to be stitched or registered together to capture the entire outcrop or produce a point cloud. This can be a major source of error, along with lens distortion, focus, occlusion from vegetation, and lighting conditions.

- **Hyperspectral imaging** is able to provide information about the composition of the rocks by their different reflectance properties at various wavelength bands. This can be used in classification studies but is not a good method for extracting 3D geometry.

- **Ground-penetrating radar**, or radar that is directed underground, is used for imaging the subsurface in geological applications. As its focus is on detecting inconsistencies below the surface, characterizing the outcrop surface parameters is not prioritized.

- **Lidar**, or lidar, sends pulses of laser light to a target to determine its range from the receiving sensor. The system can be land-based, terrestrial, or mounted on an aircraft or UAV, airborne. Airborne laser
scanning has similar issues as satellite-based instruments in outcrop analyses. Terrestrial laser scanning works well for both a large scale and close range. Although it still requires direct line-of-sight, such as photogrammetry, the range data collected can have accuracies better than a centimeter.

The study region near Vesc was selected for its abundance of accessible outcrops. At close range, it is evident that photogrammetry, hyperspectral imaging and terrestrial lidar are the most practical instruments for gathering detailed information about the sedimentary outcrops. Since a similar study was recently completed using hyperspectral imaging for classification on outcrops in the same study region (Del Pozo et al. [2015]), terrestrial laser scanning was chosen for this study. Although photogrammetry can possibly provide higher resolution and accuracies at very close range, the acquisition and post-processing time are generally considered longer which can be a problem for 5-day fieldwork surveys.

1.2. Toward Improving Semi-Automatic Characterization

With an abundance of outcrops to sample and a terrestrial laser scanner, priorities were set based on what was determined to be characterizing features of an outcrop and whether they were extractable from 3D point cloud data. Considering that the laser scanner collects range, or the distance from the scanner to the outcrop point, only geometric properties \((X Y Z)\) and signal intensity returns can be used for analysis (color is also an option, but considered only for visualization in this study). Characterizing geometric properties, or the morphology of the outcrops, is well established by geologists in the field. The orientation of the outcrop and its layers can already give geologists a very good idea about the subsurface motion of the area and the formation settings of the strata. Additionally, these exact measurements of the outcrops in the study region have been collected for several years by bachelor's students on fieldwork and can be used for validation.

Many 3D outcrop studies have attempted to create algorithms for segmenting (grouping alike features), feature extraction, or even locating discontinuities. While these studies set the ground for characteristic parameter estimation such as dip and dip direction, they do not approach the estimations themselves. One study found does aim to estimate dip and dip direction but uses manual trace lines for airborne lidar [Yeh et al., 2014]. This study was positioned to expand upon automatic extraction techniques for planar features and then to take it one step further by estimating morphological features of a sample outcrop to test and validate the algorithm. It is considered a semi-automatic approach as many input parameters, such as the number of nearest neighbors to a point considered for normal estimations, must be defined prior to getting estimates. In this way, however, the algorithm is flexible and can be modeled to fit individual outcrops.

1.3. Scientific Approach

Semi-automatically estimating morphological features of sedimentary outcrops from 3D point clouds raises many questions. The primary and secondary research questions are outlined, below, along with project objectives and a hypothesis for addressing the primary research question.

1.3.1. Research Questions

With the study region selected and an idea of the remote sensing technology necessary for collecting the data, the following questions have been formulated to guide the research process.

Primary

What morphological features of rock outcrops are characteristic and can be estimated from close-range, three dimensional, measurement data?

Secondary
These questions define what is meant by the research questions, and specifically, what will be investigated further in order to answer this question. Each chapter that follows will discuss and attempt to answer these questions leading to eventually address the final primary question.

1.1. Objectives

In addition to addressing the formulated questions, above, several objectives or goals have been set to provide new resources for fellow lab mates and future researchers in the field. These objectives include:

- Collecting laser scans of multiple outcrops in the Vesc region
- Creating a post-processing instruction manual for converting raw point cloud data to Matlab-friendly .csv files
- Becoming a Leica C10 laser scanning expert by assisting in various laser scanning projects proposed throughout the department (and by visiting scholars)
- Providing recommendations on virtual modeling environments for possible use in future (Bachelor course) fieldwork preparation and documentation
- Developing and sharing an intuitive algorithm for outcrop parameter estimation that can be built upon for further investigation

In the course of pursuing the research questions, these objectives are designed to enhance findings and produce interest in the field.

1.3.3. Hypothesis

It is hypothesized that a semi-automatic algorithm can be developed to extract the dip, dip direction, and layer thicknesses of sedimentary outcrops represented in 3D point cloud data gathered from a terrestrial laser scanner.

1.4. Thesis Organization

This proposed study is a collaboration between the Geoscience and Remote Sensing (GRS) and Applied Geology departments in Civil Engineering (CiTG) due to both the nature of the study and the potential for use of the data and methods in future research and fieldwork within both departments. The study includes preliminary background information on the subject matter, both remote sensing technologies and geology in the study region, in Chapters 3 and 2. A summary of the data acquired during fieldwork can be found in Chapter...
4. The work flow of the algorithm development, in Chapter 5, goes through each step necessary for estimating morphological outcrop features. Chapter 6 is a comparison study done on multiple virtual platforms proposed for modeling 3D outcrop data. The remaining chapters present results along with a discussion of these results and a validation. The study concludes with Chapter 9 and summarizes the answers reached for the formulated research questions.
Geology in Southeast France

The rolling Alpine foothills of southeast France, specifically the Drôme department of the Auvergne-Rhône-Alpes region, were chosen as the focus study region for this project. Located in this region is an area called the Vocontian basin, in geology terms, as it is a lower region filled with sediments from its past existence as a deep sea and sandwiched between three higher, displaced crustal rock formations, or carbonate platforms: the Jura/Dauphiné, the Ardéche, and the Provence. The basin is especially striking today for its abundance of exposed rock sedimentary layers and is an annual retreat for student geologists due to these numerous windows to understanding subsurface structure. Figure 2.1 shows this basin when it was a deep-marine sea or ocean during the upper Valanginian period (approximately 135 million years ago). The thumbnail in (b) shows the regions present form, which is perhaps more recognizable.

Figure 2.1: A paleographic reconstruction of the study region (a) showing a sea in modern-day France during the Valanginian period and (b) showing the approximate location of the La Charce formation studied in this project [Gréselle et al., 2011].

In deep-marine settings such as the sea shown in Figure 2.1, sediments in the water sink to the bottom and then cement in rocks over time and with the pressure of subsequent layering on top. These rocks can be characterized by their often relatively smooth, undisturbed layering since their formation environment was not as strongly affected by rivers, currents, or local weather disturbances. However, the cyclical nature of climate change in the past influenced the depth of the seas due to continental motion and changing insolation. Along with carbonate production and dissolution, these changes affected the composition of sediments that were transported downward. These changes are reflected in the alternating rock compositions we see today. This continual process forms sedimentary rock beds that we are now able to study directly through outcrops in the Vocontian basin. The goal of this chapter is to both explore and determine the thesis subquestion:
The rock outcrops of the study region are composed of sedimentary rocks, as mentioned, so geometric features such as the bedding layer orientations, the thicknesses and possibly even the surface roughnesses will be studied.

2.1. Sedimentary Rock Outcrops

Outcrops, as mentioned earlier, are exposed sections of bedrock that provide direct access to study and characterization. Outcrop formations give various clues about the geological history of the region, which in turn can hint towards that region’s past climate and landscape. This project will focus on outcrops primarily composed of layered, or stratified, sedimentary rocks. Each stratum signifies a new cycle of sedimentation and cementing.

Climate shapes the composition, layer thickness, and pattern of the sedimentary rocks found in outcrops. Varying insolation and water settings throughout different time periods affect how sediments are carried and deposited to certain regions and how long it takes for them to cement into a new layer. In the 1920’s, Milutin Milankovitch theorized the connection of the rhythmic sequences of Earth’s changing motion, or orbital forcings, to ice ages (or climate change, see review by Berger [1988]). His study, along with others, found that the orbital forcings, defined as eccentricity, obliquity, and precession, influenced climate through various periodicities that could possibly explain the shifts we can observe in sedimentary layers today. The diagrams in Figure 2.2 illustrate these principles:

![Figure 2.2: Key orbital parameters that affect climate on Earth, the (a) eccentricity, the (b) obliquity, and the (c) precession of Earth’s motion along with their primary periodicities at present, respectively [De Boer and Smith, 1994]. Eccentricity additionally exhibits a 400,000 year periodicity. The Sun is labeled and the remaining sphere is the Earth. Lines indicate Earth’s motion.](image)

where eccentricity is the measure of how far from circular an orbit is, obliquity is the angular difference between the orbital and rotational axis, and precession is the measure of change in rotation and/or orbit. This changing orientation and motion of Earth relative to the sun affects the insolation, or the amount of sunlight that reaches Earth’s surface [De Boer and Smith, 1994]. Changes in regional insolation can cause an increase or decrease in factors such as evaporation, weather patterns, winds, and more, all affecting the climate and regional weather. And, getting back to this project, these factors are what cause sedimentation and strata that are easily observable in the proposed outcrops.

Common goals of studying sedimentary strata, or stratigraphy, include determining the age, length of climate cycle, and composition of each sediment layer. The aim of this project is to characterize the geometric, or more precisely, morphological, properties of the strata from which the age and length of climate cycle can be estimated. A common approach is to estimate an average cycle duration by dividing the stratigraphic timespan analyzed by the number of sedimentary cycles [De Boer and Smith, 1994] and from this, a link to Milankovitch cycles may become apparent. Initially, this link is not necessarily assumed since stratigraphy was shown to provide imperfect, unreliable, noisy and poorly timed calibrated recording of the outcome of
a number of variables, of which climate is just one [De Boer and Smith, 1994]. However, more recent studies have found that sedimentary successions can be continuous at Milankovitch time scales over millions of years ... for deep marine and lacustrine successions [Hilgen et al., 2014]. From a remote sensing approach, only the morphological characteristics of the outcrops will be extracted and an interpretation of age, for example, will be left for further study.

2.2. Formations in the Vocontian Basin, SE France

The fieldwork was conducted near the village of La Charce in the Drôme department of the Auvergne-Rhône-Alpes region, France. This region was chosen for its numerous sedimentary outcrops both accessible by road and open to the public. Additionally, it has served as TU Delft geological fieldwork site for 49 years and there is interest in studying the possibilities of virtual fieldwork here. Having extra example outcrops gives a good variety for testing morphologic feature estimation algorithms. The outcrop formations that are found in the region are summarized in Figure 2.3, below. Outcrops of all of these formations can be found, but emphasis will be placed on outcrops exhibiting well-defined morphological features or strata as feature extraction and estimation is the goal.

![Figure 2.3: A sequence of rock formations that can be observed in the Vocontian basin [Del Pozo et al., 2015]. The time period of the formation of the rocks is shown to the left (approximate dates listed in Figure 2.4), while approximate composition is noted to the right.](image)

These outcrops are primarily composed of two types of rocks, limestones and marls. Limestones are generally formed in deep marine waters from organic sediments such as shells, corals, or algae and are composed of primarily calcium carbonate, CaCO$_3$ [King, 2016]. Marls are also composed of calcium carbonates, but con-
tain mudstone as well. They form from clay and silt deposits in freshwater marine environments [Pettijohn, 1957]. Thus, formations in this region can be grouped into three categories: one with rocks of high carbonate concentrations such as limestones (e.g. Formation 1), one with primarily marl stone or mud stone (clays) (e.g. Formation 12), and one that is a mixture of the two (e.g. Formation 6). The stratified sedimentary layers are most visible in this last category of formation type, and thus will be the focus of this study in the Vocontian basin. The most well-defined outcrop found during fieldwork was just outside of the village of La Charce. It is shown in Figure 2.4 (c). To give an idea of the age of the rocks that compose this outcrop, it is linked to a geologic timescale of both the region and planet in general.

Figure 2.4: A geologic time scale of (a) the history of life on Earth, (b) rock types that can be found in the Vocontian basin, and (c) the La Charce outcrop that will be primarily studied in this project. Rocks in the La Charce outcrop are approximately 135 million years old. Images from (a) Rafferty and Shiri [2015], (b) Jan Kees Blom, (c) Google Earth.

The La Charce outcrop contains rocks from approximately 135 million years ago. It is composed of two formation types found in the Vocontian basin, the Valanginian (the bottom few layers of the image in Figure 2.4) and the Hauterivian (the remaining layers). These formations belong to the early Cretaceous period of Earth’s development, when dinosaurs roamed and the first flowering plants and primates came into existence. Again, the rocks were formed at the bottom of the sea that covered the region in that time.

2.3. Morphological Features

Sedimentary outcrops in the study region can be characterized by several defining morphological features. These features include, but are not limited to, stratification, faulting, folds, and formation transitions. Examples in Figure 2.5 exhibit the unique and defining power of these features.

While examples of all of these features will be laser scanned during the fieldwork, a focus will be placed on morphological features that are extractable from a 3D point clouds, features with planar surfaces, for example. Thus, the first priority is on gathering distinct strata unobstructed by vegetation. A relative pattern
2.4. Prior Research

The abundant outcrops in the region make the area a desirable destination for geologic study. You can be surrounded by exposed examples of previously subsurface rocks, visibly displaying the passage of time, changing rock compositions, and possibly even fossils of millions of year old organisms. The Department of La Drôme has recognized the geological significance of the area by devoting both placards or signs at the sites and a website explaining the outcrops in the region [Retif and Du Jeu, 2016]. Several studies in the area have focused on how orbital forcing, explained in Section 2.1, affects the formation and sequencing of sedimentary rocks including Boulila et al. [2010], Boulila et al. [2015] and Herrle et al. [2003], while other studies focus more on creating a rock layering, or stratigraphic, record of limestone - marl sequences themselves [Boulila et al., 2008]. Many studies analyze the past sea or ocean setting in the Vocontian basin and its effect on the geologic structures of the region [Gréselle et al., 2011], [Bornemann et al., 2005]. Additionally, another common topic is the study of fossils or ammonites found in the strata [Heimhofer et al., 2006]. These topics will not be covered in this project, but they give an idea of how the formations that will be studied came to exist and their significance today.
2.5. Summary

The Vocontian basin of southeast France contains various outcrop formations, many exhibiting an alternation of limestone and marl stratum. The stratum, or rock layers, were formed approximately 135 million years ago by sediments at the bottom of a deep sea that existed in the region. The pattern of effects of cyclical climate on the sediments is evident today in the outcrops that have since been exposed (in addition to post-formation effects such as plate motion, faulting, and folds). The study will focus on outcrops with a well-defined sequence of sedimentary layers, as the goal is to extract and estimate geometric features such as bedding planes and orientation.
Laser Scanning and Positioning

As discussed in Chapter 1, several remote sensing devices are available for close-range measurements. When considering the best options for 3D measurements, photogrammetry, GNSS, and lidar can all provide point cloud data for studying rock outcrops to some extent. In this chapter, the focus will be on determining:

What close-range 3D measurement devices are available and what are their advantages and disadvantages, both theoretically and practically? Which is best for the target study region, La Charce?

Three dimensional point clouds or meshes of rock outcrops can be created by applying photogrammetry principles or overlapping images. This method requires hundreds of photos to be taken from all different angles (and possibly georeferenced). Post-processing can be lengthy as photo alignment needs to be checked. GNSS can also be used to acquire 3D data points from an outcrop, but points are gathered one-by-one and signals can be lost or weak if the outcrop or surrounding landscape, such as mountains, is in the way. Aerial, unmanned aerial vehicles (UAVs), and satellite based lidar platforms are extremely useful for larger scale digital terrain model (DTM) development due to their downward facing look angle and fast collection methods. However, since outcrops are generally oriented near perpendicular to the ground, occlusion by extended rocks and vegetation at the top can block key features of the rock formation below. Thus, this study will incorporate two primary remote sensing technologies: TLS and GNSS positioning. Both have different capabilities and strengths and will serve different purposes in the goal of estimating geometric features within sedimentary outcrops. The instruments themselves will be described further in the sections that follow. More details on their specific use in field measurements can be found in Chapters 4 and 5.

3.1. Lidar

The first explored technology is the use of lidar for close-range, three dimensional measurements. Lidar, or "light" radar, is a remote sensing technique where the instrument emits a pulse of laser light and collects the reflected return of that pulse. From this signal return, distances can be derived based on the delay it takes the light waves to return or the phase shift of the returning wave. This section covers the technology in more depth and outlines the specific instrument used in this study.

3.1.1. Prior Research and Geological Applications

The development of using electromagnetic (EM) waves for providing information about targets, as is the general principle behind lidar, started with experiments using long wavelength (centimeter to several meter scale), radio waves. Radio wave experiments for detection and ranging, or radar, began in 1904 with Christian Huelsmeyer's patent application for his "Hertzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as a Ship or a Train, in the Line of Projection of
such Waves” or as he called it, the telemobiloscope [Ender, 2002]. This device was one of the first to take the idea of reflecting EM waves and apply it to a practical engineering problem.

As interest in the telemobiloscope grew and radar technology development began for concrete engineering applications, other fields, such as particle physics, also began to ask questions. In 1917, Einstein published a proposal theorizing that photons could stimulate the emission of identical photons from excited atoms [Einstein, 1917]. After developments in testing this theory and experimentation from various labs around the world, a first recorded design for the laser, or “light amplification by stimulated emission of radiation” was noted by Gordon Gould in 1957 (with some controversy as his colleague, Charles H. Townes, also came up with a solution around that time after their discussion) [Hecht, 2010]. By 1960, Theodore Maiman of Hughes Research Laboratories had created the first functional laser: a solid-state ruby crystal that produce red laser light, at a wavelength 694 nanometers [Hecht, 2010].

The continued development and merging of both radar technology and lasers led to a new field of laser-based remote sensing, lidar, or the portmanteau of “light” radar. Early researchers such as Dr. Allan Carswell (Optech, Toronto, Canada, 1974) and Dr. Johannes Riegl (Riegl, Vienna, Austria, 1978) became interested in not only testing the new technology, but commercializing it for use in the general public as many previous application were military classified or used for space missions. However, at that time (mid-1980s) the lack of a reliable commercial GPS/IMU solutions for sensor positioning presented a significant obstacle to further development considering most applications were thought to be aerial-based surveys [Schuckman and Renslow, 2014].

Regardless, by the mid-1990s, laser scanner manufacturers were delivering lidar sensors capable of 2,000 to 25,000 pulses, or measurement points, per second [Schuckman and Renslow, 2014]. Although this signified a great progress in the lidar field, the massive datasets posed a problem for existing CAD and GIS software. Thus, the 2000s really began to realize the potential of lidar technology, and the field is evolving still today as supporting technologies such as GNSS, IMUs, and GIS are also expanding.

Terrestrial laser scanning was first introduced through a surveying campaign in 1999, and the technology has evolved from surveying primarily man-made structures such as buildings, bridges, and tunnels but also for terrain and changes in terrain such as is the case for erosion or landslide modeling [Large and Heritage, 2009]. Even more recently, researchers have been looking into applications of terrestrial laser scanning for geological studies such as stratigraphic modeling [Bellian et al., 2005], assistance in locating petroleum prospects [Hodgetts, 2013], and extracting discontinuities from rocks with applications in reservoir modeling [Slob et al., 2002], to name a few. As laser scanning is state-of-the-art in geologic research, the following study presents a suggested work flow and results from using terrestrial laser scanning for measuring rock outcrops.

### 3.1.2. Principles of Lidar

Lidar systems, referred to as laser scanners in this study, are devices that measure the distance from a target to the laser scanner itself. If the scanners position is know, or it is georeferenced, then the target point location can also be known based on its XYZ distances from the known point. A laser scanning device consists of three key elements: a controller, an optical-mechanical scanner, and a range receiver. The controller is the input interface for the user. In this system or computer, the user can input the desired scan angles, both in azimuth and elevation, the resolution, and other device-specific settings.

Since lidar is an active remote sensing technique, meaning a signal is both emitted and measured, the optical-mechanical scanner is in charge of emitting the lidar signal. This signal is a coherent stream of laser light pulses in the chosen wavelength (usually a very narrow bandwidth in the visible or near infrared). In order to measure multiple points efficiently, the laser signal is deflected between pulses to capture the locations of various targets. The goal is to create a three dimensional point cloud of the target. A common, state-of-the-art system deflects the signal using a rotating mirror both in the azimuth and elevation directions. A schematic of the system is shown in Figure 3.1, the emitted signal in green.

The range receiver is the part of the device that collects returned signals. After the signal reaches the target,
the light is backscattered to the scanner. The returning signal strength is dependent on many factors such as the reflectivity of the target object surface, the geometry and incident angle of the arriving signal, etc. All of the returns pass through a collecting lens and are registered on a photo diode. The total value of returned radiation, or the peak radiation return depending on the device, and the time it took for the return are then saved internally as the intensity value, \( I \), and relative \( XYZ \) point location. This process takes place at a rate of 100,000 to 200,000 times per second [Schuckman and Renslow, 2014].

Laser scanners can measure the point location distances using one of three types of measurements: time-of-flight, phase shift, and triangulation. Since the laser scanner used in this project is a time-of-flight scanner, the focus will be on how this type calculates distance. Time-of-flight refers to the measurement of ‘time’ from the moment a laser pulse is emitted to the moment it is received by the scanner. Since the speed of light is known, this quantity can be multiplied by the elapsed time to infer the distance from the sensor to the target and back. However, only half of this value is the desired distance measurement, or the range. The equation for range, from Lichti and Skaloud [2010], follows.

\[
\rho = \frac{c \cdot \tau}{2}
\]  

(3.1)

where the range is \( \rho \), the speed of light in a vacuum is assumed \( c = 299,792,458 \) meters per second, and the time is \( \tau \) in seconds. If the light waves travel in air then a correction factor equal to the refractive index, which depends on the air temperature, pressure and humidity, must be applied to \( c \), or \( n \approx 1.00025 \).

### 3.1.3. Terrestrial Laser Scanning

Laser scanning is done using several different platforms: satellite, airborne (aircraft or UAV) or terrestrial. Satellite lidar data is useful for lower resolution, larger areas and is best used for topographical features as the looking angle is near perpendicular to Earth’s surface. Airborne data is similar in both these senses, except the range is shorter and resolution can be better. It is also possible to study vertical features, such as rock outcrops, but a terrestrial-based system requires less time and planning. Terrestrial scanners can either be mobile or static. Mobile scanners are attached to cars, all-terrain vehicles, or even backpacks to gather 3D points while moving. Static systems are placed on a tripod and remain stationary throughout the scan. In this project, the focus is on the use of static terrestrial laser scanning (TLS).

### Scanning Considerations
The biggest considerations when planning for a static TLS survey are the: range, field of view, laser beam looking angle, resolution, and measurement speed. All of these factors have an impact on the resulting 3D point cloud. The range limits for scanning are set by the instruments specifications. Systems designed for medium-range TLS are generally recommended to be used at 5 – 200 meters from the target object. The field of view limits are also set by the manufacturer but generally not used fully to its limits. Smaller angular sections should be scanned and combined rather, depending on the size of the target object, than taking a single scan with points at high laser beam looking angles. High looking angles disperse the beam to an oblique footprint on the surface and may affect the quality of the result. The resolution, or angular resolution depending on the device, determines how dense the resulting point cloud is. This is determined by the size of the desired features that need to be analyzed in the point cloud. Finally the measurement speed can also be a consideration when large targets are measured. The scanner can only collect a certain number of points per second. If a denser resolution is desired, more time is required to complete the scan. An example of the experimental setup is shown in Figure 3.2.

Figure 3.2: The Leica C10 laser scanner used in this project shown mounted on a tripod, as used in the field. An vegetation-covered outcrop is in the background and target is shown for reference. The laser beam is diverted from the rotating mirror in the center. The scanner interface is where the user defines how this mirror spins and rotates to obtain a desired resolution of points.

Output Data

Based on the principles of laser scanning, the basic output of the instrument is the $X\ Y\ Z$ positions of every return point relative to the scanners position (either in Cartesian or polar coordinates depending on the scanner). Additionally, many scanners include an intensity return value, $I$, based on the reflectivity of the target surface. Depending on the manufacturer or device, the return can be either a ratio of the integrated emitted to returned intensity value or the amplitude, the highest energy return of the laser pulse. Depending on the scanner, the first return, greatest, or multiple intensity returns can be stored. Some scanners have integrated cameras that can link $RGB$ color values taken from gathered images to the $XYZ$ points during post-processing. With a high density of points, or zooming-out of a computer-based representation, the post-processed point cloud will appear in true color and 3D. This is especially useful for realistic interpretation and viewing. Aerial scanners are often coupled with GNSS and an inertial measurement unit (IMU) to provide georeferenced location, scan angle, and scan direction relative to the scanner platform. All returns available should be considered for extracting geometric features.
3.1.4. Leica C10 Laser Scanner

The Leica C10 has been chosen to gather data for this study primarily on its capability and availability within the department. It is new to the department, purchased in 2014, and is capable of collecting up to 50,000 points per second with accuracies of 6 mm in ideal, close-range conditions. Figure 3.3 shows a detailed image of the scanner mounted on a tripod, as will be done in the field. The interactive screen is shown to the left size of the scanner while the rotating mirror that deflects the laser for time-of-flight measurements is the black cylinder in the center of the scanner. It accepts two batteries (two more can be stored for back-up in the scanner box) and has, in practice, sustained charge for approximately 6 hours of laser scanning.

![Leica C10 laser scanner](image)

Figure 3.3: The Leica C10 laser scanner used in this project shown mounted on a tripod, as used in the field, image from Leica©2016.

This particular model has many features that make it useful for characterizing outcrops, such as a nearly complete view field and an integrated camera. The interface is simple and data can be transferred easily via the USB port. Table 3.1, below, summarizes some manufacturer-provided specifications. These values may have been reported under optimal conditions with new instruments and should be validated with the actual instrument in practice.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum scan rate</td>
<td>50,000 points/second</td>
</tr>
<tr>
<td>Accuracy (ideal)</td>
<td>6 mm</td>
</tr>
<tr>
<td>Battery life (practical)</td>
<td>6 hours</td>
</tr>
</tbody>
</table>

Although these specifications are promising, several considerations are analyzed based on the instrument itself, its operating conditions, and its limitations.

3.1.5. Instrument Quality and Considerations

The quality of a laser scan depends not only on the scanning instrument itself, but on surrounding conditions. There are three primary factors that effect the quality according to Soudarissanane [2016]:

- **Instrumental**: scanner design and technical specifications that influence the emission and reception of the laser beam light; usually reduced by instrument calibration, see Lichti and Skaloud [2010]

- **Environmental**: laser beam travel time is dependent on laser wavelength, ambient temperature, humidity, scene lighting, air turbulence, and obstacles (rain, dust particles); good pre-fieldwork planning and an averaging or comparison of multiple scans taken over several days can help with this, especially in the case of outdoor measurements

- **Object-related**: reflection properties of a target object (surface roughness, color); covering surfaces with artificially reflective material or correcting the orientation of the scanner relative to the surface can help

- **Scanning Geometry**: the incidence angle and range (distance) to the target object; controlled by meticulous fieldwork planning and chosen scanning methods or practices
3. Laser Scanning and Positioning

Table 3.1: Manufacturer specifications for the Leica C10 laser scanner.

<table>
<thead>
<tr>
<th><strong>Accuracy of a Single Measurement</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Position* / Distance*</td>
<td>6 mm / 4 mm</td>
</tr>
<tr>
<td>Angle (horizontal / vertical)</td>
<td>60 µrad / 60 µrad (12° / 12°)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Laser</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Green, λ = 532 nm visible</td>
</tr>
<tr>
<td>Class</td>
<td>3R (IEC 60825 − 1)**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Range</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>From 0–50 m: 4.5 mm (FWHH-based); 7 mm (Gaussian-based)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Spot Size</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully selectable horizontal and vertical; &lt;1 mm min spacing</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Field-of-View</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>360° (maximum)</td>
</tr>
<tr>
<td>Vertical</td>
<td>270° (maximum)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Camera</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Image</td>
<td>Single 17° x 17° image: 1920 x 1920 pixels (4 megapixels)</td>
</tr>
<tr>
<td>Panoramic</td>
<td>Full 360° x 270° dome: 260 images; auto-adjusts lighting</td>
</tr>
</tbody>
</table>

* At 1–50 m range, one sigma
** A Class 3R laser is considered safe if handled carefully, with restricted beam viewing. With a class 3R laser, the maximum permissible exposure (MPE) can be exceeded, but with a low risk of injury.

While the user often has little influence on some of these factors, efforts should be made to reduce errors cause by them since they will be carried over to later parts of the point cloud processing steps, amplifying the overall error in the estimates. A close budget of errors should be considered when analyzing final TLS results. An example of a laser scan point cloud from the La Charce formation is shown in Figure 3.4.

Figure 3.4: Some additional considerations with laser scanning including (a) occlusion or missing points due to broken line of sight and (b) undesired points caused by sun beams or car and human profiles. Features are noted in yellow, the scanner position in red.
Several other considerations are important when minimizing error and prioritizing point cloud quality. Occlusion is a major factor as leads to gaps or missing points in the 3D data set. The laser scanner can only 'see' in its line of sight. Protruding objects in the front of a scene, such as a wall or a sign, will block what is behind the objects. This can be minimized or avoided by taking scans from multiple stations or directions. Another consideration is to identify 'ghost' points that show up in the scans. These can occur if emitted EM radiation from an object, such as the sun, is collected by the scanner. The fictitious sun rays are shown by the yellow arrow in Figure 3.4(b). Moving objects can also leave a scan with undesired points. As a car or person moves through the active scan, their profiles can be captured by one or more scan lines. These artifacts can be seen on the roads and pathways of a point cloud.

3.2. Incorporating GNSS

While 3D point clouds are instrumental in determining morphologic features of an outcrop, the proper choice of coordinate system can allow for additional estimates to be made. The laser scanner collects relative $XYZ$ distances from the station location, but the 3D point cloud does not inherently link these points with their Earth-referenced positions. To make outcrop measurements such as determining the strike line, the compass direction of bedding layer orientation, the $XYZ$ points need to be transformed to Earth coordinates (latitude and longitude, such as the WGS 84). Thus, point clouds must be georeferenced with GNSS data taken of the survey region. A setup of the GNSS system used in this project is illustrated in Figure 3.5.

GNSS data was gathered by post-processed kinematic (PPK) survey techniques using the Trimble R8 – 2 receivers. Figure 3.5 shows both the base station and rover logging data at the La Charce outcrop. All position data was collected locally on the data collector computer and post-processed with GNSS software upon arrival home. Further information on the survey, equipment, and data quality follows.

3.2.1. Post-Processed Kinematic Surveys

Survey grade GNSS instruments can be either static or kinematic. Static systems are designed to collect very accurate data (typically, horizontal accuracies of ~5 mm and 1 ppm baseline and vertical accuracies of ~10 mm and 1 ppm baseline [Rydlund et al., 2016]). On the other hand, kinematic surveys optimize the amount of data attainable in a short amount of time. The setup includes one stationary ‘base station’ receiver located at known point, such as the scan station, and at least one ‘rover’ receiver that collects data while moving about the area and receiving corrections from the base station. The schematic pictures in Figure 3.6 illustrate the kinematic process through a Real-Time Kinematic (RTK) survey. Note that the radio antennas pictured were
not needed for this study since Post-Processed Kinematic (PPK) was actually used.

PPK is very similar to RTK, except in the fact that positions are calculated in a post-processing stage after the data has been downloaded to a GNSS processing software. RTK positions are calculated in ‘real-time’, having horizontal accuracies of ~1 cm plus 2 ppm baseline and vertical accuracies of ~2 cm plus 2 ppm baseline, slightly less than those measured with static surveys [Rydlund et al., 2016]. As mentioned earlier all data is logged to the data collector and saved for post processing.

3.2.2. Trimble R8-2 GNSS Receivers

The Trimble R8 – 2 GNSS receivers were chosen for this project based on department availability. The system, as mentioned above, includes two receivers (a base station and rover) and one data collector. Figure 3.7 shows the instrument in detail.

This GNSS receiver has integrated wireless capabilities allowing for the base station and rover to communi-
cate, which is useful for fieldwork as the rover is carried over rough terrain and distances that a cord would a hindrance. A summary of applicable specifications of the Trimble R8 are listed in Table 3.2.

Table 3.2: Specifications of the Trimble R8 – 2 receivers used for this project [Trimble Inc., 2016]. PPK surveying was employed to gather data and RTKPOST was used for post processing analysis.

<table>
<thead>
<tr>
<th>Accuracy of Measurements</th>
<th>1 cm + 2 ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>1 cm + 2 ppm</td>
</tr>
<tr>
<td>Vertical</td>
<td>2 cm + 2 ppm</td>
</tr>
<tr>
<td>Initialization Time</td>
<td>typically &lt; 10 seconds</td>
</tr>
<tr>
<td>Channels</td>
<td>440</td>
</tr>
<tr>
<td>Memory</td>
<td>56 MB</td>
</tr>
<tr>
<td>GNSS Tracking Networks</td>
<td>GPS, GLONASS, Galileo, BeiDou(COMPASS), QZSS</td>
</tr>
</tbody>
</table>

The collected data from the fieldwork was saved locally on the data collector. Upon return, the raw data files were downloaded in T01 format and converted to RINEX using Trimble software. The RINEX files were then passed to RTKLIBs post processing program, RTKPOST, which accepts the standard RINEX GNSS observation data and navigation message files and computes positioning solutions. The output data can be exported as a .kml file that imports into Google Earth. An example of the resulting data is shown in Figure 3.8.

Figure 3.8: Gathered GNSS positioning data from the La Charce outcrop. Position points are colored by quality: the best being green, to yellow, to red. The track shows the motion of the kinematic rover receiver in relation to the base station set at the reference position shown on the map.

The gathered GNSS positioning data shows the track of the rover around the La Charce outcrop in the Vocontian basin. Green points indicated highest data quality, while yellow and red are of lesser quality. The base station was placed at the reference position, shown, and the rover visited each of the laser scan targets.
Georeferencing the outcrop will involve matching these target GNSS points with targets visible and scanned in the point cloud.

### 3.2.3. Note on Data Quality

The quality of GNSS data gathered with PPK surveying depends on several factors. Rydlund and Densmore [2012] suggest five key error sources and supply suggestions for mitigating these errors. The errors include: 

- *inefficiency* in planning the survey,
- *ionosphere* or space weather disturbances,
- *troposphere* issues including atmospheric conditions such as temperature, pressure, precipitation,
- *multipath* reflective obstruction avoidance, and
- *PDOP* or planning for specific satellite overhead conditions.

The errors can be minimized with proper planning, elevation mask adjustment and calibration.

### 3.3. Summary

Terrestrial laser scanning and GNSS positioning have been selected to gather field data on sedimentary outcrops for this study. TLS, or lidar, has the advantage of gathering gigabytes of 3D position data in minutes at resolutions down to 6 mm with only a few button clicks. Similar results can arguably be obtained with photogrammetry, but this technology was discarded due to the time involved in taking hundreds images and extensive post-processing steps for creating a triangulated mesh from images. Both methods use line-of-sight making occlusion by vegetation, or otherwise, a consideration. Practically, terrestrial laser scanning is more feasible than aerial or satellite based lidar since the looking angle is closer to facing head-on with the outcrop at such close range. GNSS data was added to the laser scan survey to provide means of georeferencing the outcrop, targets, and scan stations. While GNSS is quite accuracy, 1 – 2 cm, it would take too long to measure outcrop surfaces if that were even possible. Issues were encountered with getting sufficient satellite signal being surround by physical barriers, mountains. The combination of the two technologies, however, provide a quick and reliable method for creating a 3D georeferenced point cloud that can be used for feature extraction and estimation. These two have been selected to study the target regions outcrops near La Charce.
The data used in this project was collected during a one-week fieldwork excursion to the rocky, Drôme region of Southeast France. Terrestrial laser scanning (lidar) and GPS were used to collect georeferenced, three-dimensional, colored point clouds of many of the outcrops in the region based on their geological type, composition, and unique features such as folds and faults. The goal being to later automate the extraction of these morphological features from the point clouds. Detailed planning was necessary to ensure the success of collecting quality and functional data within such a brief time. Through fieldwork, the following questions were explored:

- Which particular outcrops should be measured (and for what features)? How is the data collected?

This chapter outlines the planning phases, the scanning procedure, some challenges encountered, and a summary of the acquired datasets.

4.1. Preparation and Packing

Terrestrial laser scanning fieldwork planning involves instrument preparation, region specific reconnaissance, and transport organization. Specific steps taken prior to departure for this fieldwork are detailed below based on the preparation time required.

4.1.1. T - 1 Month

Starting one month before the scheduled departure, it is important to not only understand the functionality of each instrument that will be used, but also, to practice using those instruments to learn their individual nuances (see Figure 4.1). In the case of this fieldwork, both the laser scanner and GNSS system were tested extensively. The laser scanner can scan 360 degrees in the azimuth from -45 degrees to 90 degrees elevation collecting $X Y Z$ coordinates and intensity at a desired resolution. This resolution is limited by the distance the scanner is located from the outcrop (range) and the amount of time available to collect the data. On average, a resolution of approximate 3.5 cm at 40 m range was small enough to discern desired features and did not take too long. With only 4 days to scan, scans taking more than 45 minutes were considered impractical. An integrated camera can take pictures within this same range giving $RGB$ values to each of their associated $X Y Z$ points in the point cloud. Additional practice was done with integrating targets for uniting multiple station scans. The targets can be defined at the time of scanning to simplify the registration of multiple point clouds in post-processing steps.

The simple tests alone prove that the instruments are both fragile and expensive, and unforeseeable circumstances can arise easily. It is recommended to insure instruments that could potentially be ruined during transport and data collection over rugged terrain such as is common with fieldwork. An insurance request for
the laser scanner was submitted and granted a month prior to leaving. For TU Delft insurance, the following items are required to be sent to the insurance office on the sixth floor: period, location, department, project code, instrument cost, and serial number. Having insurance also aids in people's willingness to help transport such an integral part of the research and fieldwork.

With instruments ready to go and a target area in mind, refinements were researched in order to narrow down the best possible outcrops to scan and to not waste the limited, valuable time in the field. At this phase, specific knowledge of the fieldwork region including maps and stratigraphic logs were collected. Along with advice from geologists familiar with the region, Google Earth provided a preview to the region and portrayed what to expect (including feasible routes with the car). Candidate outcrops locations were documented for use upon arrival.

4.1.2. T - 1 Week

The priorities one week before leaving include scheduling, packing, and finalizing instrument details. With many uncertainties such as current outcrop conditions, accessibility, and weather, scheduling can be a challenge. The plan for this fieldwork, with flexibility in mind, was to spend the first day orienting to the landscape and to gather information about specific outcrops previously documented for investigation. Then, four full days could be spent scanning the outcrops. The goal was to scan at least two outcrops per day. Having eight various types of outcrops to choose from was considered sufficient for the task of auto-detecting features upon return.

At this point, with instrument experience and a plan, a packing list provided the guidance to ensure nothing critical could be forgotten. Major items, such as the following, were noted:

- Laser Scanner
  - scanner red box
  - (4) batteries + charger
  - tripod
  - (3) circular targets
4.2. Field Operations

- (6) square targets
- GPS
  - (2) receivers: base and RTK
  - (2) antennas: base and RTK
  - (4) batteries + charger
  - tripod
- Other
  - camera
  - laptop
  - USB storage device (> 25GB)
  - clip board / binder / notebook / pens
  - (2) safety vests
  - duct tape

The complete packing list can be found in Appendix A.1. Acquiring the items is one task, but additionally, the scanner, laptop, and camera should be cleared of old data to ensure there is enough space for whatever new data will be collected. During the fieldwork, raw outcrop files ranged from 100 MB to 3.8 GB; the amount of raw data collected for the week totaled to just under 20 GB (excluding GNSS data). An external storage device is also recommended for storing important reference documents, papers, and images that will aid in the fieldwork along with sufficient space for backing up data files collected during the fieldwork.

One final critical step is to establish how the instruments and equipment will be transported to the fieldwork site along with how they will moved from outcrop to outcrop when collecting data (since the packing list is quite long). In this case, most of the supplies were transported by car requiring only a bit of organization, but this process could take even longer if shipping is necessary or extra sensitive instruments are involved.

4.1.3. T - 1 Day

The final thing to check before leaving is the weather. Making sure that all equipment (and the person doing the laser scanning) can be protected from excessive heat, rain, and wind is important since it can affect the quality of the data gathered. Schedule adjustments may be necessary at this point.

4.2. Field Operations

Upon arrival, many considerations are taken to get the most quality data out of the limited field time available. This section details the choices encountered while selecting a site or an outcrop, the full setup of instruments and targets, and the best practices procedure for gathering repeatable quality scans.

4.2.1. Site Selection

The first day of fieldwork, as scheduled, was spent on a reconnaissance walk 'through time'. The region of study contains rocks dating from the Cretaceous to the Jurassic time periods (approximately 65 to 206 million years ago). Throughout these periods, unique sedimentary depositional formations can be identified by their characteristic alternating limestone / marl patterns or lack there of (see Appendix A.4). The walk through time took us through nearly all 12 of the formations that can be found in the region. When considering laser scanning here, many options are available.

The goal of this project is to extract and characterize physical features of outcrop point clouds. Thus, when selecting the top candidate locations, distinct layering and a spread of formation type is important. Additionally, common and recognizable features such as faults and folds could also be interesting for point cloud feature extraction. The images in Figure 4.2 show some considerations and problems.
Figure 4.2: Sample outcrop scanning sites with problems such as (a) a fault obscured by heavy vegetation, (b) a river and boulders at the base of the outcrop where the scanner would need to be placed, and (c) an outcrop that is located too far from possible scanning locations.

Figure 4.2(a) shows an outcrop with a fault running through the middle of it. This outcrop was chosen because of the fault, but as is visible in the image alone, heavy vegetation obstructs the characteristic strata making it difficult to extract any rock features. Figure 4.2(b) shows a nice outcrop but the site for scanning is full of large rocks, trees, and a river. This is bad for both transporting equipment to the site and for scanning. Figure 4.2(c) shows an outcrop of the Marnes Bleues formation. Few obstructions are present but the outcrop is very far away from the best viewpoints of the outcrop. If the range is too far, as is shown in Figure 4.2(b), the intensity returns will be weak and many gaps will be present where the signal was not strong enough for a full return.

These specific cases point to a final, very critical consideration when choosing scanning sites: practicality. As can be seen, a good site is accessible by car (or a short hike since the equipment is heavy), unobstructed by vegetation, and within a valid range of the scanning location set by both the instrument manufacturers and the environmental conditions (a range of < 100 m is recommended based on fieldwork experience). Not illustrated in the images is the importance of selecting a target object that has a better chance of fulfilling post-processing goals. The goal of this project is to extract or estimate characteristic features of outcrops, such as orientation and geometric properties of individual rock layers, or strata, using a semi-automatic algorithm developed in Matlab. Many of these features are defined by their relatively planar angles or offsets. Thus, an outcrop well suited for semi-automatic point cloud characterization should contain distinct, well-defined planar surfaces or layers. The rocks should extend out of the outcrop to give the algorithm the largest possible planes, or most possible points, for estimation. A homogeneous outcrop lacking distinct bedding layers, fractures, or defining geometric features provide little to characterize with.

4.2.2. Setup and Targets

Once the site has been selected, it is necessary to decide on the best locations for scan positions (viewpoints) and targets. First, a walk around the area can help determine the best possible viewpoints, keeping in mind that occlusion can hide vital features. Human eyesight is similar to laser scanning in the sense that if you stand at your viewpoint, you can only collect data for what you can see. Anything hidden from your view will also be hidden from the scanner. Very close-range outcrops with subtle strata may require only one good viewpoint, or station, while large outcrops with distinctly defined strata that jut out of the outcrop require several stations along its length. The station count depends on the end goal, but with feature extraction, it is critical to collect points on all visible sides of the rocks. This generally requires at least two stations.

If multiple stations will be necessary, the next task to consider is where to best place the targets. Targets, as shown in Figure 4.3, are small markers that can be securely placed anywhere within the site that will aid in linking two point clouds of the same site together (e.g. two stations, viewpoints) during post processing. This assumes that they will not be moved throughout the entire scan of the site, including all station scans. They are not necessary when physical features in the scans themselves can be used such as straight lines, corners, or known points. In urban settings, these precise and regular features are quite easily incorporated into a scan such as street signs, road lines, or buildings. However, in natural settings, locating precise features is more difficult, and thus, targets or artificial markers prove their purpose.

The key when placing targets is to locate them the furthest distance apart from each other as possible, both
horizontally and vertically spread, and within the view of the scanner. Three collinear targets allow two mapped scans to be aligned along that line but then they are free to rotate, making an accurate registration nearly impossible. Thus, the greatest 'plane' that can be virtually made connecting the target points will result in the best registration. Varying heights and distances is important along with making sure that each target is visible from all stations (or at least 3 overlap from station to station). They can be placed on the outcrop although it is not ideal since part of the outcrop is then obstructed. They can be placed opposite the outcrop but that requires continuously scanning both the outcrop and its opposite side (possibly at 360 degree scan). A 360 degree scan takes extra time and collects lots of extra data that is not needed just to include a target. The magnetic Leica targets are very steady but rotate-able making them ideal for multiple stations. In nature, though, it is difficult finding magnetic surfaces. Moving a car to a desired position can be a solution for both a magnetic surface and height, but care should be taken when slamming doors, for example, because that can move the target several millimeters. In post processing, a good registration includes target locations that vary less than one mm. Placement is key to ensure an accurate registration, the amount of targets also matters.

It is recommended to place a minimum of four targets per site. Assuming that the laser scanner is leveled properly throughout the entire scan, only two targets are required by the Leica software to perform a registration. Three is safety in case the scanner is not level and a fourth target is good for when a target is accidentally moved by the person scanning, anonymous bystanders, or the wind. These instances are all probable so placing extra targets never hurts. In the fieldwork, about six targets per scan were used. As discussed, a fair amount of time should be spent not only choosing a proper site, but also selecting the scan locations and target placement.

### 4.2.3. Scanning Procedure

After carefully selecting scan positions and target locations, the scanning can begin. The first step is attaching the scanner to a stable tripod and leveling it. It is important that the tripod is setup on firm ground as it can sink in soft materials such as mud and beach. Leveling can be done both manually with the leveling bubble on the scanner and electronically with the instrument turned on. If targets are all securely setup, a first low-resolution, 360 degree scan with corresponding pictures (for $\text{RGB}$ values) is recommended. A true colored point cloud can be useful for sharing or teaching as it looks more closely to what is found in nature. The colored, low resolution scan collects information about the surrounding site and can help orient the viewer into the scene rather than just seeing a snapshot of the outcrop itself. The low resolution scan and 360 degree imaging takes around $10 \sim 15$ minutes. It is also a good check to make sure the instrument is functioning correctly as all data is available for immediate review directly on the scanner. If all seems fine, proceed by scanning each target with the laser scanners target recording function. As mentioned earlier, this step may take time in the field, but it will save time and may give better results in post-processing. The final scan then, at this station, is a higher resolution scan of the outcrop including all targets. A manual resolution can be set by using the distance function to measure the actual range to the outcrop and then specifying the desired resolution in centimeters. If this scan includes all points needed, the laser scanner can then be moved to the next station, the targets re-scanned, and a new high-resolution scan of the outcrop adds additional and missing data to the point cloud. This process should be repeated for all stations. A step by step procedure of
using the scanner can be found in the Appendix A.2. The layout of a scan can be approximated by sketch in Figure 4.4.

Since many outcrops were scanned during the fieldwork, a method was developed to ensure that minimum requirements were met. The first consideration was to measure the overall outcrop dimensions with a laser range finders. This device instantaneously measure the distance from one point to another with a laser beam. Here, the outcrop Height $H$ and Length $L$ should be estimated. Soudarissanane [2016] recommends scanning angles, $\theta$, to be less than 70 degrees to maintain quality in collected data. Thus the minimum range required to scan an outcrop depends on:

$$R_{\text{min}} = \frac{H \tan \theta}{\tan \theta}$$  \hspace{1cm} (4.1)

If this value falls within the manufacturers range limits (0.1 to 100 m is recommended from experience), then the setup continues. However, if it does not and data at the top of the outcrop is needed, it is recommended to raise the scanner on a platform such a placing it on top of a car. The next consideration is to calculate the minimum number of scan stations needed to cover the outcrop area. This again is artificially limited to $\theta = 70$ degrees as to ensure point cloud quality. The minimum number of needed stations can be calculated as followed, rounding any decimal to the next integer:

$$S_{\text{count}} = \frac{L}{2R \tan \theta}$$  \hspace{1cm} (4.2)

As this is minimum number of evenly spaced stations needed, the station count is also heavily dependent on occlusion. If there is a clear view of the entire outcrop from each station and no rock layers block one another, then occlusion is not a problem. Often, however, extra stations need to be placed to capture the full 3D nature of the outcrop. A final consideration is estimated how long each scan will take. This is dependent on the desired scan resolution, or $r_H$ and $r_L$ in both directions, and scanners point per second (PPS) rate. Assuming only one station is used, the following equation can help determine how many minutes a scan will take:
4.3. Challenges in the Field

The average time for a one centimeter resolution scan of outcrops measured during fieldwork took approximately 15 minutes. Additionally, a 360 image capture takes roughly five minutes.

The final steps of scanning are equally as important as the first. Before turning the scanner off, all collected data should be copied to a USB drive. This can take $10 - 20$ minutes to transfer per scan, based on the size of the outcrops scanned for this project, but it ensures backup in case anything happens. Also, if the scanners internal memory becomes too full, files can easily be deleted without the chance of losing data or overwriting. Additionally, the batteries should be removed and charged as, by experience, the four included batteries last for a total of only about 6 hours. If a scan is interrupted and must continue over two days, the quality is generally reduced as the targets have a higher chance of being shifted and the environment conditions are not the same (nor are the rocks e.g. moisture content). With fully charged batteries, the scanner is ready for another day of scanning.

4.3. Challenges in the Field

The previous section outlines a streamlined method for laser scanning rock outcrops, but anyone who has been on fieldwork knows that that is not as smooth as it ever goes. The following section draws attention to both practical and theoretical challenges encountered during the fieldwork, and some ideas on working with and around those now foreseeable problems.

4.3.1. Practical

In terms of practical planning, the laser scanner seems quite straightforward. That is, until you attempt to lift it. Due to its bulky build and nearly 17 kilogram weight with batteries, transportation is limiting for a single person to be operating it. Accessibility by car is extremely helpful, along with a safe parking spot. Safety triangles and vests can really help in situations where outcrops are right next to the road and the safety of the personnel and equipment is a concern. Carrying the scanner to a further location is also an option as it comes in a weather-proof rolling box. However, the weight and bulk can be tricky on rough terrain. Having extra hands available can help with this and with the mounting the scanner on the tripod once the destination is reached. Often the tripod needs to be quite high as the viewing angle is better when outcrops are tall. This requires lifting the scanner above your head (or not, if you are tall) and holding it while screwing it securely to the tripod. If the outcrop is a cliff or in a mountain valley, wind can make this even more challenging. Weather, in general, really affects the ability to scan and the quality of the collected data. It is not recommended to laser scan in the rain since the emitted signal can be reflected back to scan by a rain drop or scattered, both giving inaccurate return signals. The weather can change quickly though so it is best to have a scanner ‘raincoat’ that can cover the instrument in unexpected circumstances. The wind can also reduce the data quality if it is strong enough to shift the position of the laser scanner or targets. The best way to handle this is to check the weather reports before going to the field and preparing by always securing positions as best as possible.

4.3.2. Theoretical

Theoretically, the largest challenges encountered were balancing the range and resolution. The larger the range, the bigger the resolution of the outcrop for the same angular rotation of the scanner. For some very distant outcrops, scans took up to 45 minutes in order to reach the desired point cloud resolution at the outcrop. The size of the outcrop also had an impact on this. Secondly, since the laser scanner does not have a built-in GNSS receiver / antenna, georeferencing the point cloud can is another challenge. It is necessary to georeference if defining bedding planes since the planes are oriented based on compass directions. Thus, a GNSS base station and rover had to be included in the measurement process. The rover can mark the location of each of the targets while the base station establishes the scan station location and provides position corrections to the rover. Linking the two systems can be an extra source of error as they are not integrated by default.
4.4. Summary of Collected Data

Throughout the week of fieldwork, laser scans of 10 different outcrops were collected. Google Maps was used to initially organize and share the data collected. Figure 4.5 shows the study region in southeast France along with a map in Google with the locations (4.5c). The red box shows the extent of the fieldwork area and the teal mountain icons show the locations of each of the laser scanned outcrops. In the interactive map (see link in caption of Figure 4.5), the user can click on any icon to select the outcrop and see basic data and images taken of that specific outcrop. The 3D point clouds through which the data will be shared is explained in-depth in Chapter 6.

The collected laser scan sites are listed in the table below. Each outcrop is named according to its nearest village, sometimes more than one scan per nearby village was collected. The same names are used in Google map, see link in Figure 4.5. 'Station' count is listed as the number of 'viewpoints' or positions the scanner was moved to to collect data. Larger, closer-range outcrops require more stations in general to scan the full dimensions. Here, the La Charce outcrop required the most stations, four, because it was chosen as the most well-defined example and was scanned in greater detail with higher resolution than the rest. The 'latitude', 'longitude', and 'elevation' of each scan location was collected with GNSS during the scans. These numbers vary slightly per station within a single scan location since secondary stations were shifted approximately 20 – 50 meters from the original station (depending on the goal of the scan) to get a better view of all sides of the outcrop reducing data shadows. The 'total points count is the merging of all station point clouds for a single outcrop; mean per outcrop and a sum of all points collected during the fieldwork are at the bottom. These reflect the final '.ptx' file size values in the last column, with a total of just over 22 GB of data for the week of fieldwork. The worst case point density or resolution in degrees ('Res') of each of the scans was greatly determined by the range ('Rng' or distance from the outcrop) and the dimensions ('L'ength x 'H'eight). In general, the larger and further away the outcrop, the lower the resolution of the collected point cloud. More details are available for the close-range scans. Column averages and sums can be found at the bottom of the table.
Table 4.1: A list of collected outcrop scans named after the nearest village. The Station count shows how many different scan locations were used to collect the ‘Tot. Points for each outcrop. The ‘Res.’olution is the worst case resolution. The Range, length (L), and height (H) of the outcrop are estimated from the scan data. The ‘Elev.’ation shows is the ground elevation of the outcrop where the scans were completed. Finally the file size in ‘.ptx’ form is presented for comparison.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Stations</th>
<th>Tot. Points</th>
<th>Res. [deg]</th>
<th>Range [m]</th>
<th>L [m]</th>
<th>H [m]</th>
<th>Elev. [m]</th>
<th>.ptx [Mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aranyon1</td>
<td>44.46803</td>
<td>5.35792</td>
<td>3</td>
<td>42,395,447</td>
<td>0.034</td>
<td>45</td>
<td>40</td>
<td>45</td>
<td>598</td>
<td>4,000</td>
</tr>
<tr>
<td>Aranyon2</td>
<td>44.48102</td>
<td>5.34635</td>
<td>1</td>
<td>236,718</td>
<td>0.115</td>
<td>115</td>
<td>85</td>
<td>125</td>
<td>679</td>
<td>994</td>
</tr>
<tr>
<td>LaCharce</td>
<td>44.46891</td>
<td>5.44379</td>
<td>4</td>
<td>69,211,402</td>
<td>0.032</td>
<td>22</td>
<td>100</td>
<td>18</td>
<td>609</td>
<td>4,800</td>
</tr>
<tr>
<td>PreGuittard1</td>
<td>44.49730</td>
<td>5.30866</td>
<td>1</td>
<td>13,322,113</td>
<td>0.024</td>
<td>13</td>
<td>15</td>
<td>8</td>
<td>878</td>
<td>1,200</td>
</tr>
<tr>
<td>PreGuittard2</td>
<td>44.49762</td>
<td>5.30861</td>
<td>2</td>
<td>30,248,769</td>
<td>0.040</td>
<td>70</td>
<td>80</td>
<td>30</td>
<td>884</td>
<td>2,200</td>
</tr>
<tr>
<td>SBenoit-en-Diois</td>
<td>44.66013</td>
<td>5.27911</td>
<td>2</td>
<td>18,956,944</td>
<td>0.028</td>
<td>120</td>
<td>180</td>
<td>50</td>
<td>414</td>
<td>883</td>
</tr>
<tr>
<td>Pradelle1</td>
<td>44.6908</td>
<td>5.28025</td>
<td>1</td>
<td>21,912,822</td>
<td>0.020</td>
<td>14</td>
<td>25</td>
<td>10</td>
<td>536</td>
<td>2,200</td>
</tr>
<tr>
<td>Pradelle2</td>
<td>44.69234</td>
<td>5.28835</td>
<td>2</td>
<td>37,645,185</td>
<td>0.029</td>
<td>10</td>
<td>20</td>
<td>5</td>
<td>532</td>
<td>2,800</td>
</tr>
<tr>
<td>SNazaire-le-Desert1</td>
<td>44.57673</td>
<td>5.27410</td>
<td>2</td>
<td>36,048,770</td>
<td>0.026</td>
<td>18</td>
<td>55</td>
<td>20</td>
<td>556</td>
<td>2,200</td>
</tr>
<tr>
<td>SNazaire-le-Desert2</td>
<td>44.58255</td>
<td>5.27707</td>
<td>1</td>
<td>15,851,238</td>
<td>0.029</td>
<td>12</td>
<td>25</td>
<td>5</td>
<td>548</td>
<td>977</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
<td></td>
<td>28,582,951</td>
<td>0.038</td>
<td>44</td>
<td>63</td>
<td>32</td>
<td>623</td>
<td>2,225</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td></td>
<td></td>
<td>285,829,508</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22,354</td>
</tr>
</tbody>
</table>

The size, range, and resolution values of each outcrop are difficult to visualize from the table. The plot in Figure 4.6 is a visual representation of these values for comparison. Dimension and range values are shown in meters while each outcrop ‘box’ is colored according to approximate point cloud resolution in centimeters. On the right, the plot is zoomed-in to just the smallest four outcrops. They have the smallest dimensions, the shortest range, and the lowest resolution. All are labeled with the names corresponding to those in the table.

Figure 4.6: A comparison of the data collected for all study outcrops. It includes the approximate size (Length x Height), range (distance from the scanner to the outcrop), and resolution (displayed color, see scale) of each outcrop. Plot (a) shows all data, while plot (b) is a zoomed-in version showing the smaller outcrops in better detail. The study primarily focuses on the La Charce outcrop, noted on the plot.

All outcrops point clouds contain x, y, and z location values, an i signal intensity return, and R (red), G (green), and B (blue) color values corresponding to each point. The La Charce outcrop has the most complete dataset (with four stations) and the most well-defined bedding layers. Testing and algorithm development will thus be completed with subsets or cut-sections of the merged La Charce point clouds. The working algorithm will then be implemented on several of the other outcrops with varying features such as size, feature definition, range, vegetation shadow, faulting, and folds for code verification and robustness.
4.5. Post-Processing Basics

After collecting data in the field, saving the information and transporting it back to the laboratory is critical. The Leica C10 scanner automatically saves all scans directly but the allotted space sometimes necessitates transferring the files to another location (also needed for backup purposes). The total onboard scanner file capacity is 80 GB on a solid-state drive (SSD). In the case of this fieldwork, all raw .bin files were left on the laser scanner with backups on a USB drive. The procedure for transferring files can be found in Appendix A.2 and sometimes can take as long as 10 minutes just to transfer one scan.

4.5.1. Registration with Cyclone

The raw .bin files collected can then be converted into a different formats, such as .xyz, .txt, or .csv, that can be read by Matlab or any post-processing program you plan to use. The first step is using Leica’s Cyclone software. In Cyclone, the raw .bin files can be imported, viewed, modified, and then exported as .ptx files. For single station outcrop scans, this step simply involves importing, opening, highlighting all points, and then directly exporting. However, if several stations were involved, a registration, or alignment of point clouds is necessary. The two scans of the Pradelle2 outcrop are shown in the left and right upper images of Figure 4.7.

![Figure 4.7: Laser scans of Pradelle2: the first station was located at the red ‘x’ in (a), the second station in (b), and the 2 point clouds merged with registration in (c). Square targets are shown on the outcrop out of necessity due to very close-range as this practice is not recommended. Point clouds (a) and (b) were merged to eliminate or reduce occlusion (shown with black missing data spots on the right and left, respectively). The camera view of all three images is the same.](image)

In the first scan, Figure 4.7(a), the laser scanner was placed at the red ‘x’. The coverage of the outcrop is quite complete except to the right side where black ‘spots’ become visible; these signifying no data values or holes in the point cloud. Either the field of view of the scanner looking toward those areas was obstructed or the scanner was unable to receive a strong enough return signal which could be due too many things such as range, incidence angle, or surface roughness. To compensate for the loss of data on the right side, the laser scanner was then moved right to the new ‘x’ location shown in Figure 4.7(b) (the camera view of all three images in the Figure is the same). Here, the right side has very good data coverage, but shadowing from the protruding strata on the left are now obscuring the data collection.

Since each scan gives a significant amount of data that the other does not, it can be advantageous to merge the two scans for a more complete coverage of the true 3D character of the Pradelle2 outcrop. A closer look reveals some targets placed on the outcrop, small blue circles with white centers and square checkerboards. These targets aid in the registration of the two point clouds. As mentioned earlier, the targets are densely
scanned to establish their centers in relation to the outcrop being scanned. When both scans are imported into Cyclone, the targets are automatically imported as well. The software can then recognize and pair targets in the two point clouds using its internal registration function. Errors exist when pairing the targets but can be adjusted and weighted based on the results; the selected targets at Pradelle2 had errors of around ten millimeters or less, similar to the accuracy of the scanner itself. The resulting merge of the two scans is the final image, Figure 4.7(c). Here, very little data is missing on both the left and right sides of the scan as seen by eliminated black space. When rotated, the outcrop has more points both improving the quality of the 3D shape and matching it closer to how it looked when the data was collected in the field. The merged point cloud can then be exported as .ptx as mentioned above. Detailed steps for performing a registration can be found in Appendix A.3.2.

4.5.2. Data Manipulation with CloudCompare

The software, CloudCompare, is a tool for further post-processing of the point clouds. It can be used to convert the exported .ptx files from Cyclone to .xyz, .txt, or .csv files or for much more complicated analyses such as feature extraction and characterization. Since most of the data analysis of this project is done in Matlab, CloudCompare is a great tool for subsampling the dense point cloud and for taking smaller sections of the data since Matlab cannot handle (or goes extremely slow for) the full merged point clouds. The subsections are helpful for quick computation while developing algorithms, but the full point cloud can be used in the end. Figure 4.8 shows one of these such sections cut from the merged La Charce point cloud. Testing can be much more easily completed with a dataset this size.

Additionally, the program and its plugins create great tools and functionalities for feature extraction, internally. Figure 4.9 shows the RSD plugin based on Schnabel et al's 2007 paper on point cloud shape detection using a RANSAC algorithm. With several input parameters, the plugin calculates planes (or other shapes) within a loaded point cloud. This function is automatic after specifying tolerance parameters and preferences.

As mentioned earlier, the CloudCompare point clouds can be exported to different formats. This includes information calculated in CloudCompare such as normals. For Matlab analysis, the .csv format works well. Point clouds in Matlab will be further discussed in the Methods section.
4. Fieldwork: Data Acquisition

4.6. Summary

Outcrops with varying features, such as distinct layer, faults, folding, etc., are most desirable when planning to use the collected data for algorithm testing. Within a set period of time, higher resolution can be sampled for close-range outcrops rather than more distant ones. The dimensions or size of the outcrop also influences the resolution for a given scan time. For extracting geometric features, it is hypothesized that a higher resolution (within the laser scanners limits) would be most useful. The more points in a certain area, higher densities, the more values available for making estimates. Thus, a close range (< 50m), medium-sized outcrop (approximate 500 square meters in frontal area) with distinct morphological features is recommended.

As for how the data is collected, a documented procedure for laser scanning rock outcrops can be found in Appendix A.2. It involves selecting an accessible site, choosing laser scan station locations to minimize occlusion, placing targets in the scan area if multiple stations are used, and scanning the targeted outcrop. The process can take anywhere from 1 hour for a single station to all day for a large outcrop with multiple stations.
In Chapter 2, the geology of the area along with measurable geometric features is discussed. These features included the dip angle, the dip direction, and the limestone to marl layer thicknesses. Extracting geometric features, such as these, is not trivial, and thus, has been one of the key focuses of this thesis. Numerous steps and methods were involved along with necessary assumptions made to best tailor the work flow of the algorithm to 3D feature extraction. The following chapter outlines these point cloud processing steps in an order that builds complexity from one step to the next. The following targeted questions will be addressed:

How could a semi-automatic work flow estimate these features from 3D measurements? Which software assists in this?

As stated, the software used for each step of the algorithm is also documented. It is important to note here, however, that the choice of software was determined by available equipment (Cyclone from Leica), ease of use and accessibility (CloudCompare), and previous experience and understanding (Matlab). The following method could be similarly implemented with other platforms depending on individual resource availability.

5.1. Targeted Parameters for Extraction

As mentioned above, this study aims to extract the dip, dip direction, and layer thicknesses from 3D outcrop point clouds. The raw information that is available to work with is the 3D point cloud that includes the $X$, $Y$, and $Z$ location of every point, the intensity return of that point, and the $R$, $G$, and $B$ values of that point collected from the scanner’s internal camera. For the sake of algorithm development, the La Charce formation was chosen for its characteristic and well-defined limestone / marl layers, the large amount of data gathered on it (4 scan stations), and its link with a detailed GNSS survey enabling georeferencing. A quick illustration in Figure 5.1, below, shows the full extent of the point cloud gathered at La Charce during the fieldwork, an approximately 100 by 20 meter outcrop with over 69.2 million points.

If we zoom in from here, the targeted features for extraction are illustrated as in the following Figure 5.2, where each one is a measurement that can be compared and validated with results from geologists.

Due to the deep sea sediment environment that formed the layers in this formation, the dip and dip direction are expected to remain more or less constant throughout the La Charce formation area studied. However, when automating a process to extract limestone and marl thicknesses, it is key for the algorithm to recognize the difference between the two types of rocks. Geologists can tell the rocks apart by sight, but the algorithm should separate these rocks base on $XYZIRGB$ information alone. This is one of the main challenges in the extraction of the three, 3D, geometric features of an outcrop. Once characterized as limestone or marl, the angle estimates, orientation, thickness, surface roughness, and even intensity can be compared.
5.2. Related Outcrop Characterization Studies

The desire to extract these specific parameters, the dip, dip direction, and strata thicknesses, stems from a synthesis of previous work done in the field and an attempt to build upon the link between geological outcrop surveys and remote sensing techniques such as lidar. Outcrops have been studied for years in the geological sense. However, in the last ten years, the study of outcrops using lidar data has become increasingly popular. The topics of studies related to 3D outcrop characterization generally fall into three categories: feature extraction, segmentation, and parameter estimation. This project incorporates steps from a blend of these works as it addresses parts of all three categories, the primary goal being parameter estimation.

**Feature Extraction**

Studies on feature extraction, most applicable to this study, aim to extract either all shapes present in the 3D point cloud, any planar features, or irregularities. Sturzenegger and Stead [2009] creates a registered point cloud network, both with images and 3D lidar data, to locate regions of discontinuity in an outcrop. With registered point clouds, both Dewez et al. [2016] and Vo et al. [2015] suggest methods for subdividing or decimating the point cloud into analyzable pieces using algorithms such as octree for regular grid subdivision and kd-tree for irregular grids based on voxel or pixelized point count. These preliminary subdivision steps
enabled the authors to extract features of the entire cloud later on. In addition to pre-processing the point cloud in these ways, Humair et al. [2015] shows how geologic features can be semi-manually extracted using know point locations georeferenced in an outcrop.

Extracting features also requires some amount of filtering or thresholding to minimize errors of calculating features with noisy or unwanted points. Anders et al. [2016] and Jones et al. [2009] analyze the curvature of neighborhood points to define either planar features or irregularities, respectfully, based on a pre-defined threshold or variation of fit. The curvature or covariance of neighboring points can additionally be sorted into groups using histogram binning as discussed by Blomley et al. [2014]. Another common method of fitting planar or feature models to the 3D point data is to employ a tensor analysis (using the moment of inertia) as illustrated by Park et al. [2012], Fernández [2005], and García-Sellés et al. [2011]. This method can even quantify the quality of the fit. In this project, planar features will be extracted using a combination of the methods described above.

Segmentation

Outcrop segmentation of 3D point clouds, or the division of data points into subcategories based on similar characteristics, has been attempted and demonstrated in varying levels through the use of semi-automatic, identifying algorithms. Many outcrop studies have shown success using the corrected intensity return of point cloud points to segment the cloud based on rock type, such as Franceschi et al. [2009], Franceschi et al. [2011], Franceschi et al. [2015], Burton et al. [2011] and Matasci et al. [2015]. Olariu et al. [2008] uses clustering on planar normals for segmentation. Vo et al. [2015] approaches segmentation with a region growing solution. Here, the subject is building facades, but a similar method could be used for outcrop analysis. Since much work has been done on outcrops using corrected intensity, the developed method for this project will focus more on the possibilities of using planar normals.

Parameter Estimation

A final study completed by Yeh et al. [2014] attempted to estimate parameters such as the dip and strike from 3D lidar date of outcrops. Although this is also one of the main goals of this project, Yeh defines his extracted bedding layers manually using digital tracing and uses airborne lidar rather than terrestrial laser scanner to gather his data. Thus, Yeh's goal, along with feature extraction and segmentation methods described above, have directed the path of this project as will be explained in the work flow of outcrop characterization that follows.

5.3. Characterization Work Flow

The work flow of the developed, automatic algorithm for extracting key geometric features can be divided into three phases: pre-processing the point cloud, defining bedding layers, and estimating parameters. Each of these phases feed data to the proceeding phase, starting from the raw point cloud, all the way to numerical estimations of the outcrop dip, dip direction, and layer thickness.

The following sections explain each sub-process in detail along with the software used and any built-in functions or assumptions made. Plots used to illustrate each step are created with Matlab.

5.3.1. Pre-Processing the Point Cloud

The pre-processing phase includes all preparation steps necessary to start analyzing and manipulating the data in Matlab. The raw point cloud of La Charce is over 4.8 GB. At this file size, Matlab runs very slow or crashes on the computer available for analysis. The vegetation and irregularities in the outcrop can also prove challenging for algorithm development. The best approach for development is to select a small, well-defined sub-sample of the dataset and improve upon that. The steps below detail how this sub-sample of La Charce is created along with how it is imported into the Matlab environment retaining its Earth reference for use with later measuring the dip direction.
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5. Geometric Characterization

Figure 5.3: A visualization of the three-part algorithm workflow along with sub steps for reaching the ultimate goal of parameter estimation for an outcrop or outcrop section.

Point Cloud Registration

The La Charce formation has well-defined limestone layers that protrude beyond the marls that have eroded away over time. Although these protrusions are a major advantage when it comes to extracting planar features, it requires multiple station scans due to occlusion. Thus, at La Charce, four station positions were chosen to reduce the ‘shadowing’ effect and to gather sufficient information for both types of rocks. The diagram in Figure 5.4 shows the approximate extent (best quality; all scans included the entire outcrop) and location of each scan.

Figure 5.4: Scan station locations at the La Charce outcrop. Stations 1 – 4 shown right to left. Projected scans show an estimate of the best quality data gathered for each station (the full extent of the outcrop was scanned at all station locations).

The scans collected at various locations, or stations, then need to be merged into a single point cloud. This is most easily accomplished by the use of targets or ‘known location’ markers during the scan. The Leica software, Cyclone, can then detect these targets in each scan and merged them based on the fact that the targets do not move. A detailed explanation and ‘how to’ register a point cloud can be found in Appendix A.3.2.
Decimation and Cropping

The next issue, as mentioned earlier, is that the merged point cloud is, in general, too large for testing algorithms in Matlab on the machines available. Retaining the shape of the original cloud, along with keeping enough points to accurately define a plane, sets limits on the amount of points that can be deleted or decimated. Here, sharp edges and rough surfaces are key while flat planes can afford to lose points. Ideally, a selective algorithm could decimate the point cloud based on these criteria, but for the sake of time with repeated calculations, the point cloud used in this project was decimated with CloudCompare’s subsample function. Within the function, subsample by octree was chosen at a subdivision level of 7. The octree method is a “recursive partitioning of [a] cubical volume of space,” or the outcrop bounding box, into eight equivalent sub-cubes per octree [EDF-R&D, 2016]. This means that the subdivision occurred 7 times resulting in much smaller cubes or voxels. The first two octrees are shown in Figure 5.5. The nearest point to the center of the octree cell is kept while other points within the octree voxel are deleted.

![Figure 5.5: The sample La Charce point cloud section divided by two octree levels. Octree level 1 (a) and level 2 (b) are shown here, but a total of 7 octree levels were used to reduce the point cloud size. Only one point per octree voxel (or cube) remains in the final step, the one nearest the center of the voxel.](image)

The results of this level 7 octree partitioning are shown in Figure 5.6, below. This method can significantly reduce file size depending on the level of octree chosen: the original file size of this small section was 18.7 MB, while the decimated one is 2.2 MB, almost a 90% reduction. That is going from an average point density of 10,757 points per square meter to 1,462 points per square meter.

![Figure 5.6: The difference between (a) a full point cloud segment with 347,850 points and (b) a decimated one with 47,271 points. This is the result of the section of the La Charce outcrop decimated to a level 7 octree, as shown in Figure 5.5. The remaining points are still sufficient to develop the algorithm, but the full resolution will be used once the algorithm has been developed and tested.](image)
Another issue encountered even after decimation is the ‘noise’ of vegetation, streets, people, cars, etc. that can also be found in the scan. All of these create unwanted points for features that can distract the algorithm from computing desired outcrop parameters. These would not be as big of an issue for a robust version of the algorithm, but under current development, they must be factored out. One of the simplest ways to do this is with CloudCompare’s ‘segment’ function. The software allows the user to draw a box around a section of the data that should be kept. In this project, a 5 square meter section of particularly distinct layering without vegetation was chosen as shown in Figure 5.6, above. Both segmenting and subsampling are shown step-by-step and explained in Appendix A.3.4.

Georeferencing with GNSS Data

The final step in pre-processing point cloud data for estimating morphological parameters is to incorporate GNSS data. GNSS data for this project was collected with the Trimble R8 kinematic system and processed with RTKPOST, RTKPLT, and Google Earth. The three hour survey included placing the GNSS base station at the first scanner position, station1, and walking around the scene with the GNSS rover to gather positions of the targets and other stations. Due to the mountainous landscape of the scene, often signal was not strong enough to ensure full quality achievable by the system. The result of the survey at La Charce is shown in Figure 5.7. As shown, the formation is facing eastward toward the road that winds around it. A river is east of the road and a parking lot can be seen to the north. Data points are shown in three colors indicating quality (red = poor, yellow = moderate, green = good). More information on data quality of GNSS data can be found in section 3.2.

A vector has been drawn from the GNSS base station to the location of one of the target points, ‘t33’ in Figure 5.7. It is oriented just south of west, globally, with reference to the north arrow pointing up on the map. In theory, this vector should match the vector drawn between the same two locations in the Matlab plot of the scene (assuming that the ‘x’ axis indicates south-north and the ‘y’ axis indicates east-west). However, Matlab takes the imported local coordinates from the laser scanner station1 as its orientation. Orientation is relative to an arbitrarily chosen ‘north’. Figure 5.8 shows a polar plot displaying both vectors in their own coordinates systems. The blue ‘global’ arrow is the direction indicated in Figure 5.7, just south of west. The red arrow shows how the outcrop is oriented in Matlab, or ‘local’ coordinates, pointing just north of west. Since the GNSS-referenced global points are correctly georeferenced, the Matlab coordinates need to be transformed to match. Although the angle is small (13 degrees), it will add to errors in outcrop orientations estimates if not adjusted.
The angular difference between the GNSS and Matlab orientation vectors can be eliminated with a counterclockwise, rotational coordinate transform about the 'z' axis (assuming the scanner was leveled) by the 13 degrees between the two vectors. The coordinate transform is defined as follows:

\[
\begin{bmatrix}
  x' \\
  y'
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
  x \\
  y
\end{bmatrix}
\]  

(5.1)

where \([x, y]\) are the local point coordinates in Matlab, \(\theta\) is the rotation angle, and \([x', y']\) are the new global, georeferenced points. Since the scanner was leveled, 'z' coordinates remain the same. Figure 5.9 shows the resulting coordinate transform on the point cloud in Matlab (x is north-south, y is west-east).

Figure 5.8: The angular difference between GNSS coordinates on Google Earth and local scanner coordinates in Matlab of the orientation vectors. Scanner coordinates in Matlab need to be transformed to true GNSS coordinates for actually estimated strike, or outcrop orientation in Matlab.

Figure 5.9: Matlab coordinates (a) before and (b) after the global coordinate transformation. This top view shows the tiny La Charce outcrop section in the lower left along with locations of the GNSS base station and target #133. The scan station 1 location is also shown for reference, as the coordinates come from its perspective. All points were rotated about the scanner station, 'x' is north-south, 'y' is west-east, and 'z' is constant up since the scanner was leveled.
As can be seen in Figure 5.9, the GNSS base station to t33 vector now lies just south of west, as well, and both vectors are now equally pointing toward a compass direction of 261.06 degrees. With the point cloud registered, decimated, cropped, and georeferenced, calculations necessary for extracting features can begin.

### 5.3.2. Defining Bedding Layers

The data manipulation phase involves all processing in Matlab leading up to estimating parameters. For a manual algorithm, this step, or at least a majority of it, would not be necessary since points would be selected by the user and then analyzed. The goal of this project’s algorithm, however, is to automate this process. The goal is to simply input the outcrop along with several parameters in order to receive information about that outcrop’s dip direction, dip, and layer thickness (composition). The following method describes one solution for calculating the planar features of the outcrop (the top and base of the limestone layers). Planar features are needed to estimate the dip and dip angles of the bedding planes. There are many methods for extracting planes within a point cloud, but this method was chosen for its relatively simple execution but sufficient to good results that fall within 5 degrees of field measurements. With the planar features, the third and final phase of the algorithm aims to discern rock type and present desired parameters.

#### Calculating and Sorting Normals

In this project’s method, the first step in extracting planar features is to calculate local surfaces normals per point. Several built-in Matlab algorithms already do this, so the first attempt was to try the `pcnormals` function within the Computer Vision System Toolbox. This function takes the 6 (or whatever the user specifies) nearest neighboring points and fits a local plane through them based on least squares best fit through principal component analysis (PCA). PCA minimizes the orthogonal (perpendicular) error to determine principal component vector directions, an example from 50 neighboring points of the La Charce outcrop is shown in Figure 5.10.

![Figure 5.10: Planar fitting is accomplished using least squares best fit through principal component analysis (PCA). The plot shows a subset of the La Charce outcrop point cloud in 3D. A gray plane has been fit to the points using PCA, which minimizes the perpendicular distances of points to the plane. Points above the plane are shown in blue, points below, in green.](image)

In 3D, the planar normal is the third eigenvector of the covariance matrix and the orientation (either positive
or negative) is based on nearby normal estimates [Hoppe et al., 1992]. Hoppe et al. [1992] also presents ideas for automatically determining the number of nearest neighbors to based on an analysis of an unstructured point cloud. Here, six points were chosen to keep the normals local and to reduce the smoothing effect of selecting too many points. Also, the surface that a compass covers when manual measurements are taken is approximately five centimeters long. It was estimated that six nearest neighbors give a similar surface area for comparison and validation since compasses are considered accurate instruments in the field. Other planar measurements throughout the algorithm require different amounts of nearest neighbors based on the goal of that particular step.

The normals resulting from the algorithm, see Figure 5.11, appear to be perpendicular to the surface as expected. They are local normals and thus capture the curvature of the shape. The normals of bedding layer edges point one direction while those of the tops and bases point nearly perpendicular to the edges. This dichotomy will lead to the next algorithm. For now, one thing to note is the fact that the normals point both 'in to' and 'out of' the point cloud regardless of the attempt to align with neighbors.

![Figure 5.11: Point normals were estimated from six nearest neighbors. A subset of these normals are plotted in the La Charce section in blue. The (a) rotated front view and (b) top view show normals facing both the 'front' and 'back' side of the point cloud. The blank space behind the back side of the point cloud does not exist in reality since the point cloud is only a surface shell while the outcrop is composed of solid rocks.](image)

Although this is not necessarily a problem, sorting the normals to all face 'out of the outcrop' can help organize the results and make layer extraction easier later on. To do this, a 'scanner' location point was defined in the middle of the front side of the outcrop section. The angle between a vector pointing from the 'scanner' location point to the point in question and the vector normal was calculated. If the measured angle was not between −90 and 90 degrees, the signs of the normal were switched. The resulting vectors are shown in Figure 5.12, below.

To better visualize these normals and differences once they have been adjusted to face the scanner, a polar histogram of the normals for both cases are plotted in Figure 5.13. They show the compass direction as well since it is not easily evident on the 3D outcrop plot.

Bins are displayed in six degree increments. These normals are expected as can be verified with the Google Earth, georeferenced GNSS image in Figure 5.7. It appears from the adjusted plot that the largest occurrence of data due south is primarily the result of the top (and some of the bases) of the limestones, while perpendicular to that and due east, the edges of both rocks are apparent. This interesting result foreshadows to point
5. Geometric Characterization

Figure 5.12: Again, a section of the La Charce outcrop showing point normals in blue. Normals have been adjusted to face the ‘scanner’, or red point, so they more closely fit reality (all face outward). The plots show a front view (a) along with the same plot rotated to a top view (b).

Figure 5.13: A polar histogram of all georeferenced point normals on the La Charce section. Plot (a) shows the raw estimated normals from Figure 5.11 and plot (b) shows the normals after their transformation outward, Figure 5.12.

extraction based on patterned normals, which is precisely the next proposed sub-step followed.

As hypothesized, the top bins of the angular histogram correlate with the points on the top and base of the limestone beds. To test this, the points in the top three bins were extracted and plotted. If the plot is rotated, Figure 5.14, the bedding layers appear quite distinctly and the edges of both rocks seem to mostly be filtered out.

This result is already promising considering the bedding planes are present and distinguishable. However, not all points plotted belong to the desired dataset of limestone tops and bases. Some ‘cleaning’ should be done to the extracted data to limit these unwanted points and to better define the planar features.

Filtering Out-of-Plane Data
5.3. Characterization Work Flow

The cleaning or filtering of the dataset shown in Figure 5.14, above, was approached by first consulting the Computer Vision System Toolbox in Matlab. The function \texttt{pcdenoise} was first developed for removing sparse outliers caused by measurement error in the laser scanner [Rusu et al., 2008]. Although the undesired points in the plot are most likely not due to scanner measurement errors, the method still seemed applicable and was thus tried. Two inputs allow the user to specify how the cloud is filtered: number of nearest neighbors to consider and the threshold for keeping or getting rid of a point. After experimenting with different values for each input variable, the best results in this case came from using 6 nearest neighbors and a threshold of 0.02 meters. Decreasing the neighbor count makes the filter more sensitive to noise while decreasing the threshold more strictly defines planar limits. The function calculates the mean of the distance from each point to its nearest neighbors. If that mean value is greater than the threshold, the point is thrown away. A discussion of these input parameters can be found in Chapter 8. The resulting filter is plotted in Figure 5.15, below, and shows retained points in black, filtered points in red.

The remaining points now define the tops of limestones and can be used to calculate the first primary plane.
Planar Fitting with Sedimentary Layers

A final function from Matlab’s Computer Vision System Toolbox was utilized to recognize the most defined planar feature among the remaining points. This function is called `pcfitplane` and uses the M-estimator SAmple Consensus (MSAC) algorithm, a variant of the RANdom SAmple Consensus (RANSAC) algorithm. This method uses the same sampling strategy as RANSAC, but chooses the solution to maximize the likelihood rather than just the number of inliers [Torr 2000]. The RANSAC method can be broken down into four main steps:

1. Randomly select a subset of points in the dataset
2. Fit an ordinary least squares plane to the selected subset
3. Determine the number of outliers (or maximum likelihood, in this case)
4. Iterate steps 1 to 3 until the best-defined plane is recognized

This function has three input parameters that help guide the algorithm: the maximum distance, a reference vector, and the maximum angular distance. The maximum distance refers to the maximum distance an inlier point can be to the calculated plane. If the point distance is beyond the input parameter, the ‘inlier’ becomes an ‘outlier’. A reference vector is used as a-priori information that assists the algorithm in locating a desired plane. The maximum angular distance is the maximum absolute angular distance between the normal vector of the fitted plane and the reference vector orientation. It is recommended to iterate this entire function for finding a good reference normal and to balance it with the threshold parameters. For the La Charce outcrop, a maximum distance of 0.05 meters was used along with a maximum angular distance of 5 degrees from the estimated vector of [-0.84, -0.33, 0.42]. Of course, these parameters were varied to converge on optimal settings for plane extraction. The resulting plane is plotted in Figure 5.16, below.

This new calculated plane is now the best estimate for consecutive bedding layers as well. Each of the layers can then be distinguished separately by calculating the distance from each point to the estimate plane. If the
distances are then plotted in a histogram with the same amount of ‘bins’ as planes expected, each histogram bin will contain the points closely equidistant (including signs / direction) from the estimate plane. New planes were then calculated again using principal component analysis as described in section 5.3.2 for all points per bin. The distance of all point cloud points to these defined planes, within a tolerance of 0.1 meter, determined which points fell into one of these top limestone layer planes. The results are plotted in Figure 5.17, below.

Figure 5.17: Each consecutive plane estimated from RANSAC plane model (Figure 5.16) and binned points. Tops of limestone bedding planes are individually defined and plotted on the La Charce section decimated point cloud. Planar points grouped by color.

Since only the tops of the limestones were extracted in this step, the remaining points belong to both the limestone bases and the edges of the limestones and marls. The method described above was then repeated for this remaining point cloud. The normals were calculated per point and compared. Top bins, again, represented the bases of the limestone and were thus extracted and planar fit with tolerance. The tops and bases were sorted with the point to plane distance measurements described above. The remaining points can be classified as layer edges. At this point, the planes have been determined so parameter estimation, the final phase, is possible.

5.3.3. Geological Parameter Estimation

The final phase of the algorithm involves calculating the desired parameters. With planar normals already defined, the dip and dip direction are easily derived. However, the challenge comes when measuring layer thicknesses. First, the layers must be divided between limestone and marl. The methods involved in doing this are built off of the point to plane distance calculations completed in the previous phase. Identifying the rock type is key and three methods are explored here. With the two classes of rock, layer thickness can be calculated and compared.

Calculating Dip and Dip Direction

The dip angle and direction can be derived from the planar bedding surfaces of the outcrop. normal of the bedding surface. From the planes, the perpendicular vector point outward from the planar surface, the normal, was defined. The normal and the planar surface then define the strike line, or the line on the plane both
perpendicular to the normal and perfectly horizontal \((z = 0)\) to the ground since the scanner was leveled. The dip direction is also perfectly horizontal \((z = 0)\), but instead projects outward from the planar surface in the direction of the normal and perpendicular to the strike. Finally, the dip vector extends down to the planar surface of the bedding layer perpendicular to both the normal and the strike. The dip angle is then the angle between the dip direction vector and the dip vector. Figure 5.18 shows a visualization of these parameters.

The dip angle and direction were estimated for each of the top surfaces of the limestone beds. The dip direction was also estimated using bases of the limestone beds. These two parameters characterize the orientation of the outcrop, while the last desired parameter, the layer thicknesses, help to characterize the history of the region providing clues to the climate cycles occurring during formation of the beds.

Calculating Layer Thickness

The thickness of bedding layers can be estimated in many different ways. The method chosen for this project was to take a horizontal cut section at \(z = 3.5\) meters (half way through the sample section). Points were located along this cut section at the outer edges of the bases (and tops, just for visualization) of the limestone layers. Since the planar estimate of each top (and base) was previously calculated, the normal vectors were used to calculate the minimum distance from an edge point to the nearest top plane. The measure direction (either measuring to the nearest point before or after the plane in the x-direction) determined if the thickness was limestone or marl, manually. This method, with limestone layers colored blue and marls, green, is illustrated in Figure 5.19. The measurement points along the z-cut section are shown by the black circles for reference (both on tops and bases).

Another method could be to take several cut sections and average the extracted values. Using the point to plane measurement method requires an accurate plane estimate. Since only this small section was used and distances were measured to planar features, the middle of the sample is considered representative.
5.4. Error Budget

In addition to the errors gathered during field measurements, new errors arise throughout the work flow. These are errors that are expected to impact the final parameter estimations. Below is a list of expected errors, or at least considerations, for the previous steps mentioned:

- **Registration**: Accuracy depends on how well the targets were constrained, typically target merging has over 5 mm error but errors over 15 mm were not accepted. This is another reason that having extra targets is helpful; you never know until post-processing how well individual targets sustained.

- **Decimation and Cropping**: While decimation removes data that could be useful, the decimated point cloud is only used for testing purposes, so any incurred errors do not affect final estimations.

- **Georeferencing**: The GNSS system used is reportedly accurate within 1 – 2 cm. Considering the accuracy of the laser scanning is around 6 mm, this is a significant error. However, georeferencing only affect the dip direction or strike estimates as they are the only ones relative to global coordinates. It will not affect the accuracy of points to each other.

- **Calculating Normals**: This error quantity is difficult to evaluate as the true plane is unknown and imperfect as it is an artifact of millions of years of natures forces. An additional precaution could be to calculate planar normals several times to statistically determine the 'best' normals. Trying different numbers of nearest neighbors could also help define the best plane. For now, this steps error is considered negligible.

- **Filtering**: Errors in filtering can occur when too many points are removed. However, when the entire point cloud is added back in an re-analyzed, the errors are lost again. This is just a preliminary step and is also considered to have a negligible effect on the quality of the estimation.

- **Planar Fitting**: The final step of planar fitting contains the inherent errors discussed for calculating normals. The choice of threshold and nearest neighbors will have an effect, but again, the true plane cannot be know exactly. The more points, the better the quality of the estimated plane.

Thus, the largest errors to considering during the work flow, post-processing phase is the effect of both GNSS accuracy and registration. Combined they give an expected error of around one centimeter for dip angle.
estimates, two to three centimeters for dip direction, and also up to two centimeters for layer thickness since
both planes could have errors. Estimated planes are in the range of several meters so the expected errors are
still reasonable.

5.5. Summary

The developed automated algorithm is a three phase work flow that takes an input 3D outcrop point cloud in
Matlab, along with several other input parameters, and calculates the dip, dip direction, and layer thickness.
Methods such as RANSAC, PCA, and selective filtering were employed both through Matlab toolboxes and
in-house developed Matlab scripts. Many limitations apply, but for the test case of La Charce, the chosen
methods estimate these parameters with an expected error of a few centimeters (and could quite possibly be
more accurate). The results and a discussion of the advantages and drawbacks of the algorithm follow.
3D Virtual Environments

The goal of this thesis was not only to collect 3D point clouds of rock outcrops and to analyze them, but also, to communicate those results through an intuitive interface. One of the most suitable platform interfaces for communicating laser scan data is through 3D virtual environments, a computer-based realistic look into the collected field data. In this chapter, various platforms will be compared and contrasted with respect to optimal and desired platform criteria. The primary investigation aims to address:

In what ways can the results be communicated in order to demonstrate the additional value of characterized 3D close-range measurements?

The final part of this chapter presents a working platform, chosen by the best ranking criteria, of the collected outcrop data. Its feasibility for local viewing on the 3D stereo projector is also evaluated. Recommendations are provided for communicating 3D outcrop data to various audiences.

6.1. Motivation

The first part of addressing this data communication is determining who benefits from the results and what additional value they derive from them. Really, who are the stakeholders? The primary goal of communicating close-range lidar results is to locate, visualize, and enable manipulation of the data, or realistic scenes as in the case of outcrops. An ideal virtual, realistic representation is a 3D model of the scene that expresses all that exists in the actual landscape in proper scale and color. Additionally, these 3D virtual environments can take users to viewpoints that could be difficult or impossible to reach in normal circumstances in the field or even while back in a laboratory. For instance, with a 3D virtual outcrop model, the user can zoom in to a specific fault line or 'climb' to the top of the outcrop to learn about its features without actually leaving the laboratory. The entire scale of the outcrop can be analyzed, not just the area that the geologist could reach. The results are repeatable and the user can always re-visit the space, unlike time and monetary constraints that limit repeated fieldwork surveys. In this way, the model is useful for scientists, researchers, and especially students. Scientists and researchers can use the data for added value to studies of the Earth and the built environment where field observations alone are not sufficient or accurate enough. The 3D realistic view can give students a unique and collaborative grasp of the geological formations right in the classroom, a good pre- and post-analysis platform for gaining added insight to fieldwork experiences.

Additionally, a chosen data communication platform is also limited by the availability of facilities and equipment. The 3D virtual reality lab in the faculty of Electrical Engineering, Mathematics and Computer Science has a stereo projector and 3D glasses for viewing. This setup used for outcrop representation has been demonstrated by Waggott et al. [2005] in Figure 6.1, below, and is a virtual environment possibility at TU Delft.
Ideally, users should be able to interact with the model or platform, given the ability to select surfaces, define lines, and/or measure a particular feature’s dimensions and orientation. Specific model criteria can be assigned that meets the needs of the targeted users. These criteria will then narrow down the best options for communicating virtual outcrops in this project.

### 6.2. Criteria and Requirements

Sharing data can be indispensable to innovation and education, but data alone is not always the most helpful. Useful data is communicated well, can be easily re-shared, and ideally fits a protocol including other data for validation. With the outcrop data gathered in this study, there are three subsets of data that will need to be represented within one virtual environment: the location and orientation data of each outcrop within the region, the 3D geometry of the outcrops themselves, and all measurements associated with geometric features extracted from the outcrops. The following section defines the necessary criteria of accurately representing each of these subsets along with general requirements of a virtual environment that communicates the data effectively.

#### 6.2.1. Geo-referenced Outcrop Locations

The first subset of the collected outcrop data contains the location and orientation of each of the 10 outcrops measured. The latitude, longitude, elevation, and orientation of the outcrop, within 1–2 centimeter accuracy, was obtained with GNSS.

An effective representation of this data alone could be as simple as a customized Google map or any other 2D spatial model. The primary purpose is to communicate the outcrop locations in relation to one another both in distance and in setting. The application of the data determines most of what is necessary to show, but since this projects data will most likely be used for geologic analysis, it is important to have an interpolated terrain background (incorporating the elevation of each outcrop) and the orientation. This additional data gives clues to the processes that both created and exposed specific outcrops. They are not individual, unconnected entities. An example of displaying this subset is with the Google map pictured in Figure 6.2.

The outcrop locations relative to each other are clear from the geo-referenced terrain map. Outcrop orientation is not shown in this representation, although on the zoomed-in image in Figure 6.2(b), the orientation can be visualized from the terrain background. Thus, the key criteria for communicating this subset of data is:
6.2. Criteria and Requirements

Figure 6.2: A Google Earth topographical map of the present day Vocontian basin in southeast France showing outcrops that were scanned during fieldwork for the project. The map is a 2D representation of (a) the outcrops locations shown in red and (b) a zoomed-in portion of the map that shows surrounding terrain in detail. Outcrops are marked in green, roads are shown in white with yellow labels. Scale is shown in the bottom left.

- Locations (relative and global)
- Background / Setting
- Multiple Outcrops

A 2D map of the relative locations and outcrop settings communicate numerical data visually. Another, less important criterion of this subset is the view and manipulation. As seen above, the virtual environment should enable zooming and panning capabilities. Zooming out should quickly orient the user to the region of study while zooming in shows details in the terrain around the selected outcrop sites. Easy panning or ‘fly-through’ options give the user quick manipulation to filter only to their region of interest. Google Street view adds a ‘walk-by’ option for more realistic views of the outcrop locations. A 2D map or Google customized map handles multiple data points and large interpolated spaces well. However, our full dataset also contains 3D point clouds with much more detailed information (such as $XYZ$ positions and true colors) on the outcrops than Google provides. Thus, this second subset should also be utilized fully.

6.2.2. 3D Outcrop Geometry

The second set of criteria for communicating outcrop data is to consider the subset of data containing only a 3D point cloud of an outcrop. This subset consists of $x$, $y$, and $z$ coordinate points from the local origin of the laser scanner, a laser intensity return, $i$, for each point, and corresponding RGB values collected by the laser scanner’s internal camera. This type of data would not be well-represented on a 2D Google map, for instance, because the wealth of the information lies in the 3D nature of the returned points. The 3D colored point cloud gives detailed information about the geometry of the outcrop and view as to how it looks in reality. Its relation in space and to its surroundings are not as critical for this criterion. Figure 6.3 shows a raw imported point cloud colored according to the intensity return.

These data, displayed with Leica’s Cyclone software, can be rotated, zoomed, and panned for various viewpoints of the geometry. These give both a realistic and intuitive look to the virtual representation of an outcrop. Additionally, several options are available for post-processing within this platform such as registration of multiple scans and 3D cropping (or ‘fencing’, as it is called in the software) of unnecessary data. CloudCompare is a software that enables similar options along with more post-processing functions such as auto-decimation, feature identification, and clustering. Both of these software platforms lead to the key criteria for displaying 3D outcrop geometry:

- 3D Manipulation (zoom / pan / rotate)
6.3D Virtual Environments

Figure 6.3: The resulting point cloud, viewed looking south, of the La Charce outcrop colored by intensity return in Leica’s laser scanner software, Cyclone. Intensity return values range from high: green, yellow, orange, to red: low. Black points are missing points that had no intensity return.

- 3D Detail Display
- Realistic Quality (shape, colors)

However, unlike Google Maps, Cyclone and CloudCompare data files are not available by a shareable link online. Users must have the software in order to view and manipulate the files. They do not enable multiple outcrop views (without significant rendering times) nor have background data, such as terrain elevation, to place the outcrops within a setting. As shown, Cyclone and CloudCompare are excellent resources for communicating the subset of 3D point cloud data, but not the region outcrop settings.

6.2.3. Geometric Measurements

The final key subset to communicating the full outcrop story is to visualize and quantify key geometric measurements such as sedimentary layer thickness, orientation, and rock roughness. These parameters can give geologists and students further clues as to the formation setting, possible deformations, and post-deformation processes of the region. Measurements such as these can be taken in the field, but a 3D virtual representation of the data allows for both validation and a more complete coverage as some parts of an outcrop are inaccessible.

As a research or learning tool, virtual outcrops need to be both interactive and customizable when it comes to measurements. The software should be interactive in the sense that the user can define or toggle measurements that are useful for their particular purpose. Extra information, such as knowing the exact thickness of every sedimentary layer labeled on the outcrop, can make the model busy and too difficult to interpret. The user should be able to select the necessary information to display and be able to change those selections for different studies or views. This also makes the software customizable. Users should also have the option to save and export defined measurements. This enables a more streamlined work flow since daily results can easily be returned to and assists in data sharing.

Finally, a good virtual outcrop platform would incorporate built-in tools that help users extract the measurements they need. Typically for outcrops, researchers and students are interested in the geometric features listed above: sedimentary layer thickness and planar orientation angles (specifically strike and dip). A plane can be defined simply by three points; with an interactive software, there could easily be a tool that allows the user to pick three points and the software draws the plane and gives information about that plane’s orientation. Distances can also easily be measured from planes, lines, and points. This could also be a helpful tool in a virtual outcrop viewer. Thus, the following criteria outline some ideal characteristics of 3D geometric
measurement software:

- Interactive Measurements
- Customizable
- Built-in Outcrop Measurement Tools
- Save / Export Measurements

One such software that enables customized and interactive outcrop measurements is Matlab. The view in Figure 6.4, below, shows a small cut section of the La Charce outcrop. Matlab cannot handle large datasets or point clouds, but for testing, it is very versatile and customizable platform.

![Figure 6.4: Matlab's 3D viewer showing a section of the La Charce outcrop in true color. True color is derived from the RGB values gathered by the laser scanner's internal camera. Additionally, points and vectors not belonging to the outcrop itself can be imposed on top easily.](image)

Matlab requires both obtaining the software and the knowledge and experience of basic programming in order to make full use of its customizing features. As shown in the figure, strike and dip angles can be calculated from the planar surface of a sedimentary layer (along with other measurements such as the plane's normal and horizontal direction). The visualization is good and many online resources are available to aid in calculating these measurements. A specific outcrop toolbox is not built-in to Matlab but there are tools for working with 3D point clouds. Matlab is not visually intuitive as the representations are not interactive and are only displayed after running the code that defines them. This can be an issue for users unfamiliar or uncomfortable with programming language. Overall, Matlab fits most of the criteria for 3D geometric measurements quite well, but again, incorporating the full setting and multiple outcrops is still a challenge as subsampling only works well initially, but the full dataset is desired for viewing.

6.2.4. General Requirements

In addition to communicating each of the three subsets of collected data properly, several other criteria can determine whether or not a virtual environment is suitable. The first consideration, as mentioned earlier, is the target audience. Scientist, researchers, and professionals in industry generally collaborate on teams or...
present findings that others may use. In this case, the virtual environment must fit for a ‘global’ audience meaning that the data can be easily shared or passed on from one person to the next. An online database is especially suited for this purpose. In the case of teaching, however, the ‘local’ audience or students just need access or possibly a single representation that the teacher can show. Here, using software and files on a local computer fills the demand adequately. The target audience determines the level of sharing required. Since sharing to some level is inevitable, file size, file storage, and data hosting becomes another key criteria. Global online software may allow uploads but the file size is usually limited or a personal server for hosting is required. With local environments, file size can be a major limiting factor due to the typical amount of data collected in laser scans. Many methods can help reduce file size, such as surface triangulation and point decimation, but this should be considered when choosing the most suitable platform. Finally, and intuitive design is best when sharing and communication is the goal. Users should be able to easily navigate the outcrop data and be able to visualize its location, setting, geometric features. To summarize, these additional criteria should be considered:

- Intuitive
- Sharing and Audience
- Free File Storage / Hosting
- Input Effort

Keeping these criteria in mind, the following section proposes several additional platforms that do well at communicating one or more of the subsets of outcrop data collected. All considered platforms will be compared, contrasted, and given a ‘grade’ based on how well they meet the desired criteria for 3D representation.

6.3. Virtual Platform Comparison

There are several solutions available for communicating the subset results of characterized 3D close-range measurements, or 3D point clouds, in our case. This section explores four viewing platforms, in addition to Cyclone, CloudCompare, and Matlab mentioned in the previous section. The four ‘new’ platforms demonstrate a more holistic approach to outcrop modeling whereas the others focused on presenting only one or two subsets very well.

The first, briefly covered before, is Google Earth. It handles nearly all criteria quite well except for the difficulties of uploading your own 3D data. Since this is one of the most important factors, along with measurements that are not handled well either, Google Earth is not recommended for communicating all data gathered during the fieldwork. The map in Figure 6.5, below, does illustrate the best example of location setting and easy-to-share information of the four evaluated platforms.

The second, a versatile 3D point cloud viewer, is called PoTree. Figure 6.6 shows just one basic example of a 3D landscape displayed in the environment. As shown, the point cloud is only an imported entity that ‘floats’ in space, and its lack of options for placing multiple outcrops within a blended setting is considered a negative for this project. However, it is an open source program and has an active user base working on developing new functions such as ‘georeferencing’, as shown by the linked map below Figure 6.6(a). The visualization and rendering is great in comparison to Matlab, as are the manipulation controls. Several customizable options are available to change properties such as point size and interpolation. Files need to be stored on your own server, which can be a draw back. Overall, the platform displays raw 3D point clouds effectively, with customizable features, and is easily shared online.

Safari is an online database for outcrop data, centered around sharing geological information about outcrops worldwide. It also has the option to including 3D outcrop meshes to aid in the understanding of the outcrop. This database is private and can only be accessed by creating a user account. Outcrops are documented on the site based on published research and the 3D visualization may accompany this data. The viewer, as shown in Figure 6.7, is very similar to PoTree. It is intuitive, easily manipulated, and displays outcrops in customizable detail. Point clouds must be converted to triangulated meshes and then photo draped for
6.3. Virtual Platform Comparison

Figure 6.5: Online customizable map from Google showing outcrop locations, detailed metadata, added notes, and embedded images of the outcrops, both shareable and public with a link.

Figure 6.6: One example of the PoTree online interface showing a point cloud with associated (a) RGB colors and (b) real satellite image colors taken from Bing Maps.

realistic effects. The problem with this method is demonstrated by the warping of the outcrop in Figure 6.7(c). Multiple outcrops can be added, as in Figure 6.7(b), but no interpolated space in between is mapped. The platform gives nice visualization but does not allow for adding measurement information.

Finally, another platform developed by Uni Research CIPR in Bergen, Norway, called LIME will also be considered. Unlike Safari, LIME is not a database, but instead, a software used locally on your machine. Its primary purpose to create insightful visualizations of 3D rock outcrops. Figure 6.8 shows one example of how LIME can be used to distinguish bedding layers within an outcrop. It is extremely versatile as any colors, designs, or notes can be projected on to the 3D surface of the outcrop. Again, the outcrop appears to float in space but a bottom plane can be added with a map projected on to it. Sharing can be done locally by sending LIME files or
through its built-in stereo projector mode. Raw point cloud files must be converted into triangulated meshes (and photo draped for a realistic look). Overall, the platform provides excellent 3D visualization compared to the others.

Figure 6.8: An example outcrop with annotated and color-coded bedding layers and a stratigraphic column superimposed for more information in the LIME software [Virtual Outcrop Geology Group, 2016].

Combined, each software offers its own advantages and disadvantages. Table 6.1, below, summarizes a personally assigned grade based on user-experience and the specific criteria defined for this project. The scores range from ‘–’, not meeting the criteria at all, to ‘++’, a perfectly met criteria. Summaries of each criteria category are added to the heading rows. The final summary is simply an average of all of the category scores. No weighting was applied since most criteria are equally important for this project.

<table>
<thead>
<tr>
<th>Criteria (key: bad – o ++ good)</th>
<th>Google Earth</th>
<th>Cyclone, CloudCompare</th>
<th>PoTree</th>
<th>Safari</th>
<th>Matlab</th>
<th>LIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo-referenced Outcrop Locations</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Locations (relative and global)</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Background / Setting</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Multiple Outcrops</td>
<td>++</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>3D Outcrop Geometry</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>3D Manipulation (zoom / pan / rotate)</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>3D Detail Display</td>
<td>–</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Realistic (shape, colors)</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Geometric Measurements</td>
<td>–</td>
<td>–</td>
<td>o</td>
<td>o</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Interactive Measurements</td>
<td>–</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Customizable</td>
<td>++</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Built-in Outcrop Measurement Tools</td>
<td>–</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Save / Export Measurements</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>General Requirements</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Intuitive</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>–</td>
<td>++</td>
</tr>
<tr>
<td>Sharing</td>
<td>++</td>
<td>–</td>
<td>++</td>
<td>+</td>
<td>–</td>
<td>o</td>
</tr>
<tr>
<td>Free File Storage / Hosting</td>
<td>++</td>
<td>–</td>
<td>++</td>
<td>–</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>Input Effort</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>–</td>
<td>o</td>
</tr>
<tr>
<td>Summary</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>

As illustrated, the clear top contenders for communicating the subset of georeferenced outcrop locations are both Google Earth and Matlab. Inherently, Matlab would not score high in this category, but it is extremely flexible and customizable with the option of importing Google maps into the Matlab environment. Thus, a
Google Earth map and the imported Google map in Matlab are quite similar in the sense of those criteria listed.

In the sense of representing 3D outcrop geometry, the online platforms of PoTree and Safari, along with software-based Cyclone, CloudCompare, and LIME, do an adequate job. Manipulating 3D data is very key in making the experience feel realistic. The controls should be intuitive and the rendering fast. Delayed motion and fuzzy outcrops do not enhance the understanding of the outcrop.

Measuring geometric features of outcrops in 3D has proven to be a rarer option in virtual outcrop environments. The only two options that really represent morphological features are LIME and Matlab. Although LIME does not actually measure features numerically, it allows the user to draw, color, and add notes to visually call out individual features. Matlab numerically computes measurements, but they are not visually represented well and require a sufficient time and knowledge to calculate.

Finally, general requirements not covered in the previous subsets showed a range of fulfillment across the board. Google Earth scored highest due to its strength as a commonly used, online database already. People are familiar with the platform, especially with Google maps, and they know how to upload and share this information. The others take some experience to become comfortable with using the platform. Overall, as highlighted in red in Table 6.1, most virtual environments evaluated do a 'neutral' or 'average' job of representing a 3D outcrop in one aspect or another. LIME stands out as the only platform that scored a 'ok' or 'good' score. Thus, a demonstration of the La Charce outcrop in LIME is presented in the results, Chapter 7.

6.4. Summary

Characterized morphological, 3D, close-range measurements can give geologists hints to the formation of rocks in an outcrop, their age, and even possibly the processes that have led to their exposure. The morphological parameters, such as strata orientation and thickness, are just numbers that tell the trained ear about the specific outcrop. However, this data can be better communicated, especially in the case of education where raw numbers without context can be difficult to visualize. Six 3D virtual platforms were analyzed and were rated based on their fulfillment of desired outcrop modeling criteria. In the end, the LIME software is recommended as the best communicator for in-house sharing based on its excellent representation of 3D geometric measurements, its customizable features, and clear display of 3D geometry.
Results

The three-phase work flow demonstrated in Chapter 5, along with the analysis of virtual environments in Chapter 6, lead to the estimation and representation of 3D outcrop characteristic features. These features give insight to the formation and evolution of the specific outcrop, which in turn, can begin to describe past climates or cycles that occurred many years before in that geographic region. The selected extractable features were chosen for this purpose and, since they are also features measured by geologists in the field, provide a good basis for comparison and validation. The virtual representation of the sample outcrop (La Charce) is also included as it proves to be the best available platform for the purposes of communicating 3D outcrop data.

7.1. Geometric Features Extracted

Three characteristic geometric parameters were chosen to be extracted from the point cloud: the dip, the dip direction or strike, and the layer thickness (percentage composition). These parameters are define by mathematical planes fit to each top and base surface of the limestone strata. For review, Figure 7.1 shows a schematic of the geometric parameters that will be extracted. The gray / tan top surface of the rock stratum is a mathematical plane derived from points measured on the actual rock surface. The dip angle is illustrated by the blue horizontal, intersecting wedge. The strike is shown by the line intersection of this wedge with the gray / tan planar surface. The dip direction is just an outward pointing vector on the surface of the blue wedge, perpendicular to the strike. Layer thickness is the perpendicular distance between the top and base surfaces of the gray / tan and orange layers, for example (not shown).

![Figure 7.1: A schematic showing several geometric parameters of an outcrop. The blue wedge illustrates an imaginary horizontal surface while the tan, orange, and green layers represent rock strata. The dip angle, dip direction (or strike), and the layer thicknesses (not shown) will be considered in this study. (Earle, 2015).](image)
The following sections present the resulting values for these three parameters along with the statistics summarizing all layers in the outcrop sample. Again, the outcrop sample is simply a small 5 x 5 meter representative section cut from the full, merged La Charce outcrop. Results gathered by Bachelor’s students during the fieldwork are also included for comparison and validation. The similarities and differences are discussed in Chapter 8, following.

7.1.1. Limestone Top and Base Planar Estimates

The top and base surfaces of the limestone strata were estimated with planes as described in Chapter 5. The plot in Figure 7.2 shows a limestone top decimated point cloud from the La Charce sample outcrop. The distances of point cloud points to the estimated plane are visualized as colored, see color scale to the right. As noted, rocks are not perfect planes and the geometry can be seen more clearly here.

![Figure 7.2: A top limestone bedding layer plane extracted from the La Charce sample outcrop. Points are colored based on distances to the estimated planar fit. Distances are not spatially distributed equal as the rock is an imperfect surface.](image)

The estimated normals from these planes are described in the tables below. An average of the U, V, and W normal components was calculated, then, along with the angular difference of each planar estimate to the average plane. The top surfaces are shown in Table 7.1.

<table>
<thead>
<tr>
<th>Normals</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>Mean Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>-0.816</td>
<td>-0.828</td>
<td>-0.832</td>
<td>-0.819</td>
<td>-0.828</td>
<td>-0.819</td>
<td>-0.842</td>
<td>-0.845</td>
<td>-0.829</td>
</tr>
<tr>
<td>V</td>
<td>-0.373</td>
<td>-0.341</td>
<td>-0.339</td>
<td>-0.372</td>
<td>-0.358</td>
<td>-0.380</td>
<td>-0.334</td>
<td>-0.330</td>
<td>-0.354</td>
</tr>
<tr>
<td>W</td>
<td>0.441</td>
<td>0.444</td>
<td>0.440</td>
<td>0.436</td>
<td>0.431</td>
<td>0.430</td>
<td>0.423</td>
<td>0.420</td>
<td>0.433</td>
</tr>
<tr>
<td>Diff.[deg]</td>
<td>1.419</td>
<td>0.940</td>
<td>0.908</td>
<td>1.189</td>
<td>0.300</td>
<td>1.646</td>
<td>1.488</td>
<td>1.809</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Similar results are shown in Table 7.2, this time for the estimated limestone base planes. As shown, top planes show less variation in estimated normal directions than the bases do. This could be due to the fact that many more points were available on the top planes due to the way the outcrop was exposed.
7.1. Geometric Features Extracted

Table 7.2: A summary of the final estimated planar normals for Limestone bases in the sample La Charce section. There is one column extra because the extracted planes begin count with a base and end with a base as well.

<table>
<thead>
<tr>
<th>Normals</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>15</th>
<th>17</th>
<th>Mean Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>0.868</td>
<td>0.856</td>
<td>0.885</td>
<td>0.735</td>
<td>0.862</td>
<td>0.847</td>
<td>0.850</td>
<td>0.816</td>
<td>0.870</td>
<td>0.8428</td>
</tr>
<tr>
<td>V</td>
<td>0.233</td>
<td>0.280</td>
<td>0.193</td>
<td>0.521</td>
<td>0.287</td>
<td>0.297</td>
<td>0.315</td>
<td>0.368</td>
<td>0.287</td>
<td>0.3104</td>
</tr>
<tr>
<td>W</td>
<td>-0.438</td>
<td>-0.433</td>
<td>-0.423</td>
<td>-0.435</td>
<td>-0.419</td>
<td>-0.440</td>
<td>-0.423</td>
<td>-0.447</td>
<td>-0.400</td>
<td>-0.429</td>
</tr>
<tr>
<td>Diff. [deg]</td>
<td>4.721</td>
<td>1.238</td>
<td>7.161</td>
<td>13.623</td>
<td>1.788</td>
<td>0.996</td>
<td>0.520</td>
<td>3.775</td>
<td>2.633</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The base planes were very thin and included significantly less points.

7.1.2. Dip Angle

The dip, as shown in Figure 7.1, is the acute angle measured from the horizontal (or flat xy-plane) to the planar surface of a bedding layer. Since the bedding layers of the sample outcrop were created by deep marine sediments (and there is no visible faulting or folds), they are assumed planar in the section analyzed. The dip angle is usually measured in the field using a geological compass with a clinometer. As instructed, several teams of Bachelor's students at this particular outcrop recorded the following dip data in Table 7.3:

Table 7.3: Anonymous student team dip angle measurements from the La Charce outcrop with mean and standard deviation.

<table>
<thead>
<tr>
<th>Team1</th>
<th>Team2</th>
<th>Team3</th>
<th>Team4</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dip (deg)</td>
<td>62</td>
<td>80</td>
<td>60</td>
<td>60</td>
<td>66</td>
</tr>
</tbody>
</table>

Of course, a high standard deviation can be attributed to the fact that this is a very small sample size of data gathered by students with varying levels of geologic fieldwork experience. Using the methods described through the work flow of the algorithm, a planar surface was derived for each bedding layer. Due to the way this outcrop was exposed, the tops of the limestone bedding layers were most distinct and, therefore, it was easier to estimate planes with higher precision using the algorithm. From the planes, the perpendicular vector point outward from the planar surface, the normal, was defined. The normal and the planar surface then define the strike line, or the line on the plane both perpendicular to the normal and perfectly horizontal \((z = 0)\) to the ground. The dip direction is also perfectly horizontal \((z = 0)\), but instead projects outward from the planar surface in the direction of the normal and perpendicular to the strike. Finally, the dip vector extends down to the planar surface of the bedding layer perpendicular to both the normal and the strike. The dip angle is then the angle between the dip direction vector and the dip vector. The resulting dip angles for each of the eight limestone top bedding planes are plotted in Figure 7.3, below.

Figure 7.3(a) shows a 3D representation of the outcrop sample with characterizing vectors added for an example bedding plane. The green vector is the outward bedding plane surface normal. The black horizontal line following the plane of the layer is called the strike. Perpendicular to this line on the outward facing horizontal is the dip direction vector in blue. Both the strike and dip direction are used to orient the outcrop in space with compass headings through georeferencing. Depending on the convention, compass degrees are used to describe these quantities as viewed from above the outcrop. The final vector is the red dip angle vector that is perpendicular to both the normal and the strike line. It lies on the surface of the bedding plane and defines the inclination of the layers with respect to the horizontal. This measurement is shown in more detail in the plot in Figure 7.3(b). Here, the outcrop has been rotated to face frontally, and the vectors are plotted on an adjusted polar plot with zero at the left `-x' and increasing degrees in the lower left quadrant. The dip direction has been aligned with zero degrees since it is horizontal and the normals and dip angles are plotted for each limestone top bedding plane. The resulting average dip angle of all 8 top limestone planes is 64 degrees (shown by the dashed red vector) with a standard deviation of 0.6 degrees.

Interestingly, if plotted by consecutive layers (and at actually distances), the dip angle increases with almost every layer as shown in Figure 7.4. This implies that each layer is getting slightly steeper (going right to left in the image).
7. Results

Figure 7.3: The results from estimating dip angles for each of the limestone tops. The 3D point cloud of the La Charce sample in (a) shows the illustrated dip angle vector (red), dip direction (blue), and strike line (black). The angular plot in (b) starts at zero to the left and increases downward. The vectors each bedding plane, as displayed in (a), superimposed on a frontal outcrop view perpendicular to the strike line. Means and standard deviation are noted in red.

Figure 7.4: The dip angle increases with horizontal distance from the scanner1 location. Dip angle is plotted as a function of of `-X` or meters south of the scan position. Each layer data bar is colored based on the number of points used to estimate the plane that defines the dip angle. It is assumed that the more points available to estimate the plane, the closer the estimate is to the actual plane.

The bar plot shows the dip angle as a function of horizontal distance from the scanner1 location. Only the second bedding layer decreases from the angle before it (note adjusted axes values). This apparent trend will be discussed in Chapter 8.

7.1.3. Dip Direction / Strike

The dip direction is the compass direction (as seen from the top of the outcrop) of the dip angle or the vector perpendicular and facing outward from the strike line, the dip direction vector, see Figure 7.3. The 3D outcrop in Figure 7.5 is rotated to show a view of the layering from the top or aerial view.

The dark blue arrow points outwardly from the planar surface of the limestone top. Since the outcrop is georeferenced in Matlab, an estimate of the dip direction can be made already by referring to this image. The x-axis is decreasing to the south while the y-axis is decreasing to the east. The dip direction of the top of the bedding plane appears to be south south-east. Opposite the top is the base plane with its dip direction...
Figure 7.5: Two dip direction vectors of the top and base of a limestone bedding layer. This is a top view of the La Charce sample outcrop. The extending limestone has a top, base, and edge in its 3D representation, while the marls only have an edge.

depicted in cyan. Here, the angle seems to be 180 degrees rotated, which is as expected for sedimentary layers. The Bachelor's students also collected dip direction measurements for the La Charce outcrop. Their results in Table 7.4, below, are slightly more precise than their dip angle measurements and seem to fall in line with the south south-east heading estimate.

Table 7.4: Student team dip angle and direction measurements from the La Charce sample outcrop with means and standard deviations.

<table>
<thead>
<tr>
<th></th>
<th>Team1</th>
<th>Team2</th>
<th>Team3</th>
<th>Team4</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dip (deg)</td>
<td>62</td>
<td>80</td>
<td>60</td>
<td>60</td>
<td>66</td>
<td>9.7</td>
</tr>
<tr>
<td>Dip Direction (deg)</td>
<td>160</td>
<td>154</td>
<td>160</td>
<td>145</td>
<td>155</td>
<td>7.1</td>
</tr>
</tbody>
</table>

The dip directions estimation for each top and base of the limestone beds is best illustrated in the polar plot in Figure 7.6. This shows the vectors emanating from zero to a compass direction if viewed from above. North is at the top and angles increase clockwise. Indeed, we see that the top planes are oriented towards the south at 157 degrees with a standard deviation of 1.4 degrees. The base planes are nearly opposite the tops, as expected, at −20 degrees with a standard deviation of 6.6 degrees.

The base planes have higher variation than the tops mostly due to the difficulty in defining a plane with far fewer points. Several other factors add to this variation and will be discussed further in Chapter 8. For comparison, the dip direction with respect to location and point count for planar estimates is plotted in Figure 7.7 for both top and base layer direction estimates.

Here, the limestone tops clearly were estimated by more points in general than the limestone bases. Other than that, no trend is apparent from these two factors as it was for the dip angle.

7.1.4. Strata Thicknesses

The final outcrop characterizing feature for extraction from the point cloud are the layer thicknesses of both limestones and marls. The thickness is the perpendicular distance from the top to the base of one bedding layer. A summary of the measurements at La Charce, along with the added thickness, are in Table 7.5, below. Alternating limestone and marl bedding layers are illustrated in the 3D plot in Figure 7.8 (left). Thickness
7. Results

Figure 7.6: The final estimates of dip direction for limestone tops and bases of the La Charce sample outcrop. The (a) 3D point cloud of the outcrop shows two example dip directions plotted for a single limestone stratum. The (b) dip directions of each bedding plane (tops and bases) are shown from the aerial outcrop perspective on the compass plot. The standard deviation of the limestone tops is noticeably lower than that of the bases. The point count for those same tops is noticeably higher.

Figure 7.7: The dip direction with respect to ‘x’ meters south of the scanner1 position. Data points are plotted in colors that indicate how many points were used to estimate that particular plane. The tops face nearly south and are thus at the top row of the figure. They exhibit higher point counts in general. The base planes are below.

Table 7.5: Student teams strata orientation and thickness measurements for the La Charce sample outcrop. Team4 did not report strata thickness estimates.

<table>
<thead>
<tr>
<th></th>
<th>Team1</th>
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<th>Team4</th>
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<td>60</td>
<td>60</td>
<td>66</td>
<td>9.7</td>
</tr>
<tr>
<td>Dip Direction (deg)</td>
<td>160</td>
<td>154</td>
<td>160</td>
<td>145</td>
<td>155</td>
<td>7.1</td>
</tr>
<tr>
<td>Limestone Thickness (cm)</td>
<td>10-50</td>
<td>20-80</td>
<td>5-40</td>
<td>N/A</td>
<td>12-57</td>
<td>7.6 / 20.8</td>
</tr>
<tr>
<td>Marl Thickness (cm)</td>
<td>30-40</td>
<td>20-80</td>
<td>30-300</td>
<td>N/A</td>
<td>27-140</td>
<td>5.8 / 140.0</td>
</tr>
</tbody>
</table>

estimates were calculated from extracted layer edge points shown with black circles and their perpendicular distance to either a top or base plane depending on the desired rock type. All thicknesses are plotted in the (right) plot based on layer number. Layer number corresponds to the sample section of the outcrop increase from right to left. The layer numbers in the plot have been reversed to match the 3D plot next to it.

To un-clutter the plot, limestone and marl thicknesses are shown separated in Figure 7.9, below. Where no trend was evident from the merged layer thickness plot above, the separated rock type plots seem to hint toward a sinusoidal trend. This is a very small sample size and thus, could be of coincidence, but ideas as to
7.1. Geometric Features Extracted

Figure 7.8: A summary of the marl and limestone thickness estimates. A (a) 3D visualization of alternating limestone and marl layers with black estimation point markers and (b) estimated thicknesses of the bedding layers sorted by type.

The reasons for this will be discussed in Chapter 8.

Figure 7.9: Strata thicknesses separated by rock type. The (a) limestones and (b) marls both show periodic signals. Since this is only for the La Charce sample outcrop, more investigation is necessary.

The resulting sample limestone bedding layers have a mean thickness of 32.17 cm with a standard deviation of 6.27 cm. The marls have a slightly greater mean thickness of 32.68 cm and almost half the standard deviation of limestones at 3.29 cm. Thickness is a feature strongly dependent on the location measured within the outcrop as layer thicknesses vary throughout time. That is why the estimated thicknesses may not fit as well with the students measurements, although in general, they are within the same order of magnitude. While these show the individual rock layer thickness, Figure 7.10 combines the each consecutive limestone / marl sequence to visualize sequence layer variations. Here the mean was expected to be much larger and
the standard deviation, much smaller. However, we can see that the sinusoid pattern is still visible even at this level possible indicating another, sequence in climate pattern. The standard deviation was slightly larger than was illustrated with the marls but this could be investigated further.

Figure 7.10: Strata thicknesses are now plotted with full limestone / marl sequences combined. Here, interestingly, a sinusoidal pattern is still visible but standard deviation has been reduced, as expected. Each column combines the limestone and marl sequences as labeled, corresponding to layers numbered in Figure 7.9.

For comparison with the other two extractable features, dip and dip direction, a plot of thicknesses with respect to layer order and point count per estimation plane is shown in Figure 7.11. As with the dip direction, no noticeable thickness trends are evident based on the layer location or the quality of the estimated plane. However, we expect, for example, the combinations of layers 12 and 13 to be a relatively good estimate considering the number of available points to estimate the planes with. Again, this is assuming that more points provide more accurate planar estimation. If that is the case, then the fact that the combined bar for those layers in Figure 7.10 are at the edge of the standard deviation but not the mean is an interesting result. Initially, it was assumed that combined bars more or less show no trend but be constant. If 'good' quality data is not the mean, then the trend might actually be present.

Figure 7.11: Limestone and marl bedding layer thicknesses shown in layer order and colored based on the number of points available for the layer planar fit.

The resulting values were the primary target of this investigation, but also considered was how to communicate these results. An example from the LIME software can do just that and is described in the next section.

### 7.2. 3D Virtual Outcrop Representation

The chosen software to present 3D virtual outcrops was determined through passing a set of criteria based on the project goals. LIME, the Lidar Interpretation and Manipulation Environment, accepts mesh files and en-
ables the projection of image files to the surfaces in an intuitive interface. It has built-in tools for viewing common outcrop characteristics such as dip angle (see Figure 7.12), strike, and planar normals. Although these features are not extractable, the platform focuses on visually presenting outcrop characteristics as clearly as possible, which is key to a target audience such as Bachelor’s students learning about what to expect during fieldwork.

Figure 7.12: A LIME representation of the La Charce sample outcrop colored by dip angle. Although a scale for values is not included, the image shows variation in the dip angles as limestone tops are shown in yellow / green and edges in red. The platform contains numerous other options for communicating ideas such as projecting images the manually depict layering or local map setting.

The platform provides methods to georeference, display 3D geometry, and illustrate measurements. Further development and testing within this platform has interesting potential. Initially there was interest in projecting outcrops in 3D for teaching purposes on the departments stereo projector. Unfortunately, LIME is only available for release in the Windows environment while the stereo projector is currently only compatible with Linux machines. As hardware is updated, using LIME in 3D could be an interesting possibility.

7.3. Summary

Close-range, 3D lidar data gives key insights to the geometric structure of well-defined sedimentary outcrops, such as the chosen sample presented in this chapter. On the chosen sample of the La Charce outcrop, the dip angle, dip direction, and alternating limestone / marl thicknesses were extractable with varying accuracies. In addition, the same features measured by students in the field also vary but are within several degrees of the algorithms estimates, validating each other. Highly variable thickness measurements are difficult to compare. These results, along with notable trends taken from the results, will be analyzed further in Chapter 8.
Discussion and Recommendations

With the results of the study presented in Chapter 7, the estimated planar surfaces, dip and directions, and strata thicknesses, several questions come to mind concerning their validity. Specifically,

How can the estimated features be validated?

Since the developed work flow is not entirely automatic, several input parameters were chosen after extensive testing. These ‘assumed’ parameters provide direction for algorithms in the work flow leading up to the final parameter estimates. All influence the final results. In the following chapter, these input parameters are defined along with a sample sensitivity study that shows parameters with the greatest effect on the results. Additionally, the results are validated through both measured field data and approximate estimates, with estimated errors included. The chapter concludes with limitations of the study paving way for both future research and adaptations for other suggested applications.

8.1. Assumed Parameters

The developed work flow, broken down into various algorithms, runs on the basis of several assumed, user-input parameters. These parameters range from filtering thresholds to the amount of nearest neighbors considered for planar calculations. The input parameters can be broken down into six key algorithm steps. The assumptions made for each step, follow.

8.1.1. Calculating Point Normals

One of the first analysis steps is to calculate the normal, or perpendicular, vector of each point on the outcrop point cloud (see Figure 5.11). This algorithm is necessary to later enable the grouping of similarly oriented normal vectors (ideally, to extract planar surfaces). Two assumptions are made in order to calculate a point normal within a point cloud:

- Nearest Neighbor Count [6]: the number of points, out of the points closest to the sample point, that should be considered when calculating a small local plane.
- Scanner Location [-71.60,20.82,4.53]: the location in coordinate space that the laser scanner is located; tells the direction of the ‘outward’ side of the outcrop.

If more nearest neighbors are used, normal smoothing occurs. This means that if, say in the most extreme case, all points were considered ‘nearest neighbors’, the computed normal would be a best fit plane through the entire point cloud. All concurrent sample points would have nearly the same normal since the data set of
points for planar fitting only changes by 1 out of thousands of points. The fewer nearest neighbors chosen, the smaller the local computed plane, the more variation in planar normals will arise assuming the outcrop has differently oriented surfaces. Too small of a choice of nearest neighbors will pick up on either the actual surface roughness of the rocks or errors associated to the measurements. These details again are not an accurate representation of the planar surface features.

The scanner location, or any point chosen on the ‘outside’ of the outcrop, is used to re-orient normal vectors. Planar normal vectors should not point to the interior of the outcrop, although they sometimes do, since only the outer surface can be measured with lidar. For analysis and grouping of similar point normals, all normals should be oriented outwards. This location tells the algorithm which general direction the normals should point (the angle between the vectors drawn from a sample point to the scanner locations should be between $\pi$ and $-\pi$).

8.1.2. Histogram Binning

The next analysis step is to group the point normals by similar directions (see Figure 5.13). This was accomplished through histogram binning, or the division of data based on like values. It was assumed, by looking at an image of the outcrop, that the most abundant surface was that of the stratum tops. Thus, the greatest amount of normals pointing in a similar direction should correspond with top surface points. Additionally, all surface points then need to be sorted into individual strata. This was also accomplished with histogram binning, but bins were filled by distances from point to point rather than normal direction. The following assumptions were made for these two algorithms:

- **Total Bin Count** [60]: the number of bins that all point normal compass directions should be sorted into.
- **Bins to Keep** [3]: the number of most populated bins; included in the bins should be a maximum number of normal points on the top surfaces and a minimal number of ‘non’ top surface points.
- **Strata Bin Count** [7]: the estimated number of suspected tops of strata; used to place extracted ‘tops’ points in individual strata bins.

Out of a total of 360 possible degree directions, bins containing directional ranges in increments of 6 degrees was sufficient to note trends in high bins; several bins in the same direction had the highest counts. As chosen, only the top 3 bins, of normal directions, were selected from this sample outcrop. Three bins already contain points not exactly on the top surface of a strata, and thus, need to be filtered out and sorted into distinct layers before a plane can be fit to each layer. The next algorithm step shows the assumptions for this filtering.

8.1.3. Point Filtering and Selective Grouping

Point filtering, in this context, is the process of getting rid of undesired points from a mixed set of both desired and undesired points (see Figure 5.15). In the first filtering algorithm, this refers to getting rid of non-top surface points from the subset of points that was determined by histogram binning. The second algorithm of this type is referred to as selective grouping. This means that points are selectively placed in groups based on a threshold value from a point or feature. Here, all points in the point cloud are selected and grouped based on their distances from estimated planar tops. These processes are completed for both tops and then bases of the protruding strata. The following assumptions were made:

- **Nearest Neighbor Count** (again, but different) [80]: the number of points, out of the points closest to the sample point, that should be considered when calculating the average distances to the sample point.
- **Average Point Distance Threshold** [3.5 cm]: the maximum average distance from nearest neighbor points to the sample point that determine the sample point to be an ‘inlier’ or included for the next step.
- **Point Distance Threshold** [0.1 m]: the maximum distance from a sample point to the nearest plane to be considered on that plane; a preliminary step
Although filtering considers nearest neighbors as well, this algorithm does so in a completely different manner. Here, the average distance from a sample point to its 80 nearest neighbors is considered. If that average distance is greater than the threshold of 0.035 m, the point is ‘thrown out’. In this way, undesired points are sorted from desired ones. Eighty points were chosen in this case since only points on the top surfaces were desired. The point density on these surfaces is very high from the histogram binning so considering many neighbors helps to get rid of points not on this dense surface. A very small threshold was chosen, again, to only keep points that are located very close to at least 80 other points. A study on the sensitivity of these values will be demonstrated in Section 8.2.

The point distance threshold was used to gather all points in the original point cloud that were at least 0.1 meters close to an estimated plane. From this new, more complete subset of data, a better estimate of the plane can be calculated. Ideally, this number can be reduced iteratively as the planar fit converges to minimal residuals for all points on the plane.

**8.1.4. Initial Planar Fit**

Going back to when all 'tops' point were extracted with histogram binning (from point normal directions), an initial estimate plane was calculated using a form of the RANSAC algorithm (see Figure 5.16). This algorithm randomly searches for planar features until it finds a plane that fits all input criteria and is the plane that contains the most points. There are three input criteria for defining this plane:

- **Maximum Distance** [0.05 m]: the maximum distance a point is allowed to be from the estimate plane; any point at a further distance is an 'outlier' or not considered
- **Reference Vector** \([-0.84, -0.33, 0.42]\): initial guess of the estimate plane normal vector
- **Maximum Angular Distance** [5°]: the maximum absolute angular distance between the normal vector of the fitted plane and the reference vector

This process, again, is an iterative one as the reference vector can be updated for faster convergence, reducing the maximum angular distance each time. Many different values for the maximum distance were considered before selecting the value listed above. The maximum distance limits how much surface roughness is captured. If the reference vector matches well with the point data and the maximum angular distance is small (< 5°), the maximum distance is just the roughness of the plane.

**8.1.5. Semi-Automatic Classification**

Semi-automatic classification is the grouping of points in the point cloud, in this case, based on an estimate of how many limestone/marl cycles are present, a guess for the cycle thickness, and a tolerance for which points should fall between in order to fit in one layer or another (see Figure 5.17). Since, at this point in the workflow, both tops and bases have been extracted, this algorithm just must sort the points into individual data sets (per strata, and distinguished between tops and bases). Thus, general guesses about the layering and iteratively converge on separating the planar surfaces. The assumptions for grouping points in this way are as follows:

- **Cycle Count** [7]: a guess as to how many full cycles (limestone + marl stratum) are represented in the sample point cloud.
- **Cycle Thickness Guess** [0.68 m]: a guess as to how thick the average cycle is in the sample outcrop.
- **Layer Thickness Guess** [0.34 m]: a guess as to how thick a single average layer is in the sample outcrop.
- **Tolerance Guess** [0.1 m]: an estimate of the variance of the planar points; used to ensure all points in the plane are recognized.

These input parameters are not as sensitive as the others listed. They are only used for sorting planar points that already show planar adherence when plotted. Basically, various values were tried until points were group visibly. A cycle count of 7 means that the algorithm searches for 7 tops and 7 bases in both directions from
the estimated RANSAC plane. These estimates should be higher than reality so that all points are considered, ‘empty’ planes are cleared later. The cycle thickness is used to look for top planar points since the RANSAC plane is also a top, while the layer thickness looks for bases (only a layer away from the top RANSAC plane). Since the layering occurs naturally, not every plane will be those exact distances from the RANSAC plane (and actually, they diverge with further distances since the thicknesses are not always equal). The tolerance is used to catch points regardless, both 0.1m ahead and behind of where the plane should be if cyclic layering was exactly equal. Again, the purpose of this algorithm is to simply separate planar points into individual data sets.

8.2. Assumed Parameter Sensitivity

As mentioned, many of these parameters are flexible and were chosen after observing the effects of iteration on the algorithm results. For key input parameters assumed for point filtering, Section 8.1.3 for example, a sensitivity study was done to ensure that the optimal parameters were reached. In the example that follows, points with similar normals have been collected using histogram binning. These points are supposed to define the top of the stratum surface, but some base points and outliers are also included in the data data. The goal of filtering is to get rid of these unwanted points so that only top surface points remain; with tops surface points alone, the planar fit algorithm can be implemented.

For the filtering algorithm, two key input parameters were discussed: the amount of nearest neighbors to consider and the threshold of the average distance from the nearest neighbors to the sample point. Thus, a sensitivity study on both parameters follows, but the process was iterative as the resulting point cloud relies on both parameters as they influence each other.

8.2.1. Nearest Neighbors

Two tests for determining the optimal number of the number of nearest neighbors (see 8.1.3) to use were conducted and compared. The intersection of the two give the optimal value. It is important to retain as many points as possible for better planar estimates, but also, to exclude all ‘outliers’ or unwanted points. The first test kept the value of the threshold constant, and at a reasonable value of 2.4cm, in order to compare the amount of points retained to how many nearest neighbors were considered. This relationship nearly exhibits exponential decay, as illustrated in Figure 8.1, meaning it is quite sensitive to the value chosen. The second test was to visually inspect for outliers. This was done iteratively until it was clear that using 76 nearest neighbors displays no outliers, but at 75, outliers appear (assuming a threshold of 2.4cm). The results of the two tests are plotted, below.

The first test of nearest neighbors versus retained point count is shown by the sampled trend in blue. Significant point loss occurs rapidly, just over 12 points deleted per additional nearest neighbor, up until about 120 nearest neighbors. The second test in red shows that any value below 76 nearest neighbors results in outliers that effect following algorithms. It is important to select the lowest number of nearest neighbors that filter out all outliers. Figure 8.2 shows the results of using three different values of nearest neighbors, for comparison.

Since the goal of this particular filtering step was to only extract ‘top’ planar points, base points need to be filtered out (highlighted in green on the plot). Using a threshold of 2.4 cm and 80 nearest neighbors clearly shows that no unwanted points are retained anymore. However, using 100 nearest neighbors reduces the amount of retained points making planar estimation less accurate. Therefore, the optimal value of 76, or near that, seems reasonable.

8.2.2. Average Distance Threshold

Inversely, the higher the maximum threshold (see 8.1.3), the greater the number of points that are retained. Here, it is important get the greatest threshold up until unwanted outliers appear. The same two test, as completed with the nearest neighbor study, are plotted in Figure 8.3, below.
8.2. Assumed Parameter Sensitivity

Figure 8.1: The plot shows the results of a sensitivity test for point filtering. Test 1 was to check how many points remained after varying the amount of nearest neighbors considered in the filtering, blue line. Test 2 shows the threshold of when all undesired points are filtered, red shaded portion. The solution or optimal count of nearest neighbor should retain the most amount of points for better planar estimations but also be above the threshold excluding unwanted point. This plot shows that 76 is the optimal number of nearest neighbors.

Figure 8.2: Filtering algorithm run on the La Charce sample outcrop point cloud. Black points are retained points, while red ones were filtered out. Using a constant threshold of mean distances, the plots show results of (a) 10, (b) 80 and (c) 100 nearest neighbors. In plot (a), points not on the limestone tops are retained, these are undesirable since the goal is to calculate top planes. Plots (b) and (c) contain no unwanted points, but (b) retains more wanted points for estimating planes.

The nearly linear relationship, a 42 remaining point increase per centimeter of threshold allowance, shows that the parameter is less sensitive (the entire viable range is only 0 – 2.4 cm). Again, plotted in red is the threshold of unwanted outliers showing up. The begin to show up at 2.4 cm and increase as higher thresholds are allowed. Plots showing the sample outcrop point cloud in Figure 8.4 are shown for comparison with the range of values seen in the nearest neighbor test.

8.2.3. Summary

Through iteration, the optimal parameters of 80 nearest neighbors and a threshold of 2.4 cm both retained the most amount points while getting rid of all unwanted outliers. The nearest neighbor count was determined...
8. Discussion and Recommendations

Figure 8.3: The results of the second sensitivity test for point filtering are plotted here. Again, test1 was to determine the amount of remaining points, but this time based on the mean distance threshold to a points nearest neighbors, shown in blue. Test2 also shows the cutoff at which point unwanted points begin to appear. Larger thresholds allow more points to be kept. The almost linear trend shows approximately 2.4cm to be the optimal threshold distance.

Figure 8.4: Filtering algorithm run on the La Charce sample outcrop point cloud. This time, the nearest neighbors considered were held constant at 80. The results of using (a) 2cm, (b) 2.4cm and (c) 5cm average distance thresholds are plotted. Plots (a) and (b) contain no unwanted points, but (b) has slightly more points retained. Plot (c) shows some unwanted points, circled in green.

first since it is more sensitive than the threshold. Using these final input parameters, nearly 72% of original points are retained, and now, only 'top' planar points remain as desired.

8.3. Validation of Results

The results presented in Chapter 7 summarize the findings of the cumulative algorithms in the work flow. Both Google Earth and student measurements taken during the fieldwork were included for validation. The sections below define these methods for validation.
8.3. Validation of Results

8.3.1. Dip Angle

The dip angle is the angular measure of declination from the horizontal plane to the surface of the top of a stratum. It is illustrated with Google Earth in Figure 8.5. Here, the entire outcrop is shown and the dip angle is highlighted in yellow. It is clear, even without the best view, that the dip angle of this outcrop, La Charce, lies between 45 and 90 degrees. This is the simplest validation to ensure that estimated number are within the correct range.

![Figure 8.5: A Google street view of the La Charce outcrop. A horizontal (level) line is drawn for reference in red. The dip angle follows the steepest descent from this line along the bedding layers. The dip angle is the measure shown by the yellow arrow.](image)

A second validation is using the data provided by students throughout the past few years of fieldwork in the region. As noted in Chapter 7, the students estimate the dip angle to be anywhere between 60 and 80 degrees, already a smaller range. The numbers, however, were measured by different people, during different years, and generally by students learning how to used the compass and clinometer. These sources of error add uncertainty to the estimates, but combined with estimates from Google Earth, reinforce each other. They also reinforce this studies estimate mean dip angle of 64 degrees, falling between the range limits of both sources.

Additionally, it can be noted that the dip angle with respect to increasing location along the outcrop 'length' axis away from the scanner location also increase with almost every strata. This could be due the rotation of the point cloud in order to georeference the outcrop in the case that the scanner was not completely leveled.

8.3.2. Dip Direction

The dip direction, once again, is the compass direction in which the dip angle vector is pointing. The dip direction is shown on the interpreted Google Earth image in red in Figure 8.6. As shown, not all layers appear to align with this south, south eastward facing direction (north is up). This could be due to tectonic shifting, faulting, etc. For the sample chosen in this study, the dip direction appears to point very near south.

The measurement, as can be seen in the image is variable to the specific layer measured. Here, the bachelors students measurements range from a compass direction of 145 to 160. Directly south would be a compass direction of 180 degrees so the students estimates seem reasonable. The work flow estimates the average dip direction to be 157 degrees, also falling between the range established by both the students and an evaluation of Google Earth.

8.3.3. Strata Thicknesses

Strata thicknesses are more challenging to validate. As seen from the Google Earth image in Figure 8.7 already, the strata have varying thicknesses even without knowing the scale.

In this case, the best validation available is a combination of the students data and sources from literature.
Discussion and Recommendations

Figure 8.6: A Google aerial view of the La Charce outcrop and surroundings. The formation runs along the road as called out with the white label. A red strike line parallel to the bedding planes has been added along with a perpendicular vector signifying the dip direction. Since the dip direction is a compass direction, the north arrow to the right of the figure indicates that the dip direction points south, south east. A map scale is shown in the bottom right.

Figure 8.7: A zoomed-in front or ‘street’ view of the La Charce outcrop from Google. The varying strata thicknesses are apparent, along with vegetation which causes occlusion in the data. Thicknesses are measured as the perpendicular distance between two estimated bedding planes and only taken as a slice section approximately 4m up the outcrop. Image scale is shown at the bottom.

The students estimate a limestone thickness between 5 and 80 centimeters and a marl thickness between 20 and 300 centimeters. Gréselle et al. [2011] finds the entire outcrop to have a total thickness (or length really) of approximately 7 meters. This section of La Charce contains 10 limestone layers and is estimated to be 40% limestone, 60% marl. That means that the average limestone layer would be 28cm and the average marl would be 42cm. These two estimates are close to the final values calculated by the proposed work flow, a mean of 32cm thick limestone and 33cm thick marl.

One interesting thing to note is the almost sinusoidal patter of thicknesses when limestones and marls are separated. This is either a random phenomenon or it hints toward another climate process occurring between layers. It would be interesting to compare the results of a different sample section in the same outcrop to note
if the trend is still noticeable.

### 8.4. Error Budget Summary

Several factors contribute to the overall expected error in estimated parameters. These errors come from both the data acquisition and work flow stages of the project. Some can be controlled, others limited by instrument design and precision itself. Calibration and Monte Carlo-type simulations can further reduce these inevitable errors but those methods will be left for another study. A summary of errors from both stages of the project are presented in Table 8.1 as follows:

<table>
<thead>
<tr>
<th>Data Acquisition</th>
<th>Expected Error [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>Resolution</td>
</tr>
<tr>
<td>Instrumental</td>
<td>4</td>
</tr>
<tr>
<td>Environmental</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Object-Related</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Scanning Geometry</td>
<td>&lt;1*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Work Flow</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Registration</td>
<td>5-15</td>
</tr>
<tr>
<td>Decimation /Cropping</td>
<td>&lt;1**</td>
</tr>
<tr>
<td>Georeferencing</td>
<td>10-20</td>
</tr>
<tr>
<td>Point Normals</td>
<td>&lt;1**</td>
</tr>
<tr>
<td>Filtering</td>
<td>&lt;1**</td>
</tr>
<tr>
<td>Planar Fitting</td>
<td>&lt;1**</td>
</tr>
</tbody>
</table>

* assuming proper planning and consideration
** errors greatly reduced in final estimates

While these values reflect what was noted during the process, not all quantities were measurable in the scope of this project. With data acquisition, Leica states the accuracy of the instrument. However, this depends on calibration and optimal working conditions. Thus these values are assumed to be slightly underestimated. Environmental and object-related errors are uncontrollable parameters, but if sampled as advised in section 3.1.5, can be greatly reduced in comparison to the instrumental error. Scanning geometry highly influences the quality of the point cloud but it is a controllable factor. Selecting scan locations that reduce occlusion and minimizing large scan angles (on the target object surface) already reduce the errors. Assuming proper planning for reducing these factors was considered, these error are small compared to the instrument.

Additionally, errors are introduced as discussed in the work flow. The largest contributors to error in the post-processing steps are created during point cloud registration and georeferencing with GNSS data. Registration depends on the placement and fixed factor of the targets scanned during data collection. A good spread of target locations that are fixed securely during the scan will produce very low errors in registration. Higher errors can be noted with near linearly aligned targets, strong winds, or human interaction. Georeferencing accuracy is limited by the GNSS system itself. Since the system used in the project reported accuracies of 10 – 20 mm, we can not expect to get better accuracies for the dip direction, for example. This accuracy is also affected by lesser signals received between mountainous terrain. The others work flow steps initially lose accuracy as not all points are considered for algorithm testing, but in the end, points are added back and estimated accuracy can be considered negligibly affected.
8.5. Suggested Applications and Limitations

The developed work flow for estimating planar features in an outcrop and the outcrops morphological characteristics was specifically developed using the La Charce outcrop sample section data set. Although the scope of one sample is limiting in itself, the developed work flow is a solid start for developing into other applications. In theory, this algorithm should be adaptable to estimate or derive different types of information from the same or similar outcrops. Extracting fractures in an outcrop, deriving the block size distribution, or incorporating subsurface knowledge, just to name a few, are all possible applications.

In this project, the primary focus was on extracting planar features to derive dip, dip direction and strata thicknesses. However, similar methods could be applied for extracting linear fracture features such as faults and joints. An automated algorithm that extracts fractures could be useful for reservoir modeling as the fractures can possibly hint towards seal or seepage points, or in general, help in creating a fluid flow path model [Wilson et al., 2011]. An example of some fractures in an outcrop near Pradelle are shown in Figure 8.8, nearly perpendicular to the bedding strata.

Figure 8.8: The Pradelle2 sample outcrop from the Vesc area showing some fractures perpendicular to the bedding strata and folds.

In addition to fractures, block size distribution can be derived from morphological surface properties. A similar process to calculating point normals and binning them based on similar characteristics is the first step in making these estimates [Tanner et al., 2013]. The In-situ Block Size Distribution (IBSD) is self-explanatory, as it is a measure of the distribution of sizes of individual blocks that make up an outcrop, for example. The known IBSD can specifically be used for quarry yield estimates [Vanhaekendover et al., 2014] and for knowing what size rocks to expect when explosions free the rocks from the quarry wall.

A final proposed application to 3D outcrop point clouds is to actually link them with other available information. For instance, if seismics or ground-penetrating radar data are available for the region, correlating the surface with the subsurface can lead to a whole new understanding of the geological regions. The data can be used to help geologist estimate possible reservoir locations and sizes without costly subsurface measurements or to explore enhance oil recovery options [Enge et al., 2007]. These are just three possible applications along this line of research, but more applications are emerging as interest grows in lidar for geological mod-
8.6. Ideas for Future Research

This project adequately addresses the research questions and objectives of the study, however, with more time, there are several additional studies that could build off of the results and workflow presented here. Explained below are four of the most relevant ideas for future research concerning feature estimation from terrestrial laser scanning for rock outcrops.

8.6.1. Surface Variation

One of the most interesting questions formed during this study is whether or not morphological features alone can determine rock type or at least discern between two different types of rock such as the limestone and marls present in the La Charce outcrop. The suggested direction would be to first extract each strata edge separately (which has already been implemented in the current work flow). Then, calculating the surface variation or RMS error for each point based on its neighbors can give a visual representation of the roughness of the surface. The results of this could look something like the following plots in Figure 8.9.

![Figure 8.9: Three selected limestone and marl edge RMS variance plots. These were a first attempt at comparing surface roughness but requires a point density analysis for comparable results. Here, a plane was fit to a points 10 nearest neighbors and the room mean square (RMS) variance was calculated. This RMS is plotted in color at the points location in the 3D point cloud. Plots (a) and (c) are marl edges, while plot (b) is the limestone edge physically located between them.](image)

Scaling these surface roughness estimates based on point density and per individual scan could then give an idea as to whether or not it is possible to distinguish rock types from geometric features.

Continuing on this study, it would be equally interesting to see if the classified (by rock type) extracted edges could be aligned to calcium carbonate logs available on the outcrop [Gréselle et al., 2011]. If indeed the rock type can be matched to CaCO₃ records, necessity of taking core samples could possibly be reduced and just used for validation, for example. Additionally, other factors such as the intensity return of the points could also be compared in this way.

8.6.2. Algorithm Development

Clearly, there is always room for improvement with a semi-automatic workflow or algorithm. To simply expand directly on this project, several key weak-points within the code should be addressed. The first consideration would be to expand the analysis to another sample section in the outcrop, or ideally, the entire outcrop. The pre-processing phase of point cloud analysis would have to include filtering for undesired data such as vegetation, stationary man-made structures like signs and roads, and ‘ghost’ points caused by intense solar radiation, bugs, and fast cars.

Another step would be to expand the robustness of the algorithm by testing the workflow on other outcrops. A total of 10 different outcrop scans, at various resolutions and sizes, were collected during the fieldwork. The extent of this data alone gives many challenges to the algorithms since most other outcrops did not have such
well-defined, characteristic layering.

The final two suggestions would be modifying the code rather than the raw data input, or point cloud. One is to remove the ‘semi’ in semi-automatic. The reason the current algorithms are not fully automatic is because many require input parameters based on user knowledge or iteration. It would be interesting to develop routines that could be used to automatically decide the optimal input parameter, iterate if necessary, and arrived at the final parameter estimates on its own. Perhaps an input file could be developed instead that contains all input parameters. Secondly, the algorithms are all aimed at estimating planar-surface derived features. Another idea would be to look into extracting other features such as lines or triangular surface. However, there is a lot of literature on this task already so it would be more of a synthesis study.

8.6.3. Single vs. Multi-Station Scan Comparison

One idea considered, but not tried, was to do a comparison study of data from a single station versus merged data from a registration of several stations (as was used in this study). Varying conditions between scans and registration errors causes some skepticism in the final merged point clouds. This would be especially interesting for analyzing the intensity return as the angular view, and thus return, varies greatly with scanner location.

8.6.4. Streamline Georeferencing Work Flow for TLS

A final idea would be to streamline the georeferencing procedure for terrestrial laser scanner. Of course, this depends on the features that need to be extracted (strike, dip direction depend on it) or how it will be shared and displayed (will the 3D data be placed on a map?). Since the Leica C10 laser scanner does not include GNSS, position data must be collected with an additional GNSS receiver. However, one common encountered problem was getting sufficient signal while partly obscured by outcrops or tall, mountain structures. Another issue was discerning target locations from the collected GNSS data. A rover and base station were used in this study, but the pole the rover was attached to was 2 meters tall and was difficult to manipulate its position right on top of the targets (also a signal problem here). This could be a nice, small, cross-discipline project that could be used to develop a standard procedure and user-friendly checklist for future TLS fieldwork.

8.7. Summary

All three primary results, the estimated parameters, were validated with Google Earth and student fieldwork measurements. The estimated dip and dip directions match well with the validations, and thus, are considered to be a good enough estimate for geologists to use in the future, provided the algorithm works equally well on other outcrop samples. The strata thickness were difficult to validate both with Google Earth and student measurements due to high variability, but strata throughout the entire outcrop seem to exhibit this as well. Therefore, the thickness estimates may very well be fine for the small sample test section analyzed. A summary of the error budget is included, both errors accumulated during data acquisition and throughout the work flow. These errors possibly explain some of the variation seen in the results.

In addition to justifying the final results, several other factors were acknowledged. Rationale for assumed input parameters, along with an example sensitivity study of one of these parameters, illustrate the flexibility of the work flow and highlight possible sources requiring automation improvement in the future. A proposed next step could also be to examine the surface variation and determine if rock type can be discerned from the variation alone. This algorithm could be developed into related applications such estimating block size distribution or locating fractures as well. Validation for these goals would require more intensive fieldwork measurements or work in a controlled laboratory.
Conclusions

In this study, close-range 3D laser scan measurements were taken of sedimentary outcrops in southeast France. Of all the point clouds collected, one was selected for displaying the most well-defined, protruding sedimentary layers (see Figure 9.1). This sample outcrop was then analyzed in the sense of determining which morphological features were represented by the strata that composed it and to what extent they could be semi-automatically extracted. With the raw point cloud and information about the outcrops morphological features, the study concludes with a comparison of suitable platforms for representing the 3D data and for effectively communicating the practical findings of the study in a virtual environment.

Figure 9.1: The La Charce outcrop showing distinct strata with close-range access. This is a screen shot from Google Earth ‘Street View,’ which shows the outcrop from the perspective of a driver passing by. The orientation compass is in the bottom right corner and the scale is shown at the bottom.

9.1. Addressing Research Questions

Returning to the posed research questions at the beginning of the study, findings are summarized in the sections that follow.

What close-range 3D measurement devices are available and what are their advantages and disadvantages, both theoretically and practically? Which is best for the target study region, Vesc?

Close-range outcrop measurements have been demonstrated with many different instruments including traditional compass and clinometer measurements, all the way to remote sensing approaches such as cameras
(photogrammetry), hyperspectral imaging (both VNIR-SWIR and MIR-TIR), ground-penetrating radar and laser scanning (terrestrial, aerial). The Leica C10 terrestrial laser scanner was selected to collect morphological data from the outcrops in this project for its strength in detailed (<5mm accuracy for terrestrial), relatively fast (360° lo-res scan completed in <10minutes), 3D surface data collection scans, and practically speaking, its availability from the department and size for transport. Similar 3D point clouds can be created with images and photogrammetry principles, but the quality of the resulting point cloud is a product of the software used to join the images, distortions corrections and lighting conditions. Hyperspectral imaging works well to extract rock composition based on the reflectance properties at various wavelength bands of different types of rocks, but it is not well-suited for recognizing 3D morphological features due to its 2D nature of image capture. Ground-penetrating radar, as stated in its name, is tuned for extracting features from the subsurface, which is unnecessary when analyzing exposed rock. The final remaining possibility is to use or collect aerial lidar data. Although some studies have proven the feasibility of aerial lidar for very large scale outcrops, the outcrops in consideration can be scanned with less than five close-range (<200m) viewpoints, or stations. This area can be sufficiently covered by a terrestrial scanner with higher spatial resolution and with a much lower monetary cost of survey than with aerial (or Unmanned Aerial Vehicle) lidar. Overall, terrestrial laser scanning fits best for 3D outcrop morphological analysis.

What geometric features characterize rock outcrops in the study region?

As mentioned, the first part of the study involved collecting laser scans of outcrops that could be used for characteristic feature analysis. The region in southeast France, near La Charce, was chosen for its abundance of exposed geological formations displaying the areas deep-marine sedimentary past. These outcrops, along with sedimentary outcrops in general, are composed of bedding layers, or strata, that signify shifting climate cycles affecting the local region from around 100 – 150 million years ago. Outcrops can be represented based on their morphology, composition, setting, etc. Since 3D point cloud geometries will be used as the primary dataset, morphological features are of most interest for extraction. These features are parameters that describe the physical structure and orientation of the strata, including dip angle, dip direction, and strata thicknesses. For a given planar-fit stratum, the parameters will be estimated as illustrated in Figure 9.2.

Which particular outcrops should be measured (and for what features)? How is the data collected?

All point cloud data used for the project was collected during four days of fieldwork near La Charce, France. Learning to use the equipment and detailed planning were necessary to insure quality data was collected most efficiently. It was particularly important to determine the type of outcrops that were most desirable for the study; this includes clearly-defined sedimentary strata, varying strata thicknesses and orientations, varying overall outcrop sizes, all located at varying distances from suitable scan locations. It was predicted that the best results would come from an outcrop with distinct bedding layers, larger in dimension (at least 50 m x 50 m), and close range (<50 m) for measurements, hopefully resulting in an adequate resolution for discerning morphological features. Since the La Charce outcrop (Figure 9.1) fit these parameters best, an entire day was devoted to collecting multiple scans along with GNSS coordinates for georeferencing. A summary of all collected data from that week is shown in Table 9.1, below.

How could a semi-automatic work flow estimate these features from 3D measurements? Which software assists in this?

The collected data was reduced down to the La Charce outcrop for semi-automatic parameter estimation and algorithm development. To pre-process the point cloud, multiple scans of the outcrop had to be merged, reduced, and georeferenced. Merging, or the registration of, several point clouds from various scanner locations can minimize occlusion and increase point density since it makes use of all available data. This process was completed using targets in the field for matching within Leica’s point cloud software, Cyclone. The registered point cloud, now too large (18.7 MB) for testing algorithms efficiently, was decimated using octree subsampling in CloudCompare. The remaining points (2.2 MB) were then cropped to a small but representative section of the La Charce outcrop. This sample section was used for the remainder of algorithm testing.
Figure 9.2: Limestone layer point cloud fit with a plane showing extractable morphological parameters. The black dots are points selected from a sample section of the full La Charce outcrop. The purple plane is a best fit plane to the points on the top surface of the limestone layer. The arrows show parameters that were estimated.

Table 9.1: A Summary of the collected outcrop laser scans during fieldwork. Outcrops are named based on the nearest village. The total point count is the sum of all points collected for that outcrop. The resolution is maximum estimated resolution of the combined station data. The range, length and height are estimates of the coverage of the merged point cloud. The file size gives an idea of the amount of data collected.

<table>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aranyon1</td>
<td>42,395,447</td>
<td>0.034</td>
<td>45</td>
<td>40</td>
<td>45</td>
<td>4,000</td>
</tr>
<tr>
<td>Aranyon2</td>
<td>236,718</td>
<td>0.115</td>
<td>115</td>
<td>85</td>
<td>125</td>
<td>994</td>
</tr>
<tr>
<td>LaCharce</td>
<td>69,211,402</td>
<td>0.032</td>
<td>22</td>
<td>100</td>
<td>18</td>
<td>4,800</td>
</tr>
<tr>
<td>PreGuittard1</td>
<td>13,322,113</td>
<td>0.024</td>
<td>13</td>
<td>15</td>
<td>8</td>
<td>1,200</td>
</tr>
<tr>
<td>PreGuittard2</td>
<td>30,248,769</td>
<td>0.040</td>
<td>70</td>
<td>80</td>
<td>30</td>
<td>2,200</td>
</tr>
<tr>
<td>SBenoit</td>
<td>18,956,944</td>
<td>0.028</td>
<td>120</td>
<td>180</td>
<td>50</td>
<td>883</td>
</tr>
<tr>
<td>Pradelle1</td>
<td>21,912,922</td>
<td>0.020</td>
<td>14</td>
<td>25</td>
<td>10</td>
<td>2,200</td>
</tr>
<tr>
<td>Pradelle2</td>
<td>37,645,185</td>
<td>0.029</td>
<td>10</td>
<td>20</td>
<td>5</td>
<td>2,800</td>
</tr>
<tr>
<td>SNazaire1</td>
<td>36,048,770</td>
<td>0.026</td>
<td>18</td>
<td>55</td>
<td>20</td>
<td>2,200</td>
</tr>
<tr>
<td>SNazaire2</td>
<td>15,851,238</td>
<td>0.029</td>
<td>12</td>
<td>25</td>
<td>5</td>
<td>977</td>
</tr>
</tbody>
</table>

The points were georeferenced within Matlab by aligning vectors within the local scanner coordinate system to the GPS Earth coordinate system. This is necessary as some desired parameters for extraction depend on compass orientation.
All desired parameters, the dip, dip direction, and strata thicknesses, depend on the defined planar surface of a bedding layer. To estimate this plane, along with segmenting each layer of rock individually, a procedure was developed for estimating planar normals. The perpendicular normals of each point in the cloud were calculated using nearest neighbors to form local planes. These normals were then placed in histogram bins according to their compass directions. All point normals belonging to the greatest bins (in one general direction) were considered most likely to fall within the tops of the bedding layers (the surface illustrated in Figure 9.2). Many of these points indeed belonged to stratum tops, but filtering based on nearest neighbor distances was applied to refine the selection. An estimate plane was then calculated for these points based on a derivation of the RANSAC algorithm. Points were again placed in bins, but according to the distance of the points to the estimated RANSAC plane this time. In this way all tops of bedding layers were defined individually. This process was repeated with remaining points for defining the bases and edges of the rocks, and new planes were better fit to the segmented data using a variation of PCA. With each stratum top and base planes defined, the desired parameters could be extracted with basic geometric relationships. A summary of the estimated parameters are shown in the plots of Figure 9.3.

The resulting morphological parameters extracted from the sample outcrop section were recorded, and then validated with several sources. The average dip angle of all planes in that sample outcrop section was estimated to be 64 degrees with a standard deviation of 0.6 degrees (Figure 9.3(a), red). An estimate from observing the outcrop in Google Earth shows that the strata are not exactly vertical, but inclined somewhere between 45 and 90 degrees. The estimate falls within these values and was also validated with students measurements gathered during the fieldwork using compasses and clinometers. The average dip direction of stratum tops was estimated at 157 degrees with a standard deviation of 1.4 degrees (Figure 9.3(b), dark blue). Again, a look at Google Earth shows that the outcrop is generally oriented in the north-south direction with stratum tops facing towards the south. The algorithm estimate falls very near south and also agrees with student collected field data. Finally, layer thicknesses resulted in a mean of 32.17 cm with a standard deviation of 6.27 cm (Figure 9.3(c)). This quantity is more difficult to validate due to extremely varied student estimates and variation in layer thicknesses evident from one side of the outcrop to the other. The order of magnitude agrees with most student data and a generalization from field estimates seem to confirm these measurements as well. Additionally, the work flow can be validated from prior research in the field along with testing the sensitivity of input parameters.

How can the estimated features be validated?

In what ways can the results be communicated in order to demonstrate the additional value of characterized 3D close-range measurements?
9.2. Objectives Reached

The added value of estimating morphological parameters on 3D outcrop point clouds can be appreciated only if shared and communicated well. Several platforms address this need depending on many criteria such as the audience, ease of sharing, available hosting space, 3D geometry vs. location priorities, etc. The LIME software developed at Uni Research CIPR in Bergen, Norway, was found to best incorporate good 3D visualization along with many options for personalization and annotation. Assuming that this data will be used for instructing students about outcrops prior to and following fieldwork experiences, the platform is well-designed and intuitive for students to gain a deeper understanding in a controlled and repeatable environment.

What morphological features of rock outcrops are characteristic and can be estimated from close-range, three dimensional, measurement data?

Overall, it has been demonstrated that characteristic features of rock outcrops (strata orientation and thicknesses) can be estimated, semi-automatically, from close-range 3D measurement data. The terrestrial laser scanner provides adequate information about the rocks themselves to enable planar fitting that eventually supports parameter estimation. These estimated values can give better context to outcrops that are difficult or dangerous to measure with traditional methods and can be used for validation of measurements on outcrops that are easily characterized.

9.2. Objectives Reached

Several other objectives were defined for the project, as listed below.

- Collecting laser scans of multiple outcrops in the Vesc region
- Creating a post-processing instruction manual for converting raw point cloud data to Matlab-friendly .csv files
- Becoming a Leica C10 laser scanning expert by assisting in various laser scanning projects proposed throughout the department (and by visiting scholars)
- Providing recommendations on virtual modeling environments for possible use in future (Bachelor course) fieldwork preparation and documentation
- Developing and sharing an intuitive algorithm for outcrop parameter estimation that can be built upon for further investigation

Each of these objectives have been met, and have all added to the experience of the study. Practical skills handed off to others interested not only stimulates interest in the field, but also encourages further study.

9.3. Results of Hypothesis

As hypothesized, it is confirmed that a semi-automatic algorithm can be developed to extract the dip, dip direction, and layer thicknesses of sedimentary outcrops represented in 3D point cloud data gathered from a terrestrial laser scanner.


A.1. Fieldwork Preparation

Packing

- Laser Scanner
  □ scanner red box
  □ (4) batteries
  □ battery charger
  □ tripod
  □ tripod road stand
  □ (3) circular targets
  □ (3) circular target bases
  □ (6) square targets
  □ (3) wooden stakes
  □ (2) target tripods

- GPS
  □ (2) receivers: base and RTK
  □ (2) antennas: base and RTK
  □ tripod
  □ (4) batteries
  □ battery charger

- Other
  □ camera
  □ camera battery / charger
  □ laptop
  □ mouse
  □ laptop power cord
  □ GPS connectivity cords
  □ large USB storage device
  □ external phone battery bank + USB cord
☐ clip board / binder / notebook / pens
☐ (2) safety vests
☐ nails for wooden targets
☐ hammer
☐ duct tape
☐ clear packing tape

To Do

• Logistics
  ☐ book transportation to / from
  ☐ book housing
  ☐ reserve car
  ☐ allocate transportation of supplies
  ☐ select (8) outcrops

• Instrument Preparation
  ☐ work out GPS issue with Hans
  ☐ apply labels to all instruments
  ☐ submit scanner insurance form
  ☐ locate DSLR camera and reserve
  ☐ complete worksheets / manuals / checklists

• Supplies
  ☐ order USB storage device
  ☐ purchase clip board / binder / tape
  ☐ download GPS app and add outcrop locations
  ☐ download offline driving GPS app and load destinations
A.2. How to Laser Scan

Using the Leica ScanStation C10/5

Materials

- Laser Scanner (red box)
- (4) charged batteries
- tripod
- metal tripod stand
- (4+) targets + tripods (?)
- hammer
- GPS BaseStation + cord + batteries + antenna + attachments
- GPS Rover
- flash drive
- notebook / pen

Notes

Maximum distance from target object is recommended between 5 and 100 meters. Can be analyzed best with Cyclone (TU Delft has 1 license on a laptop). Can also be viewed with CloudCompare software on any machine. A more detailed procedure has been developed with Isabelle de Lange (TU Delft).

Procedure

1. Power On
   Do this as soon as the laser scanner is secure on the tripod as it takes two minutes

2. Level
   Both manually with central bubble and by clicking the ruler button in the center of the header bar on the screen, REMOVE HANDLE

3. Start New Project
   Manage → Projects → New (delete projects if necessary to make room, this should be done prior to coming to the field), select a new name for the entire project, Store, Cont
   Scan → StdStp → Set in Main Menu

4. Lo-Res Scan
   Settings: Fld of View = Custom View, L/R 0 → 360, B/T -45 → 90; Resolution = Low Res
   Either Sc+Img or Scan (with image is recommended for pano view orientation)
   Get out of the way, Pause on screen if necessary (Scan takes ≈2 mins, photo ≈4 mins)
   Vwimg on bottom banner to view image and insure the correct scene was scanned

5. Establish Targets
   Set targets at different heights and not in a line (secure, add warning tape if necessary)
   Click circle button in the center of the header bar on the screen
   Add target types and scan

6. Hi-Res Scan
   Settings: Fld of View = Custom View, VwSc, click and drag with fence tool; Resolution = Custom Res,
   Dist on bottom banner, select point then ruler, H/V → define (max res < 6000 X 6000)
   Either Sc+Img or Scan (image isn’t needed if done for whole area)

7. New Station
   X, Scan → StdStp (name or accept defaults) → Set
   Continue with steps 3/4
8. Saving Data
   Measure station height with plummet
   Plug in USB
   Tools → Transfer → Project

9. Power Down
   X, X, X, yes
   Remove batteries and store / charge
   Once the fan turns off you can put it away
A.3. Appendix: Post-Processing Leica C10 Scan Data

A step-by-step guide to point cloud files: laser scanner → Cyclone → CloudCompare → Matlab

Raw point cloud data files are stored directly on the Leica C10 laser scanner in .bin, or binary, format along with optional images taken of the scene. In this appendix, the following sections provide a step-by-step guide to importing the gathered data and merging multiple station data in Cyclone. After import and basic manipulation, exporting the Cyclone files to more versatile point cloud formats such as .ptx or .xyz is also discussed. These formats can be useful for further analysis and sharing in CloudCompare or Matlab, for example. The final section covers some tips for extracting only necessary information in CloudCompare and exporting that data to Matlab for further analysis (as was done in this project). The steps that follow are designed specifically for the Delft University of Technology laptop, TUD251188, which has Cyclone v9.0.0 installed.

Materials

- USB drive with .bin data files exported from scanner
- Computer with Cyclone, CloudCompare, and Matlab

Procedure

A.3.1. Cyclone: Importing Raw Files

As mentioned, raw files are stored internally on the laser scanner. These files can be transferred to your computer via the USB port on the front interface of the scanner. See the scanning manual in Appendix A.2 for how to export files to a USB device. Once imported into the computer, using the following steps, the files can be viewed, manipulated, combined (or registered), and exported from the Cyclone manager.

1. Insert USB stick with raw data into laptop
2. Open Cyclone (icon on desktop of TUD251188)
3. In the Navigator tree, expand 'SERVERS' → 'TUD251188 (unshared)' to view current projects in the program archive
4. To add a project, right click on the 'TUD251188 (unshared)' branch → 'Databases...'
5. In the Configure Databases window that pops up, select ‘Add’ to add your project and simply give it a Database Name, for example ‘X’ (note, you do not need to add a ‘Database Filename’)

![Configure Databases window]

6. ‘X’ should now show up at the end of the ‘TUD251188 (unshared)’ branch in the Navigator window; you can ‘Close’ the Configure Databases window or add another project.

7. To import raw scan files, right click on ‘X’ → ‘Import ScanStation C5/C10 Data’ → ‘Import ScanStation C5/C10 Project’...

8. Expand the folder ‘Scanner-Projects’ on the USB drive and select the project you wish to import → ‘OK’ (note, select the whole project, not a single station).

9. Confirm import and accept default settings for importing ‘OK’, ‘Continue’ (this may take a while).

A.3.2. Cyclone: Point Cloud Registration

At this point, all .bin files of the selected project have been imported into Cyclone. If multiple scanner locations, or stations, were used to collect the data for the project, these separate point clouds should be aligned and merged. The aligning and merging of several point clouds is called registration. Assuming that targets were used correctly and scanned at each station (see Scanning Instruction Manual in the Appendix), the following procedure can be implemented for creating a registration of the point clouds. The result will be a single point cloud containing all points from all stations, correctly oriented with respect to each other (within a tolerance).

1. Right click on ‘X’ → ‘Create’ → ‘Registration’; a new sub-branch should be now visible under ‘X’ in the Navigator tree called ‘Registration 1’

2. Double click on the newly created branch, ‘Registration 1’, to open the Registration wizard window.

![Registration wizard window]
3. Select the 'Add ScanWorld' button on the top banner to view available scans / stations

4. Expand each of the stations until 'SW-00#'; highlight each one and move them to the right field with the '>>' button, 'OK'

5. 'Auto-add Constraints' with the button in the top banner to initialize the targets ('Close' warnings to ignore for now)

6. Run the initial registration with the 'Register' button in the top banner

7. Expand all stations and target pairs to evaluate the initial scan 'Error's

8. If certain target pair errors are too high, three options are available: delete the bad pairs (right click the target line, 'Delete'), toggle them off (right click, 'Disable'), or reduce their weights (right click, 'Set Weight...')

9. Re-run the registration with these modifications, 'Register', until all errors are acceptable and at least two pairs for each station remain (only two are required since it is assumed that the scanner was properly leveled, three or more pairs are thus recommended, see Section XXX for more information on choosing targets)

10. Group pointclouds with 'Create ScanWorld Groups with Targets' button in the top banner, 'OK', 'OK', and 'OK' to accept ScanWorld Groups default settings

11. Finalize the registration with the 'Create ScanWorld / Freeze Registration' button in the top banner

12. Exit the Registration wizard window by closing (no saving is necessary)
13. Back in the Cyclone Navigator window, expand the newly created registration called 'ScanWorld [Registration 1]' until you see the 'ModelSpaces' folder.

14. Right click on 'ModelSpaces' → 'Create' → 'ModelSpace'.

15. Double click and select 'Open Temporary ModelSpace View'.

16. Pan around the project scene to verify the registration.

A.3.3. Cyclone: Converting File Type and Exporting

The imported and registered (optional) scan data is stored in Cyclone as an .imp file. Since analysis is limited within Cyclone itself, and limited to users with a license, it can be helpful to convert the point cloud into a more general format such as '.ptx' or '.xyz'. Both of these formats can be opened by point cloud processing programs such as CloudCompare or more general tools such as Matlab. These are only a couple of examples. The steps to convert point clouds in Cyclone to .ptx are described below.

1. In the Navigator window, right click or double click on 'Modelspace 1' to 'Open Temporary ModelSpace View'.
   - for single scans, the 'ModelSpaces' folder is under the 'Station-001' → 'SW-001'
   - for registered points clouds, the 'Modelspaces' folder can be found under 'ScanWorld [Registration 1]'
   - if no ModelSpaces exist in the folder, add one by right clicking on the folder → 'Create' → 'ModelSpace')

2. Pan around until the point cloud is visible and verify that all stations are included if multiple scans were taken.

3. In the top menu next to 'File' and 'Edit', expand the 'Selection' menu and 'Select All' (points should look slightly larger).

4. Check the bottom of the screen so verify how many point clouds have been selected.

5. Again in the top menu, select 'File' → 'Export...'

6. Select a destination, filename, and file format ('.ptx' is recommended).

7. Confirm export with 'Save' (sometimes you have to click 'Save' twice) and 'Export' with settings as shown below (this may take a while for large point clouds).
A.3.4. CloudCompare: Minimizing File Size and Exporting

Although some analysis can be completed within Cyclone (not described), many more functions and built-in plugins are available in the free and open source point cloud analysis software called CloudCompare. The .ptx files from Cyclone can be easily imported to CloudCompare, modified, and then exported to a Matlab-friendly format. Some suggested functions are outlined below, especially designed for reducing file size for outcrop analysis in Matlab.

1. Open CloudCompare (icon on desktop of TUD251188)
2. ‘File’ → ‘Open’ to open the .ptx file exported from Cyclone (this may take a while)
3. All clouds within the imported project should show up in the 'DB Tree' at the left, the point cloud visualization in the panel to the right
4. Since multiple point clouds were registered in Cyclone, they can be merged by highlighting all clouds in the 'DB Tree' and using the Merge multiple clouds' function in the top banner
5. To visualize the true colors of the point cloud (if images were taken during the scan), highlight the merged cloud in the DB Tree and select 'RGB' in the 'Properties' panel under 'Color'
6. Orient the outcrop in the visualization window so that the ground level at the bottom of the screen; the ‘Pick rotation center’ button on the left banner can assist with this (just click the button and then click on a new rotation point in the point cloud visualization panel)
7. With the cloud still highlighted in the DB Tree, select the Segment’ button in the top banner
8. Using the icon bar that appears in the right corner of the visualization panel, use a Rectangular selection’ to click and drag a rectangle over the desired section to crop
9. Continue until the shape is what you want; the Pause’ button can be used to change view points and then toggle the 'Pause' off again to select a segment shape
10. The 'Segment In' button will keep all points within the crop box while the 'Segment Out' button will do the opposite, choose accordingly.

11. The 'Clear segmentation' button can be used to undo an undesired segmentation.

12. If the results displayed in the visualization panel appear good, select the 'Confirm segmentation' button to finalize the selection.

13. In the DB Tree panel, the '*.remaining' file can be deleted by highlighting and using the 'Delete' button in the top panel so only the desired sample region remains.

14. It is recommended to 'File' → 'Save' this point cloud as .pts now for reference later with 'OK' to the following settings:

15. One final step could be to subsample the small section; with the cloud highlighted in the 'DB Tree', click the 'Subsample a point cloud' button in the top banner.
   Note: another option can be to try the 'Octree → Resample' method under the 'Edit' drop down menu. The Resample tool computes the center of gravity of the points falling in each cell (i.e. the created cloud is not a subset of the original cloud).

16. Several options are available for subsampling methods:
   - **Random**: In 'random' mode, CloudCompare will simply pick the specified number of points in a random manner.
   - **Space**: In 'spatial' mode, the user must set a minimal distance between two points. CloudCompare will then pick points from the original cloud so that no point in the output cloud is closer to another point than the specified value.
   - **Octree**: The 'octree' mode lets you select a level of subdivision of the octree at which the cloud will be 'simplified'. In each cell of the octree, the nearest point to the octree cell center is kept.

17. The '*.subsampled' cloud in the 'DB Tree' contains the subsampled data, 'Delete' the other cloud.

18. 'File' → 'Save' this subsampled, segmented point cloud as a .csv file using 'OK' for the settings shown above (.csv is recommended for easy import into Matlab, a program that can be used for further analysis).
A.3.5. Matlab: Basic Point Cloud Functions

If analysis in Matlab is desired, smaller point cloud files can greatly reduce computation time and rendering while developing algorithms. Here, the subsampled and segmented .csv exported from CloudCompare works well. The file contains comma-separated \([X, Y, Z, i, R, G, B]\) data for each point. The \(XYZ\) refer to the points location with respect to the scanner, \(i\) is the intensity of the laser return, and \(RGB\) are color channels that can be recognized directly in Matlab. Possibilities of point cloud manipulation in Matlab are endless, but some suggestions and tips to get started are below.

1. **Importing**: The simplest way to import .csv point cloud files is through Matlab’s ‘Import Data’ function on the ‘Home’ tab. Here, you just select the .csv file and, generally, the file is read automatically. Some modifications may need to be made in ‘Import’ tab of the ‘Import’ pop-up window to only select necessary data, etc. If the preview looks good, the ‘Import Selection’ drop-down gives an option to ‘Generate Script’. This can be helpful for quick importing of other files later on and can be modified for a specific function.

![Matlab Import and Plotting](image)

2. **Plotting**: There are three main functions recommended for plotting the basic point cloud: `plot3()` or `scatter3()` which are simply 3D plots of the \(XYZ\) points that can be colored by \(i\) intensity values or \(RGB\) and `pcshow()` which is part of the 3D Point Cloud Processing toolbox in Matlab. Examples are shown below:

![Matlab Plot Examples](image)

Figure A.1: The Matlab plot examples show a subsampled and classified point cloud with `plot3()` (left), the intensity return with `scatter3()` (center), and a true color point cloud with `pcshow()` (right).

The following Matlab code excerpt shows the basics of creating plots using the three mentioned commands. The raw structure contains imported raw data and is organized in \(XYZIRGB\) format. The values can either be used as is (the first two functions) or converted into a `pointCloud` object and then plotted (as with the final function).

```matlab
%% Examples of plotting ‘raw’ imported point cloud data in Matlab
```
3. Built-in functions: Some helpful point cloud analysis functions can be found in the 3D Point Cloud Processing toolbox within Matlab. These functions can be further modified and customized (with input parameters) to best model the data. A quick summary of some suggested functions follow (more functions exist):

- **Storing a Point Cloud**
  - `pointCloud` Object for storing a 3-D point cloud
  - `findNearestNeighbors` Find nearest neighbors of a point
  - `findNeighborsInRadius` Find neighbors within a radius
  - `findPointsInROI` Find points within ROI
  - `removeInvalidPoints` Remove invalid points

- **Visualizing a Point Cloud**
  - `pcshow` Plot 3-D point cloud
  - `pcshowpair` Visualize difference between two point clouds
  - `pcplayer` Visualize streaming 3-D point cloud data

- **Registration**
  - `pcdownsample` Downsample a 3-D point cloud
  - `pctransform` Rigid transform of 3-D point cloud
  - `pcregrigid` Register two point clouds using ICP algorithm
  - `pcmerge` Merge two 3-D point clouds

- **Model Fitting**
  - `pcfitcylinder` Fit cylinder to 3-D point cloud
  - `pcfitplane` Fit plane to 3-D point cloud
  - `pcfitsphere` Fit sphere to 3-D point cloud
  - `pcnormals` Estimate normals for point cloud

- **Preprocessing Point Clouds**
  - `pcdenoise` Remove noise from 3-D point cloud
  - `pcdownsample` Downsample a 3-D point cloud

- definitions from Matlab 3D Point Cloud Processing toolbox webpage: https://nl.mathworks.com/help/vision/3-d-point-cloud-processing.html

A.3.6. Notes

The view spaces in Cyclone are defined as follows:

- **ScanWorld**: A single scan or collection of scans that are aligned to a common coordinate system. Scan-worlds contain ControlSpaces and ModelSpaces.

- **ControlSpace**: Contains the constraint information used to register multiple scans together.

- **ModelSpace**: Contains information from the database that has been modeled, process, or changed in some way.
• **ModelSpace Views**: Where you make any/all changes on a point cloud or create 3D models.

• **TruSpace**: New to Cyclone 7. Truspaces are views that are constrained to individual scanner locations. Note you cannot PAN a view in a truspace. Once a series of scans are aligned, you can view their individual TruSpaces and also jump between them from within the registered ModelSpace. You can also do basic measurements and extract targets in TruSpaces. To view a scans TruSpace, simply RC on the scan (Scanworld) and select Open TruSpace.

Definitions from Payne [2011].

* This guide was developed with the help of Isabelle de Lange (TU Delft) and Rianne Broeksma (TU Delft).
A.4. Stratigraphic Column of the Study Region

Image credit: Jan Kees Blom, Susana Del Pozo
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