GROUND-BASED LiDAR
Rock Slope Mapping and Assessment

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Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
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FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The FLH has an interest in using new technology to assist in designing and constructing roads more efficiently. One emerging three-dimensional mapping technology is terrestrial or ground-based LiDAR. LiDAR (Light Detection and Ranging), also often referred to as "3D laser scanning", employs a laser and a rotating mirror or housing to rapidly scan and image volumes and surficial areas such as rock slopes and outcrops, buildings, bridges and other natural and man-made objects. Ground-based or terrestrial LiDAR refers to tripod-based measurements, as opposed to airborne LiDAR measurements made from airplanes or helicopters.

This project shows how the new technology of ground-based LiDAR could assist FHWA with highway rock slope stability. Site characterization for rock slope stability involves the collection of geotechnical data, and in the current practice, much of this data is collected by hand directly at exposed highway slopes and rock outcrops. There are many issues with the collection of this data in the field, including issues of safety, slope access, and human bias. It is shown in this report that some of the most important types of geotechnical information for rock slope stability can be acquired using LiDAR at a safe distance from the slope. In many cases, this information can also be automatically extracted from LiDAR point clouds using currently available point cloud processing software, reducing human bias issues. This report concludes that indeed there are benefits available when ground-based LiDAR is employed.

F. David Zanetell, P.E., Director of Project Delivery
Federal Highway Administration
Central Federal Lands Highway Division

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16. Abstract

LiDAR (Light Detection and Ranging), also often referred to as "3D laser scanning", is an emerging three-dimensional mapping technology that employs a laser and a rotating mirror or housing to rapidly scan and image volumes and surficial areas such as rock slopes and outcrops, buildings, bridges and other natural and man-made objects. Ground-based or terrestrial LiDAR refers to tripod-based measurements, as opposed to airborne LiDAR measurements made from airplanes or helicopters. The purpose of this report was to determine whether the new technology of ground-based LiDAR could assist FHWA with highway rock slope stability. This report includes discussions of currently available LiDAR hardware and software, the current state of LiDAR for highway geotechnical applications (rock mass characterization, rockfall characterization, as-built 3D measurements), best-practices for field scanning and for point cloud data processing, and expected trends in the industry in the near future. It is shown in this report that some of the most important types of geotechnical information for rock slope stability that is currently being collected by hand can be acquired from LiDAR point clouds and associated digital images. This includes detailed information about rock discontinuity orientation, roughness, length, spacing and block size. In many cases, this information can be automatically acquired using currently available point cloud processing software. There are advantages to using LiDAR for collecting this information, including improved safety, accuracy, slope access, and speed of analysis. It is recommended that LiDAR be utilized for future highway slope stability projects.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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This project was funded under the FHWA's Federal Lands Highway Technology Deployment Initiatives and Partnership Program (TDIPP).

CHAPTER 1 – INTRODUCTION AND BACKGROUND

Ensuring rock slope stability is a major safety goal along highways. Rock slope instability can occur in many forms, including rapid large-scale rock instability, rockfall, and time-dependent slope degradation and failure. Unstable rock slopes pose a safety hazard that results in accidents and fatalities along U.S. highways every year (Badger and Lowell, 1992; Schuster and Fleming, 1986). Unstable slopes also require costly ongoing maintenance and design improvements such as the installation of rockfall barriers to mitigate rockfall or highway realignments to avoid major unstable rock slopes.

Site characterization is required initially to determine the potential for highway slope instability and to engineer appropriate mitigation methods, which can include catch basins, rockfall fences, ground support, drainage systems, rock sheds, tunnels, etc. Site characterization is also periodically required over the life of the highway because changes in the stability of rock slopes can occur as highway slopes weather and deteriorate. Rock mass site characterization involves the collection of geotechnical data, including information about rock structure, geology, intact rock strength, hydrology, climate, and earthquakes. (Priest, 1993, Hudson and Harrison, 2000). In the current practice, much of this data is collected by hand directly at exposed highway slopes and rock outcrops, including measurements of discontinuity orientation, roughness, fill, length, and spacing. There are many issues with the collection of data in the field, including:

- Safety hazards associated with the collection of this data
- Difficulties in accessing rock outcrops on large slopes or cliffs
- Human bias and accuracy issues associated with selecting areas for measurement and the accuracy of the hand-collected measurements themselves
- Relatively slow data collection and manpower intensive
- Because of the issue above, slope stability calculations with relatively small data sets
- The lack of three dimensional information about the slope (other than surveyed points) that could be used for comparison as slopes weather and deteriorate

To address these issues, new technologies are needed that provide the following benefits:

- Automatic data acquisition over entire slope
- Remote data acquisition for improved safety
- Rapid data collection
- New technologies for data collection and processing easy to learn and operate
- Able to provide a high-resolution 3D Digital Terrain Model (DTM) of a highway slope or rock outcrop that could be compared with future DTMs as the slope ages and deteriorates
- Cost effective

The purpose of this report was to determine whether the new technology of ground-based LiDAR (Light Detection and Ranging) could assist FHWA with highway rock slope stability as described in the list above. LiDAR, also often referred to as “3D laser scanning”, is an emerging three-dimensional mapping technology that employs a laser and a rotating mirror or housing to rapidly scan and image volumes and surficial areas such as rock slopes and outcrops, buildings, bridges and other natural and man-made objects. Ground-based or terrestrial LiDAR refers to tripod-based measurements, as opposed to airborne LiDAR measurements made from airplanes or helicopters.

The output from ground-based LiDAR is a point cloud consisting of millions of laser distance measurements representing the three-dimensional scanned scene. The point clouds are then processed to extract geotechnical information, which includes discontinuity orientation, length, spacing, roughness, and block size. High-resolution digital images are also taken of the scanned scene, and these images can be "draped" onto the point cloud using texture-mapping techniques (Blythe, 1999) to provide a 3D color DTM of the scanned scene. Additional geological and geotechnical information can be extracted from the DTM that would be difficult to observe in the point cloud.

The primary goals of this 18-month study were to:

1. Investigate LiDAR hardware currently available for highway rock slope stability;
2. Investigate point cloud processing software currently available for highway rock slope stability;
3. Evaluate the current state of the technology for providing useful benefits (as discussed in the list above) and compare with other technologies such as photogrammetry;
4. Identify best-practices to be used when conducting field scanning, and also when using software for processing data;
5. Recommend standards for using LiDAR in highway rock slope stability projects; and
6. Investigate likely improvements in LiDAR hardware and software in the next few years.

The list above roughly correlates with the chapters to follow. Chapter 2 of this report provides an overview of LiDAR hardware, and the basic procedure involved in conducting a LiDAR scan in the field. Chapter 3 describes the software used in processing data from LiDAR scans, including point cloud processing software and the interoperability with CADD and other highway design software packages. Chapter 4 describes the primary highway geotechnical applications for LiDAR, including rock mass characterization, rockfall, and detailed 3D surveying. It also includes a section on the accuracy of LiDAR-generated data, and a section comparing LiDAR with ground-based photogrammetry. In Chapter 5, the "best practices" for conducting LiDAR surveys in the field and processing the data are given, based on experiences in a number of different rock and engineering environments in the past several years. Chapter 6 discusses expected advances in LiDAR hardware and software in the next five or so years. Finally, conclusions and recommendations are presented in Chapter 7.

This report concludes that indeed there are benefits available when ground-based LiDAR is employed.

CHAPTER 2 - LiDAR HARDWARE

HOW 3D LASER SCANNERS WORK

3D laser scanners work by emitting light and detecting the reflection of the light in order to accurately determine the distance to the reflected object. Rather than making a single measurement as in a laser rangefinder, 3D laser scanners have rotating mirrors (or the entire unit rotates) that allow millions of measurements to be made over a scene in just a few seconds or minutes (depending on the type of scanner).

There are two primary types of 3D laser scanners: time-of-flight scanners and phase-shift scanners. Time-of-flight laser scanners emit a pulse of laser light that is reflected off the scanned object. A sensor measures the time of flight for the optical pulse to travel to and from the reflected surface. The distance the pulse traveled is then calculated using the following equation.

$$\textbf{Distance} = \textbf{(Speed of Light * Time of Flight)/2} \tag{1}$$

Some time-of-flight scanners have the ability to measure several arrival times for an emitted pulse. In a scan of a slope with vegetation, for example, the "first arrival" would indicate the distance to the top of the vegetation, and the "last arrival" would indicate the distance to the ground surface.

In phase-shift scanners, a laser beam with sinusoidally modulated optical power is emitted and reflected off an object. The reflected light is then detected and compared with the emitted light to determine the phase shift. The time of flight can then be determined from the following equation:

$$\textbf{Time of Flight} = \textbf{Phase Shift / } (2\pi \textbf{ * Modulation Frequency}) \tag{2}$$

The values calculated by Equation 2 are then substituted into Equation 1 to find the distance. Multiple modulation frequencies are often used to increase the accuracy of the time-of-flight determination.

THE POINT CLOUD

Immediately after one pulse is received and measured, the scanner transmits another optical pulse slightly horizontal (or vertical – depending on the scanner) to the previous pulse using a rotating mirror. This process is repeated thousands of times per second, thus generating distance values for millions of points on a reflected surface. From the distance and the orientation of the laser pulse, the xyz coordinates associated with each reflected pulse can be determined. In addition, the intensity of the returned pulse is determined. In general, light colored objects and closer objects give a higher reflection compared with darker objects and objects farther away. Together, the xyz coordinates and associated intensity values for millions of data points outputted by the laser make up the “point cloud”. An example of a point cloud of a rock face along the Mt. Lemmon Highway in southern Arizona is shown in Figure 1a. This point cloud has about one million points. Also, it has a photographic quality because of the intensity values, that is, light objects are brighter than darker objects. A color point cloud can also be produced by associating color information from a digital image with the location of each point. An example of a color point cloud is shown in Figure 1b.

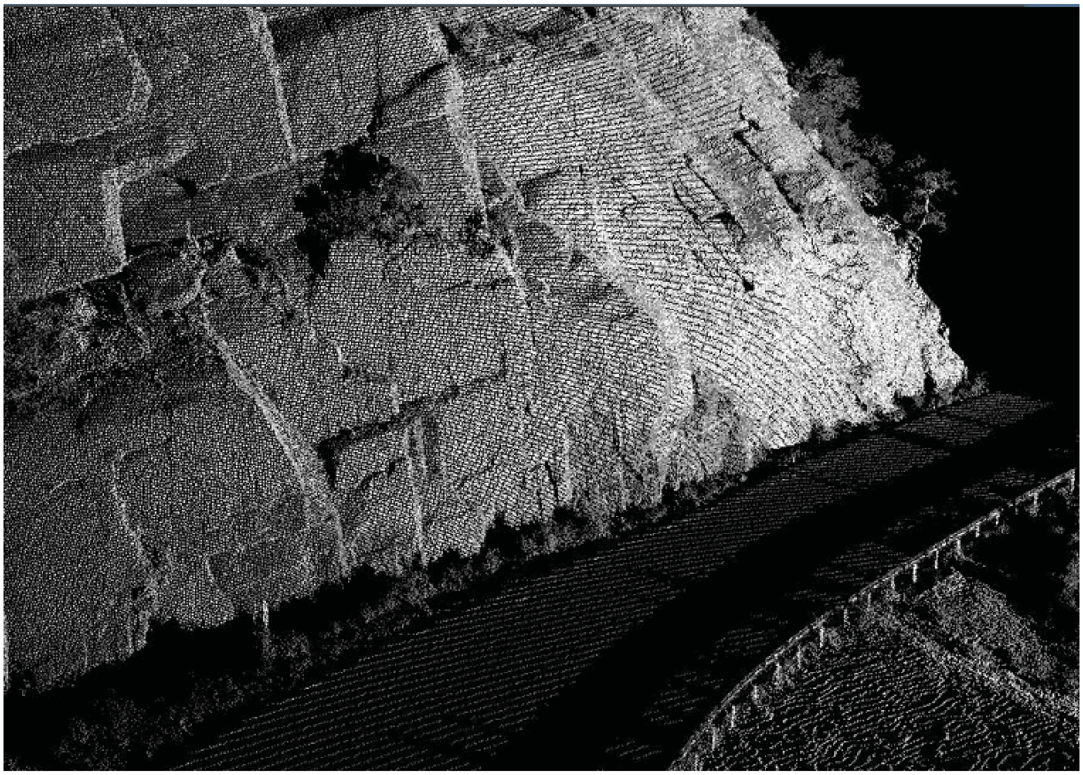


Figure 1a. Schematic. Point cloud of a rock face along Mt. Lemmon Highway, Arizona.

Figure 1b. Schematic. Color point cloud of a rock face near San Juan, Argentina.

MANUFACTURES AND PRODUCT SPECIFICATIONS

At the current time, there are a number of ground-based LiDAR manufacturers making scanners suitable for highway rock slope stability investigations. These included:

- Optech (www.optech.ca)
- Trimble (www.trimble.com)
- Leica Geosystems (www.leica-geosystems.com)
- Riegl (www.riegl.com)
- Faro (www.faro.com)
- Isite (www.isite3d.com)
- Zoller+Fröhlich (www.zofre.de)
- InteliSum (www.rappidmapper.net)

There are other scanners that are not listed because the range is not suitable for rock slope investigations (less than 10 meters). A complete list of terrestrial scanners is given in Appendix A. Several of these scanners are shown in Figure 2.

Figure 2. Photo. Examples of ground-based LiDAR scanners (time-of-flight unless noted otherwise, photos from 2006 models).

A complete list of specifications on currently available 3D laser scanners is given in Appendix A (from POB, 2008). Example specifications for the Optech ILRIS 3D time-of-flight scanner and the Leica HDS6000 phase-shift scanner are given in Table 1 below.

Table 1. Specifications for ILRIS-3D and HDS6000 scanners (from POB, 2008).

Parameter	**Optec ILRIS 3D** (time of flight)	**Leica HDS6000** (phase shift)
Wavelength	1550 nm	650, 690 nm
Minimum range	3 m	0.1 m
Maximum range	1500 m at 80% reflectivity	79 m at 90% reflectivity
Average data acquisition rate	2500 points per second	125,000 points per second
Beam diameter	29 mm @ 100 m	8 mm @ 25 m
Distance accuracy	7 mm @ 100 m	4 mm @ 25 m
Position accuracy	8 mm @ 100 m	6 mm @ 25 m
Angular accuracy	0.00115 degrees	0.0071 degrees
Scanner weight	13 kg not including batteries	14 kg including batteries
Distance and position accuracies are ± 1 sigma (68% confidence level)		

Table 1 points out some of the differences between time-of-flight and phase shift scanners. The time-of-flight scanners are capable of a much larger range compared with the phase shift scanners. Thus time-of-flight scanners would be preferred for large highway slopes and cliffs, while phase shift scanners would be preferred for small underground tunnels, for example. Also, the phase shift scanners have a much higher average data acquisition rate compared with the time-of-flight scanners. In terms of distance and position accuracies, the phase shift scanners have a slightly higher accuracy compared with the time-of-flight scanners. Both types of scanners are portable but, the phase shift scanners are lighter. When comparing weights note that the batteries are usually included in the phase-shift scanner unit, while the external batteries in the time-of-flight scanners can add at least 10 kg (22 lb) to the weight of the time of flight scanners.

PRICE

3D laser scanners range in price from $70,000 to over $150,000 (based on 2008 prices). Alternatives to purchasing a new scanner include buying a used scanner or renting a scanner on a daily or weekly basis. Distributors for the purchase of new scanners can be found on the LiDAR manufactures web sites. A good source for used scanners is the classified section of the Spar Point Research web site (http://sparllc.com/classifieds.php). Companies that rent scanners include surveying companies as well s the LiDAR manufacturers.

SCANNING PROCEDURES

A brief overview of the procedures for scanning a highway slope or natural rock outcrop is given below. Note that additional details on these steps are given in the “best practices” section of Chapter 5. Figure 3 illustrates some of the basic steps involved in field scanning.

1. The scanner is placed at the outcrop of interest, at a safe distance from moving cars and steep cliffs. The scanner does not need to be level; however, leveling the scanner simplifies the scanner registration process.

2. The manufacturer’s software is used to set the scanner field of view and the LiDAR point spacing, using either a laptop computer or a handheld device.

3. A method for survey control is established (scanner registration). Methods include placing surveyed targets in the scene as shown in Figure 3, establishing the location and orientation of the scanner, back sighting to known points, and other methods.

4. Scanning is conducted. With a time-of-flight scanner this generally requires 5-25 minutes per scan to produce a point cloud with one to three million points. A phase-shift scanner would require less than 30 seconds for a point cloud with one to three million points.

Figure 3. Photo. Scanning with the Leica ScanStation at Milepost 15 on Mt. Lemmon Highway. Point cloud shown in the lower right photo.

5. Digital images are taken. High-resolution digital images accompany each LiDAR scan. Most scanners automatically capture the images using a built in camera. Some cameras are mounted on the inside of the scanner, some are mounted on the outside. By knowing the position of the camera relative to the laser and the camera characteristics, a color point cloud can be produced, and also the digital images can be draped onto the point cloud using texture-mapping techniques.

6. Point clouds are produced, as illustrated in Figures 1 and 3. Details on the point cloud file and software used for further processing are described in Chapter 3.

7. In general, 5-10 scans can be conducted in a day, depending on terrain, scan area, and the travel time to each site. A typical scan is taken from 20 to 100 meters from the rock outcrop, and a typical scan area can vary from 15x15 m^2 to over 50x50 m^2. The smaller areas require less than 10 minutes to scan, while a 50x50 m^2 area takes about 45 minutes to scan with a time-of-flight scanner. More details are provided in Chapter 5.

CHAPTER 3 – POINT CLOUD PROCESSING SOFTWARE

Point clouds by themselves are not useful without software to process the data and make measurements and other calculations. Also, in order to be useful, the point cloud data needs to interface easily with Computer Aided Design/Drafting (CADD) and slope stability programs. This section discusses the point cloud file format, point cloud processing software, and interfacing between point cloud software and other CADD and slope stability software.

THE POINT CLOUD FILE

As discusses in Chapter 2, the point cloud is the basic output from a 3D laser scanner. The most generic point cloud file format is a 3D coordinate file (often referred to as an xyz file). The format for this file is ASCII and can therefore be read by all post-processing software. The comma or tab-separated format for a grayscale 3D coordinate file is as follows with one line for each laser point:

Grayscale point cloud: x1 y1 z1 intensity1
x2 y2 z2 intensity2
…

The x, y and z values refer to a specific coordinate system. If the point cloud is not registered, then by default the y direction is most often set to the instrument direction. After registration, the x, y and z directions are most often set to East, North and up, respectively. However these systems are not universal and the scanner or software manufacturer should be contacted for information on their specific 3D coordinate formats. The intensity for each point has a value that range from 0 (black) to 255 (white).

Similarly, the comma or tab-separated format for an rgb (red, green blue) 3D coordinate file is as follows:

Color point cloud: x1, y1, z1, r1, g1, b1
x2, y2, z2, r2, g2, b2
…

Here r, g and b each have values that range from 0 to 255. Because the xyz file is ASCII, these files are slow to read and write; they also only contain the basic point cloud information. In general, each scanner manufacturer, and also each point cloud processing software manufacturer, has their own specialized binary format. Some examples of file extensions associated with different binary formats are given below.

Scanner manufacturer:
Leica: .coe
Riegl: .3dd

Point cloud processing software manufacturer:
Polyworks: .pif file format
Split FX: .fx file format

At the present time the ASCII 3D coordinate file is the standard format for point clouds. However, because it is ASCII and only contains point cloud information, that is, no digital image or tin surface information, other formats have been discussed by both manufactures and users as better standard file formats for ground-based LiDAR output. These formats include the LiDAR Exchange Format (LAS) and the Virtual Reality Modeling Language (VRML). Additional details on these file formats are discussed in Chapter 6.

POINT CLOUD REGISTRATION

The first step in point cloud processing is to orient the point cloud into the real world coordinate system based on data taken in the field. Point cloud software usually includes several methods for point cloud registration. The most common method is to register the point cloud based on three or more targets of known position (3D similarity transformation). However, for some applications (such as slope stability), only the orientation registration is required. This means that the point cloud is oriented correctly, but the 3D coordinates are not registered to a known coordinate system (Universal Transverse Mercator coordinate system, for example). In these instances, simpler registration methods are possible, such as only measuring the orientation of the scanner (orient by scanner method) without any position surveying. In this case the scanner's position is defined by the bearing or direction of its line of sight, its inclination in the direction of the line of sight, and its inclination perpendicular to the line of sight. This provides enough information to correctly georeference the orientation of the scan (but not the position).

POINT CLOUD PROCESSING SOFTWARE

Most of the scanner manufacturers have developed their own point cloud processing software. In addition, several other companies have developed point cloud processing software. By exporting the point clouds in the xyz file format, point clouds from any scanner can be analyzed with any of the software packages. Point cloud processing software includes:

- Cyclone and Cyclone Cloudworx (Leica, www.leica-geosystems.com)
- Polyworks (Innovmetric, www.innovmetric.com)
- Riscan Pro (Riegl, www.riegl.com)
- Isite Studio (Isite, www.isite3d.com)
- LFM Software (Zoller+Fröhlich, www.zofre.de)
- Split FX (Split Engineering, www.spliteng.com)
- RealWorks Survey (Trimble, www.trimble.com)

Details on some of the software listed above are given in Appendix B (from POB, 2008).

The following editing/analysis features are found in most of the software packages:

- General point cloud visualization, including pan, tilt, and zoom;
- General point cloud editing, including adding and deleting points, noise removal, point decimation;
- Ability to make measurements such as distances, angles, areas and volumes;
- Ability to register scans, including the automatic detection of targets;
- Ability to stitch together multiple scans either using survey control or Iterative Closest Point (ICP) type algorithms;
- Ability to create a triangulated surface (Triangulated Irregular Network, or TIN);
- Ability to best-fit lines, planes, and other shapes to point cloud clusters;
- Ability to make profiles and cross sections through a point cloud; and
- Ability to handle various import and export formats (to CADD programs, for example).

The following advanced features are found in some, but not all of the software packages:

- Perform solid modeling (volume generation) based on user-defined lines, planes and other surfaces as bounds;
- Perform automatic extraction of standard shapes from cloud (e.g. pipe fittings, structural steel members, etc.);
- Have edge detection technology to determine boundaries of solids, planes and other shapes;
- Ability to drape a digital image over a triangulated surface;
- Automatically compute a full 3D polygonal mesh (not 2.5D) from a point cloud;
- Ability to integrate scans with floor plans, engineering drawings of objects and surveyed information; and
- Ability to make fly-throughs and other types of advanced visualizations.

The focus of this report is on the use of ground-based LiDAR for highway rock slope stability. Therefore, rather than describe all of the items in the above lists, this report focuses on specific features in point cloud software that allow geotechnical information to be extracted from point clouds. It should be noted that most of the point cloud software is generic in nature and is able to perform analyses for a number of applications including mechanical design, architecture, construction, and mining. The Split FX software, on the other hand, was developed specifically for extracting geotechnical information from point clouds of exposed rock surfaces and has the following features:

- Ability to automatically delineate fracture surfaces in a point cloud and determine the orientation, area, and roughness of each fracture;
- Ability to plot fracture orientations on a stereonet (pole and contour plots);
- Ability to pick joint sets, and determine statistical properties of each set set;
- Ability to delineate joint traces (automatic and manual) and determine joint spacing, length and orientation (true spacing and orientation if digital image is draped);
- Ability to trace fractures on draped photos to determine fracture orientations;
- Ability to subtract two point clouds to determine rockfall volume and rate; and
- Ability to estimate a rockfall hazard rating from a point cloud.

Many of the above items can still be analyzed using the "generic" point cloud software. For instance, to determine the orientation of a fracture in a point cloud, the points making up the fracture can be selected by hand, and the software will determine the orientation of the best-fit plane through the points. This can be done many times throughout the point cloud, and the orientations can be plotted using a separate stereonet program. In a similar fashion, the generic software can be used to estimate fracture length and spacing, roughness, etc. This is discussed in more detail in Chapter 4.

INTEROPERABILITY WITH CADD SOFTWARE

CADD software principally includes Microstation (Bentley, www.bentley.com) and AutoCAD (Autodesk, www.usa.autodesk.com), though many other programs are available. It also includes highway-specific CADD software, such as Inroads and Geopak. The interoperability between point cloud and CADD software is very important, and in the past this has been an issue with using LiDAR in highway applications. It still is an issue as will be shown in Chapter 6; however, as the point cloud software has improved with the addition of many new features in the past few years, interoperability is now greatly improved. For instance, importing a point cloud with a high density of points into a CADD program is not recommended, since CADD programs are not set up to efficiently handle the large number of points and the large file size. Many options now exist for exporting 3D information to the CADD environment, and programs such as Cyclone Cloudworx have been designed specifically for manipulating point clouds within a CADD environment. First of all, point clouds can be cropped and the density of points can be decimated so the file size is optimized. Secondly, specific 3D shapes (pipe fittings, steel members) can be extracted from the point cloud, which are much easier to work with in CADD programs than the points themselves. Thirdly, two-dimensional plans and sections can be created in the point cloud software and exported to CADD programs.

INTEROPERABILITY WITH SLOPE STABILITY SOFTWARE

Slope stability software used for highway applications include Rockpack III (RockWare, Inc., www.rockware.com), the Rocscience suite (Dips, Swedge, Rocplane, Slide, Phase2; www.rocscience.com), the Itasca suite (FLAC, FLAC3D, UDEC, 3DEC; www.itascacg.com), Slope/W (Geo-Slope International, www.geo-slope.com) and many others. Two of the advantages of using LiDAR for highway geotechnical investigations are the ease and speed at which scans can be made and rock characterization information extracted from point clouds. Along these lines, it is important that LiDAR-generated data can be easily exported to the slope stability programs mentioned above. There are three basic kinds of information that the slope stability programs import, and the ability of point cloud processing software to export this information is discussed below.

Export Individual Fracture Information

Many slope stability programs (Rockpack III, Swedge) are able to directly input individual fracture information in a spreadsheet format. For each discontinuity, this information includes orientation, size or length, roughness, etc. The specific position of the discontinuity can also be input into some of the programs (3DEC). In general, exporting this kind of information is straightforward for the point cloud processing programs, assuming that the point cloud programs can calculate the information in the first place. Most point cloud programs can fit a plane through a selected set of points and calculate the orientation and size.

Export Fracture Set Information

Some of the slope stability programs (Swedge, 3DEC) use statistical information about the number of fracture sets and the statistical properties of each set (such as the mean orientation and the Fisher constant). Once the orientation of individual fractures has been determined from LiDAR, this information is relatively easy to calculate in a spreadsheet. It is also very easy to export to slope stability programs since it only involves a few numbers for each discontinuity set.

Export Rock Mass Strength and Modulus

Many of the slope stability programs (Slide, FLAC, FLAC3D, Slope/W, Phase2) use rock mass properties (Hoek and Brown rock mass parameters or Mohr-Coulomb rock mass parameters, for example) rather than individual fracture information. To date, none of the point cloud programs have the capability to make the necessary calculations. However, these rock mass properties can be calculated from the information extracted from the point clouds using the procedures described in Hoek (2007) and others.

CHAPTER 4 – LiDAR APPLICATIONS TO ROCK SLOPES

This chapter provides details on how LiDAR can be used to assist with highway rock slope stability analyses. This chapter is separated into the three sections: rock mass characterization, rockfall characterization, and detailed 3D measurements.

ROCK MASS CHARACTERIZATION

As described in Chapter 1, rock mass characterization is the process of obtaining data for rock slope stability, and in the current practice much of this information is obtained by hand at highway slopes and natural rock outcrops. This section describes the use of LiDAR (and associated digital images) to obtain this information. At the present time, rock mass information that is being obtained from LiDAR includes discontinuity orientation, length, spacing, roughness, and block size (Kemeny et al., 2006a, 2006b, 2006c). In addition, research is presently being conducted to obtain additional information, including geology, weathering and discontinuity fill (Kemeny, 2006b).

Discontinuity Orientation

Figure 4 illustrates the general procedure used to obtain information on discontinuity orientation. The first step is to scan a field site of interest, produce a point cloud, and register the scan into a terrestrial coordinate system (as described in Chapter 2). Figure 4a shows a field site in Colorado that was scanned using an Optech ILRIS 3D scanner, and Figure 4b shows the point cloud from this site. The next step is to create a surface mesh from the point cloud data. In the process of creating a surface mesh, erroneous data points in the point cloud can be filtered. This includes the removal of points outside the area of interest, the removal of points directly in front of the area of interest (due to cars, dust or other objects causing an erroneous laser reflection), and the removal of non-rock objects on the rock slope. The first two items are easily accomplished using standard hand-editing features in point cloud processing software. The third item is more difficult and requires either significant hand-editing or the development of special vegetation or other types of filters (Virtual Geomatics, 2008; Pfeifer, 2004). Figure 4c shows a triangulated mesh of part of the point cloud shown in Figure 4b.

The most important processing step is the delineation of fracture “patches” from the triangulated surface mesh. The term “patch” is used rather than fracture, because a single large fracture may be delineated into several smaller patches, depending on the flatness and roughness of the fracture. Fractures are detected by using the basic property that they are flat. Flat surfaces are automatically found in the triangulated mesh by first calculating the normal to each triangle, and then finding groups of adjacent triangles that satisfy a flatness criterion. This criterion has parameters that can be adjusted by the user.

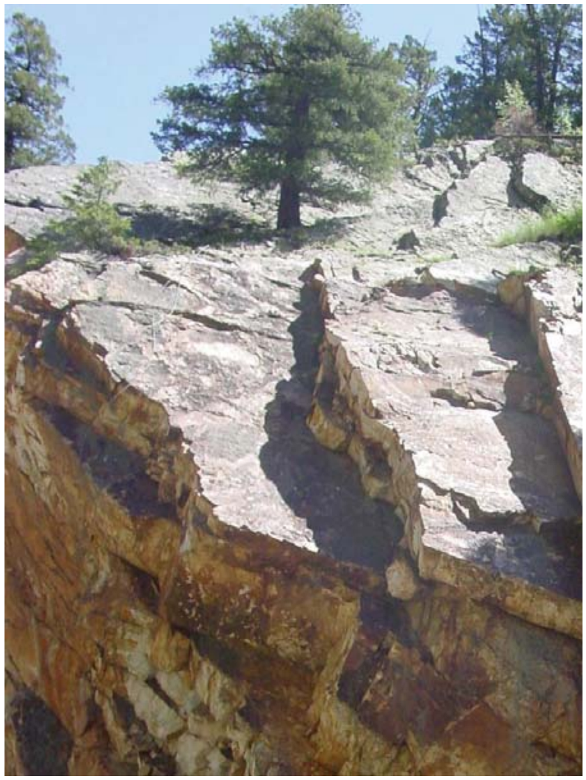


Figure 4a. Photo. Field site that was scanned using ground-based LiDAR.

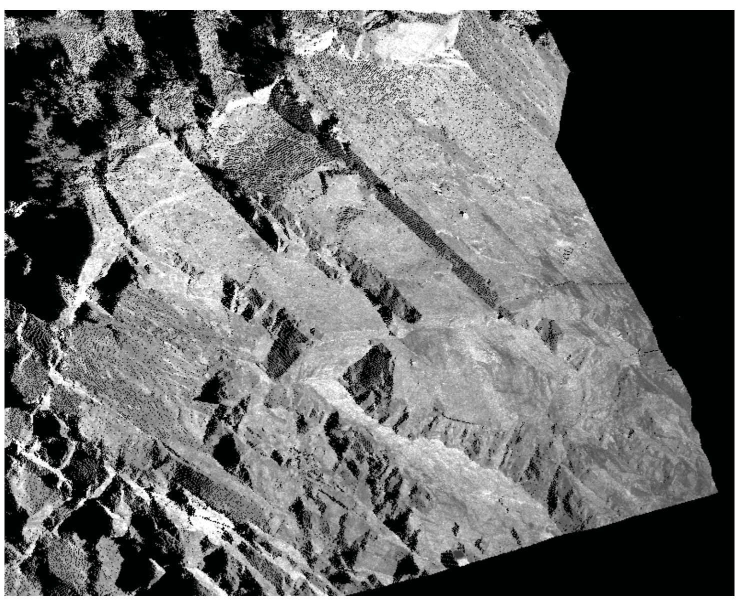


Figure 4b. Schematic. Point cloud for the field site shown in Figure 4a.

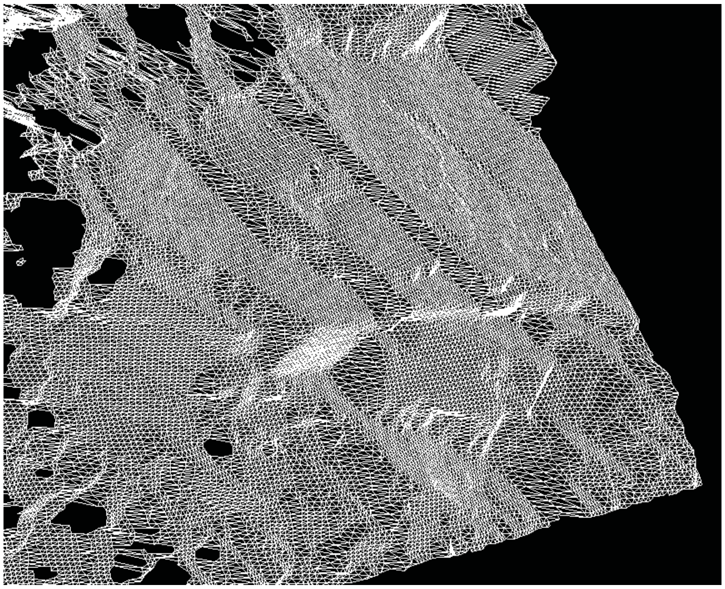


Figure 4c. Schematic. Triangulated mesh for point cloud shown in Figure 4b.

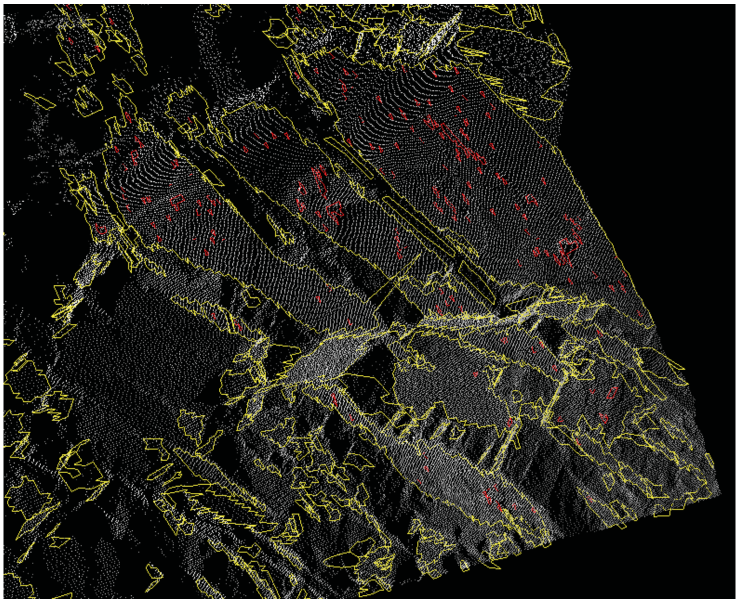


Figure 4d. Schematic. Automatic delineation of fractures for the point cloud in Figure 4b.

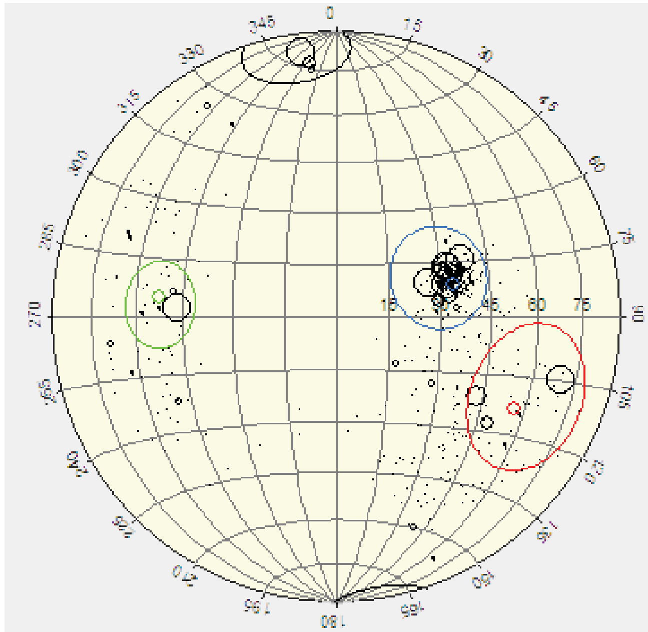


Figure 4e. Plot. Stereonet plot of fractures from Figure 4d.

Figure 4d shows the patches that were found in the point cloud shown in Figure 4b, using the criterion that a patch must be at least 5 triangles, and neighboring triangles in a patch must not deviate in orientation by more than 10 degrees. The patches are outlined in yellow and holes in patches are outlined in red. Overall this simple criterion results in a good delineation of the major fractures at the site. Patches can also be manually added, deleted and edited. Once the patches have been found, their average orientations can be plotted on a stereonet. Each patch plots as one point on the stereonet. However the size of the point can be adjusted based on other parameters such as the patch area or roughness. Large patches are a good indication of important fractures and fracture sets. Small patches, on the other hand, may not actually be a fracture but only a small portion of the surface that happens to be flat. Thus it is useful to weight the points by fracture area, and plot the smallest fractures as only a small dot. Figure 4e is a plot of the patches from Figure 4d, weighted by patch area. Four fracture sets can be clearly seen and have been outlined in Figure 4e. Once the sets are identified, the statistical properties of each set can be determined. The total time spent to produce the results shown in Figure 3 from the previous chapter, starting from the raw point cloud file, is less than one hour.

A particularly useful feature of point cloud processing software is the interaction it allows between the stereonet and the point cloud. Delineating joint sets from stereonet data is difficult and necessitates professional expertise. Normally the data is taken in the field and the compilation and definition of joint sets is accomplished at a later time. Therefore, any difficulties with interpretation of the data cannot be resolved without additional field work. With access to the point cloud, however, additional analysis can easily be conducted off site. For instance, a group of patches can be selected on the stereonet and then viewed on the point cloud. This allows the user to go back and forth between the stereonet and the point cloud to determine with a great deal of precision the delineation of important fractures and fracture sets.

Figure 5 shows an example from a highway slope near milepost 8 along the Mt. Lemmon Highway near Tucson, Arizona. In this case a single scan was made, and scanner registration consisted of Brunton measurements of the scanner position. Automatic fracture delineation was conducted and the results are shown in the black stereonet in Figure 5 (over 1000 data points). Fractures with different orientations are shown with different colors, which assists with interpreting the structure (Jaboyedoff et al., 2007). In Figure 5 the results are also compared with traditional, manually-collected scanline mapping (white stereonet with 50 measurements). The results show that there is a very good correlation between the manual and LiDAR-generated data. The man-hours needed to produce the stereonets can also be compared. Traditional scanline mapping at this site required about 5 hours, which consisted of manual measurements in the field (4 hours), data entry into the computer (30 minutes) and stereonet plotting (30 minutes).

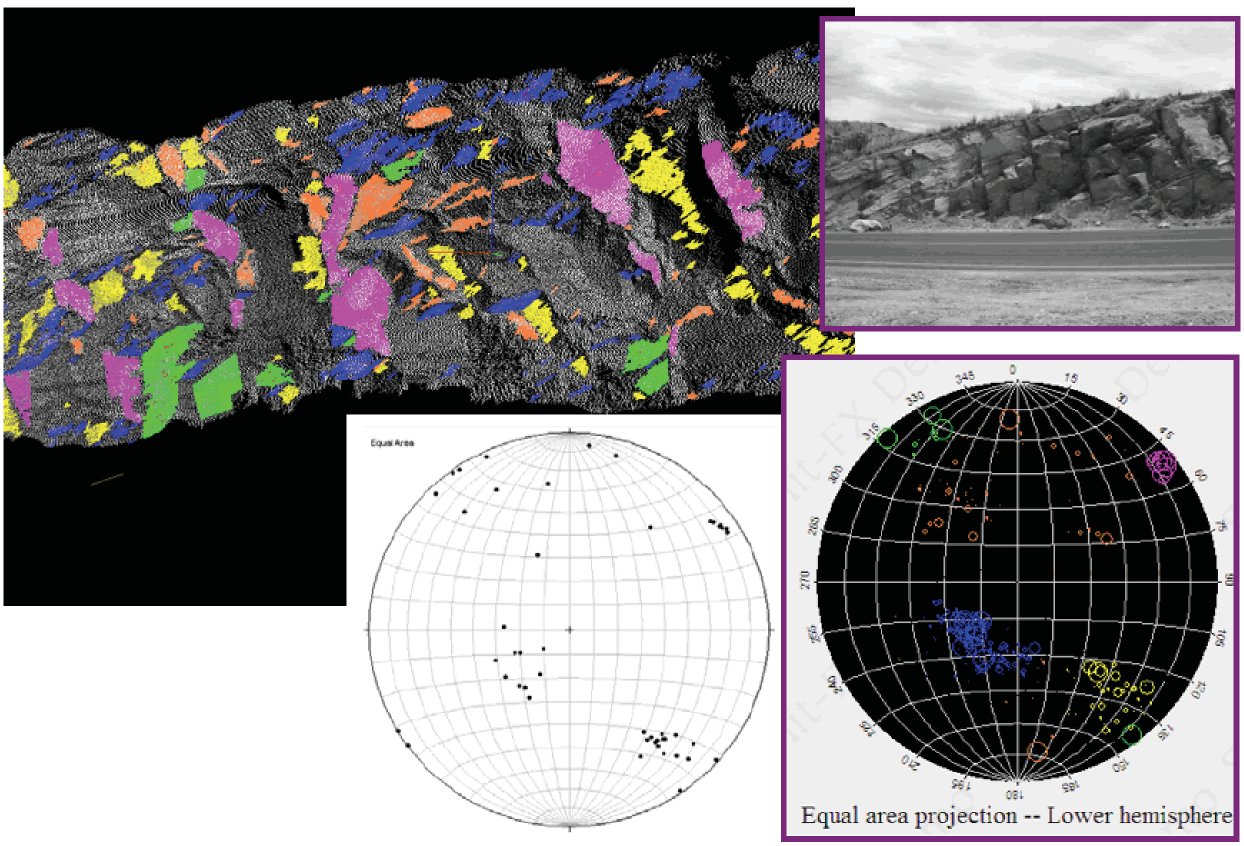


Figure 5. Photo and Schematic. Scan on Mt. Lemmon Highway. Comparison of LiDAR generated data (black stereonet) with hand measurements (white stereonet).

The LiDAR generated data required less than 2 hours, which consisted of scanner setup in the field and Brunton measurements of the scanner orientation (30 minutes), scanning (15 minutes), downloading data from the scanner to the computer (15 minutes), and processing the point cloud data in the Split FX program (45 minutes). Not only did the LiDAR scanning require less time, but 20 times more fracture poles were generated from LiDAR than in the traditional scanline mapping (1000 LiDAR generated poles vs. 50 manual). In several cases, a discontinuity set is represented by a single measurement in the manual measurements (which would undoubtedly be thrown out in the any analyses), compared with a large number of poles in the LiDAR-generated data. The shapes of the fracture sets are also much better defined in the LiDAR generated data because of the large number of data points. In some cases, particularly slopes where access is very difficult, the LiDAR generated data could represent a cost savings over traditional measurements. This is discussed in more detail at the end of this chapter.

The number of laser points that strike a fracture surface will depend on many factors, including the laser resolution, the size of the fracture, the distance of the fracture, and the orientation of the fracture relative to the scanner orientation. Fractures that are sub-parallel to the direction of scanning may be under-represented on the stereonet because fewer laser points will strike those surfaces. However, a careful evaluation of the point cloud and the stereonet can reveal those under-represented areas in the stereonet, and patches can be added accordingly using hand-editing tools in the point cloud processing software. The scanner can only detect surfaces that are in the scanner's line of sight, and the portion of the surface that is not in the scanner's line of site is referred to as the scanner "shadow zone". In some circumstances, an entire joint set may be in the scanner shadow zone, and in these cases several scans need to be taken at different angles to the face in order to adequately represent the structural conditions at the site.

If a structural feature (such as a joint set) is in the shadow zone, it is likely that traces of the structure will still be visible from the direction the scan was taken, and in these cases photo draping can be used to extract the orientation of the structure. Details on photo draping (also called texture mapping) are described in Blythe (1999). An example of photo draping is shown in Figure 6. Figures 6a and 6b demonstrate the draping of a high-resolution digital image over the point cloud for the outcrop shown in Figure 5. Three "pins" were used to align the photo over the point cloud. The pins are first inserted into the digital image at specific locations (red dots in Figure 6a), and then on the point cloud the pins are moved to the same locations (red dots in Figure 6b). Figure 6c shows a location where six traces were made on the digital image. In one case the trace was made of a fracture that showed relief so that the orientation could be determined from both the trace and the point cloud. In the other five cases, the orientation could not be determined from the point cloud. Figure 6d shows the extracted 3D orientations from the traces. Photo-draping works well in extracting 3D orientations from traces, and in studies where both traces and fracture surfaces were available, the orientation results from draping agree within a few degrees with the point cloud results.

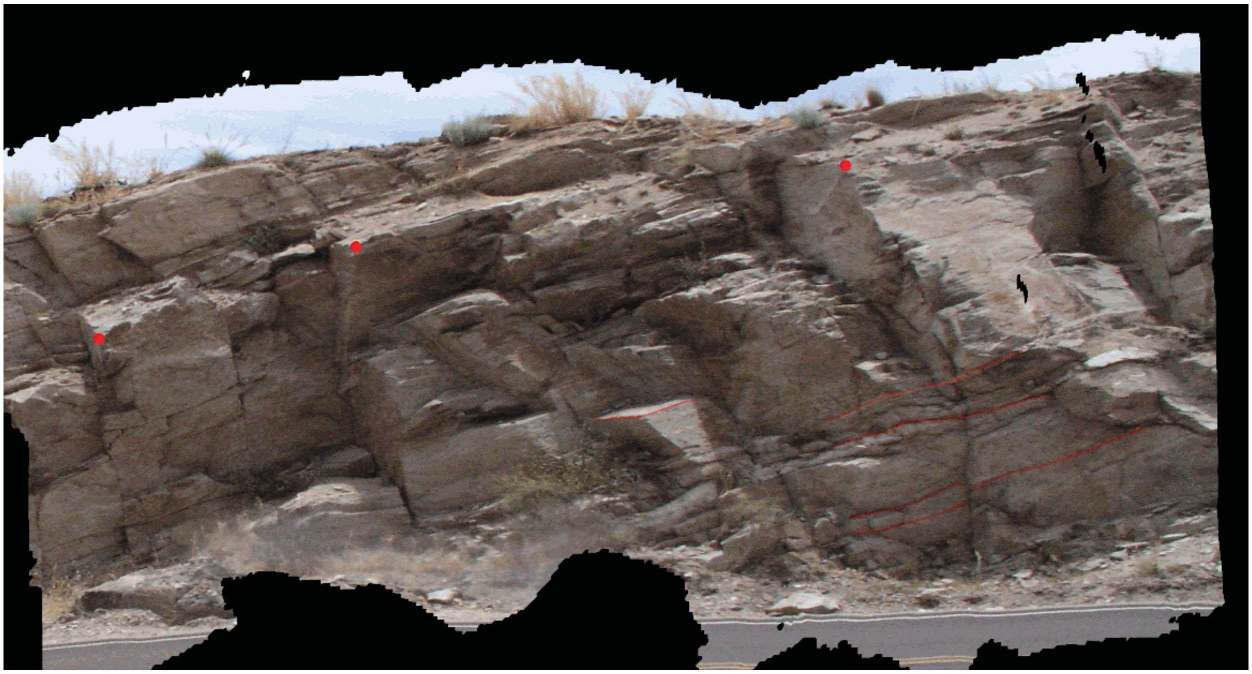


Figure 6a. Photo. Step 1 in photo draping procedure, insert pins on digital image.

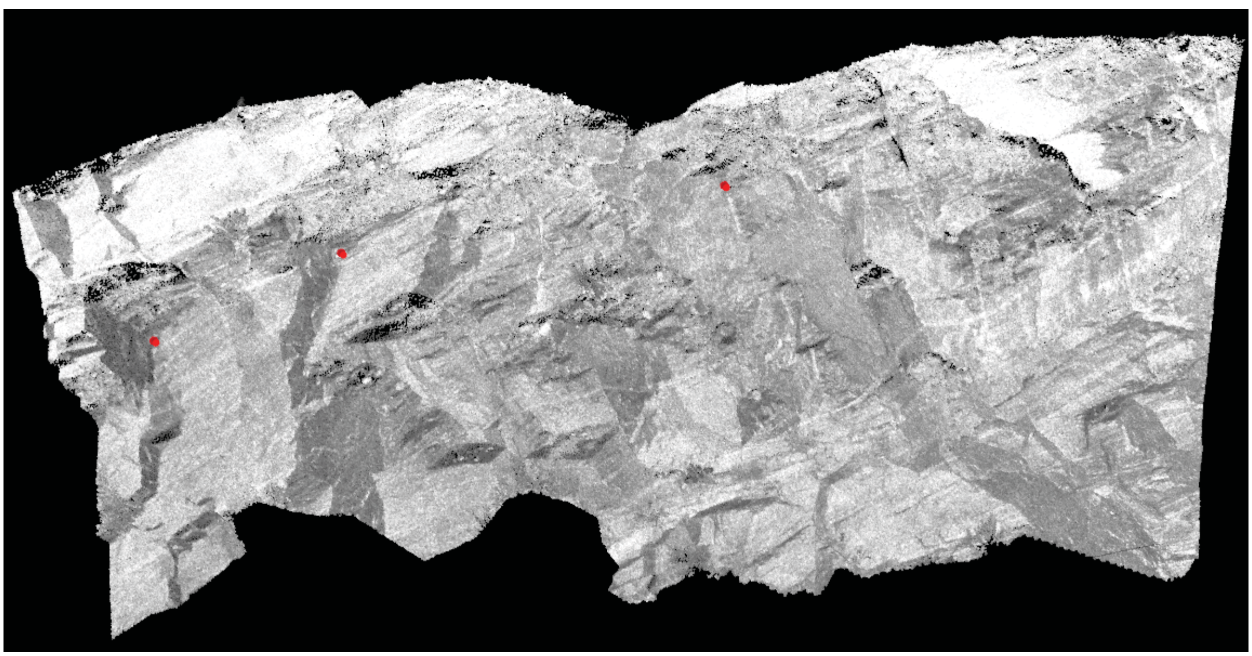


Figure 6b. Photo. Step 2 in photo draping procedure, align pins on point cloud to the same position as in digital image.

Figure 6c. Photo. Step 3 in photo draping procedure, delineate fracture traces on the digital image.

Figure 6d. Photo. Step 4 in photo draping procedure, three dimensional fracture orientations extracted from the traces.

The procedure described above can also be used to determine the orientation of a single critical structure such as a fault. A fault can be more clearly identified on the digital image rather than the point cloud. Also, because a fault is weak, it may not show any three dimensional surfaces where the orientation could be extracted from the point cloud alone. In this case the fault can be traced on the digital image and the orientation determined from the technique described above.

Discontinuity Roughness

There are several ways that LiDAR data can be used to get information on discontinuity roughness. The first way is to use a triangulated mesh of a fracture, as illustrated in Figure 7. If the orientation of each triangle is plotted on a stereonet, then the scatter about the mean orientation of the fracture gives information on the dilatation angle. In the classic saw-toothed fracture analyzed by Patton (1966), the dilatation angle is defined as the rise angle of the saw teeth compared with the mean orientation, as shown in Figure 7. The dilatation angle is directly related to the additional friction angle due to roughness (Goodman, 1989), and on a stereonet, the dilatation angle can be directly determined by the angle between the mesh triangle orientation and the mean orientation of the fracture. The example in Figure 7 shows a scatter of triangle orientations, with the mean fracture orientation at the center of the scatter. The stereonet in Figure 7 is marked off in degree increments of 10 degrees, and indicates dilatation angles ranging from a few degrees to over 30 degrees. Also the shape of the scatter in the stereonet is elliptical, indicating roughness anisotropy (dilatation angle varies with direction). By varying the triangle size of the mesh, scale-dependent roughness can be determined. As an important note, the triangle size needs to be greater than the scanner error, or else roughness due to measurement error will be calculated. For example, in Figure 7 the triangle size was about 8 cm, compared to the point spacing of about 1 cm and scanner error of about 0.5 cm.

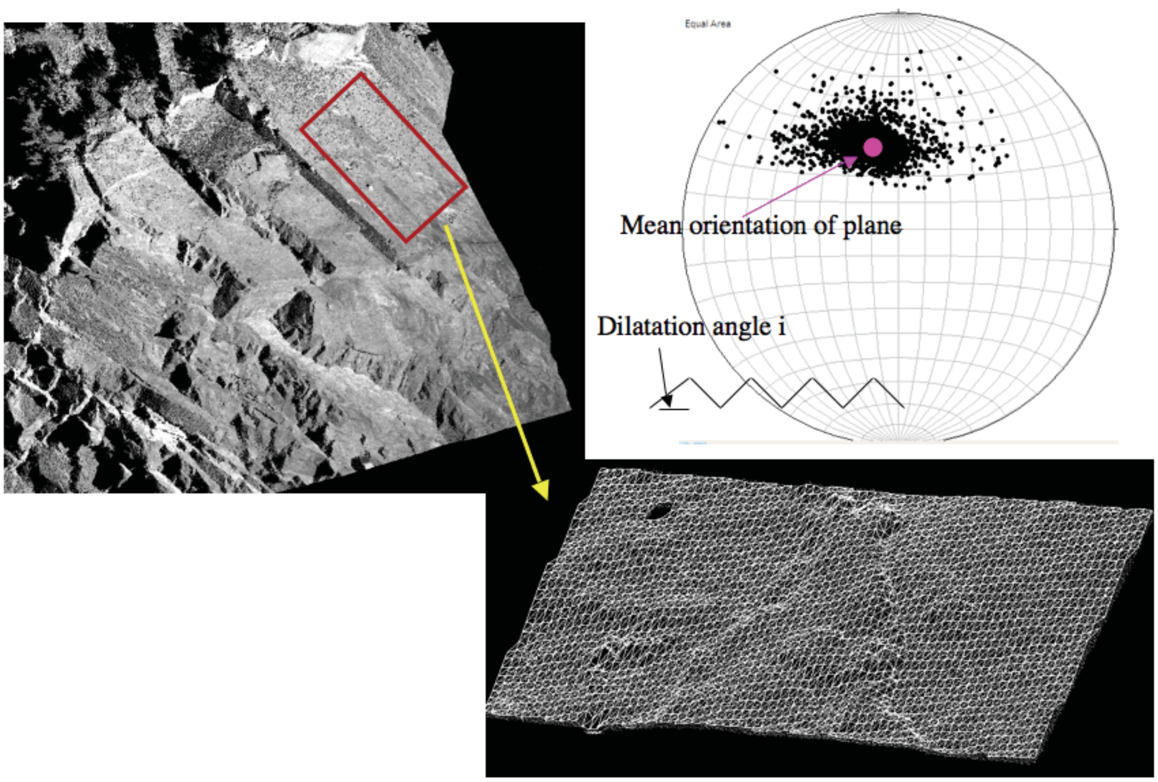


Figure 7. Schematics. One method of analyzing fracture roughness using LiDAR data, by making a triangulated mesh of a fracture and plotting the pole for each triangle on a stereonet.

Figure 8 gives a second example taken from the scan of an open pit mine in Montana. Two large fractures shown in Figure 8 have been analyzed using the technique described above, and the triangle orientations are presented in contoured stereonets in Figures 8b and 8c. Eliminating the outlier triangles and considering the contour representing about 90% of the poles (lightest blue contour), maximum dilatation angles of 10-15 degrees are revealed.

Figure 8a. Photo. Location of two large fractures for determination of maximum dilatation angle using the method described in Figure 7.

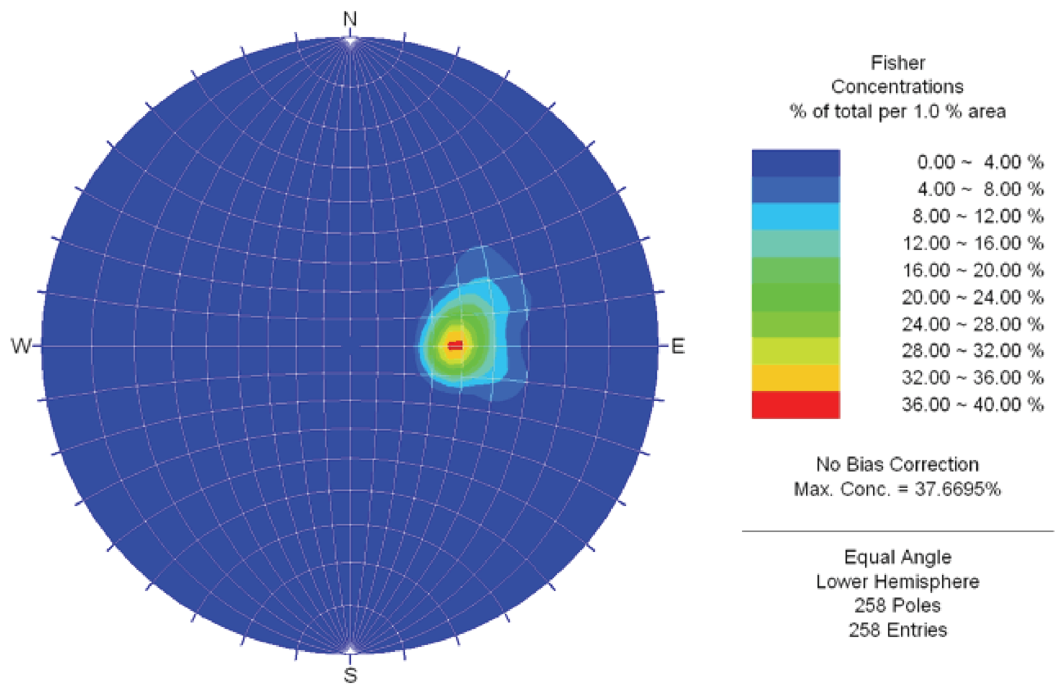


Figure 8b. Chart. Contoured stereonet of poles of each mesh triangle in left fracture shown in Figure 8a.

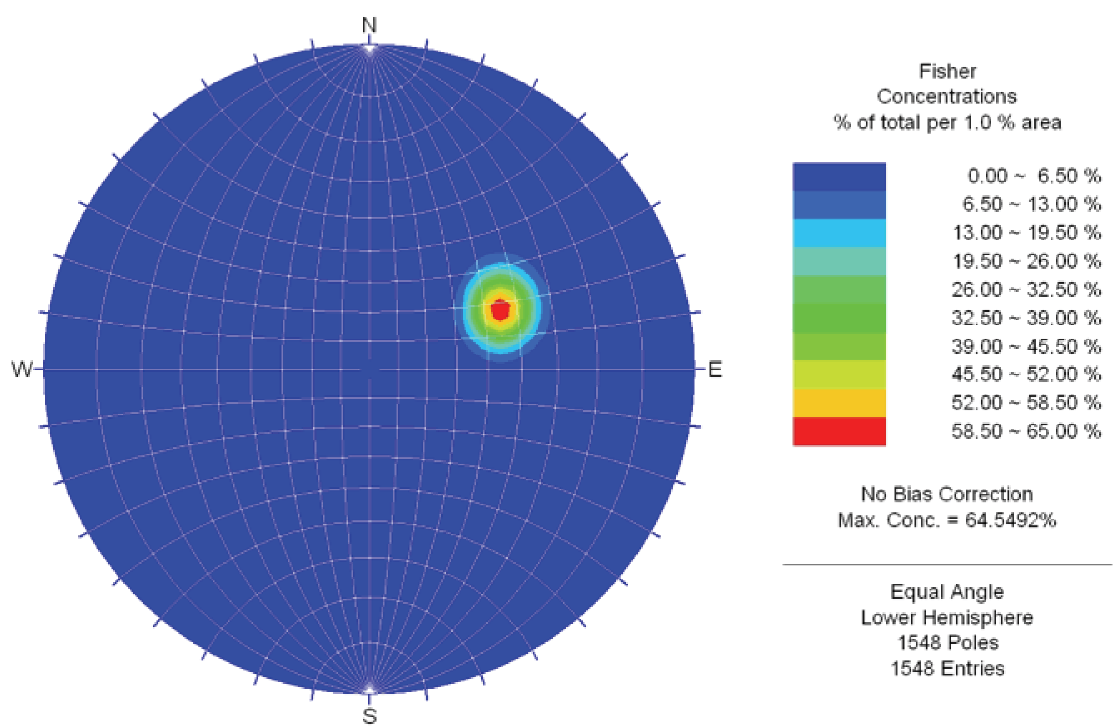


Figure 8c. Chart. Contoured stereonet of poles of each mesh triangle in right fracture shown in Figure 8a.

The second way to get information about roughness is to make cross sections through a fracture at different angles (a cross section in the direction of the dip vector, for instance, would be relevant for slope stability purposes). Figure 9 illustrates the procedure. The roughness profiles are calculated from the triangulated surface, and therefore the same aforementioned scale-dependence and caution about noise are applicable. There are several published methods for extracting fracture roughness information from two dimensional roughness profiles. For instance, Tse and Cruden (1979) describe a technique where Z_2, the root mean square of the derivative of the profile, is first calculated. The Joint Roughness Coefficient (JRC, see Hoek, 2007) is then calculated using the empirical formula:

$$JRC = 32.2 + 32.47 \log Z_2. \quad (3)$$

This technique was used successfully by Haneberg (2007). Studies with this technique have shown that it can sometimes give values of JRC outside the range of 0-20, and therefore the technique described in Figures 7 and 8 is preferred at this time.

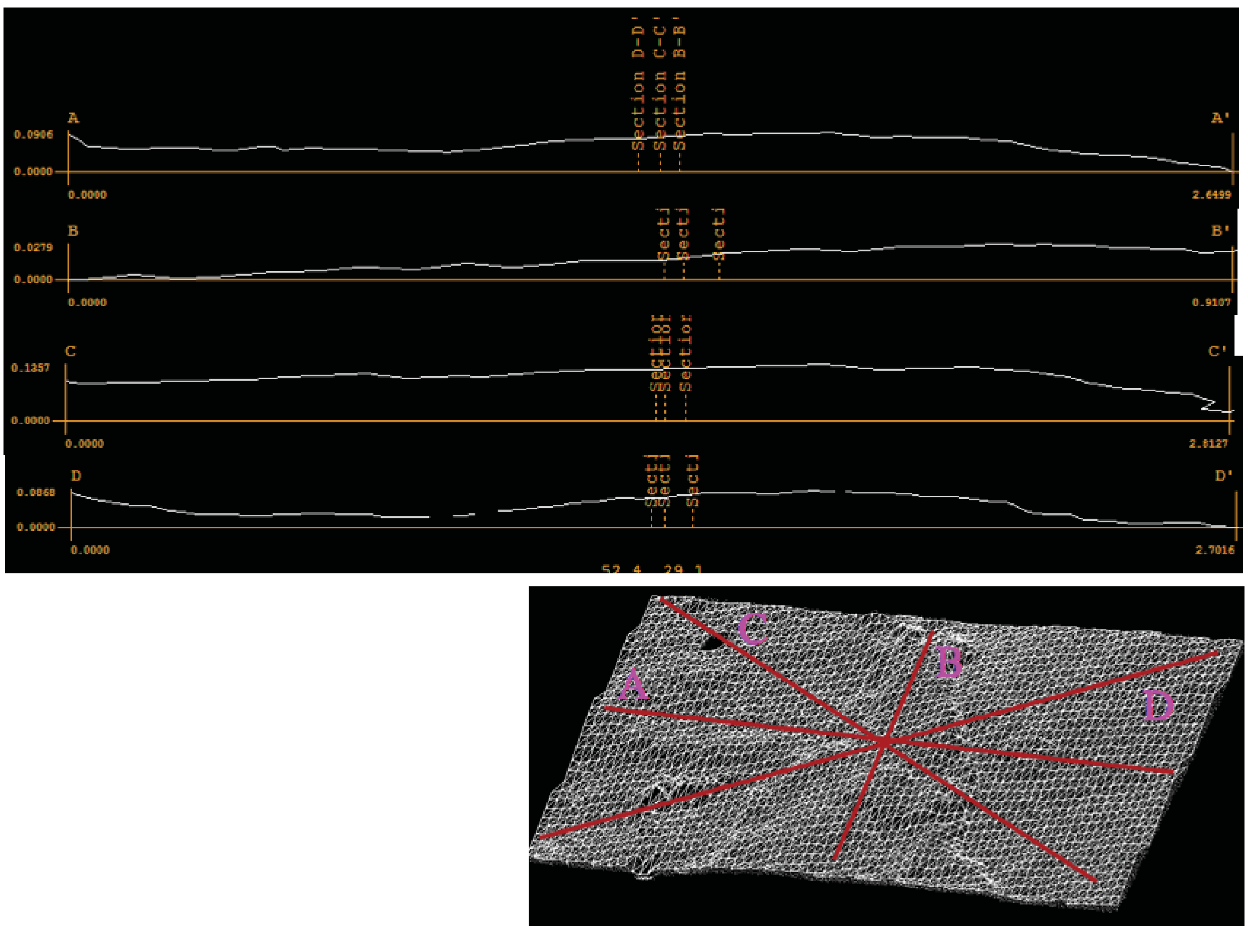
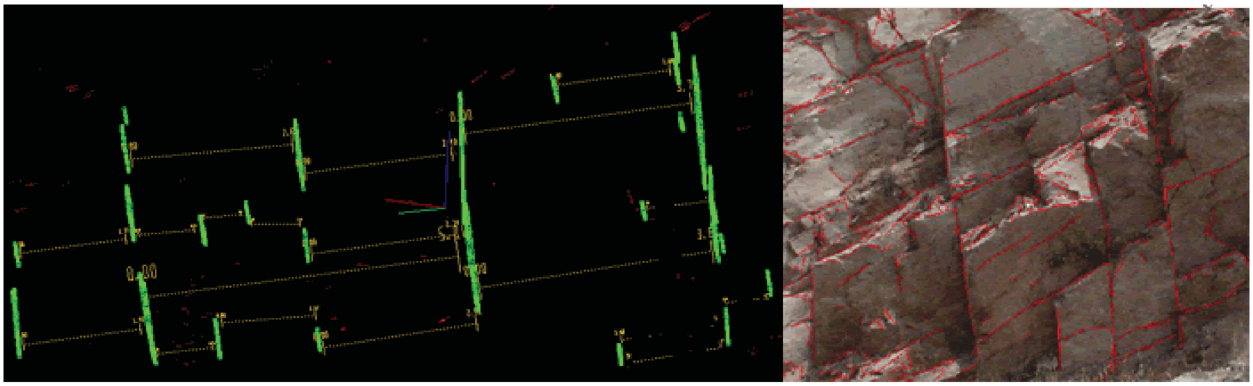


Figure 9. Schematic. A second method of analyzing fracture roughness, by making topographic profiles of the fracture in different directions, and processing the roughness profile to extract roughness parameters such as JRC.

Fracture Length and Spacing

Fracture length and spacing can be measured from either digital images or point clouds, as shown in Figure 10. In two dimensions (measured from a digital image of a road cut, for instance), the measured fracture spacing is referred to as the "apparent" spacing, and can be corrected if the true average orientation of the set is known. In three dimensions (measured from a point cloud or a draped photo), the true spacing can be measured directly if the measurement is made perpendicular to the average strike of the set.

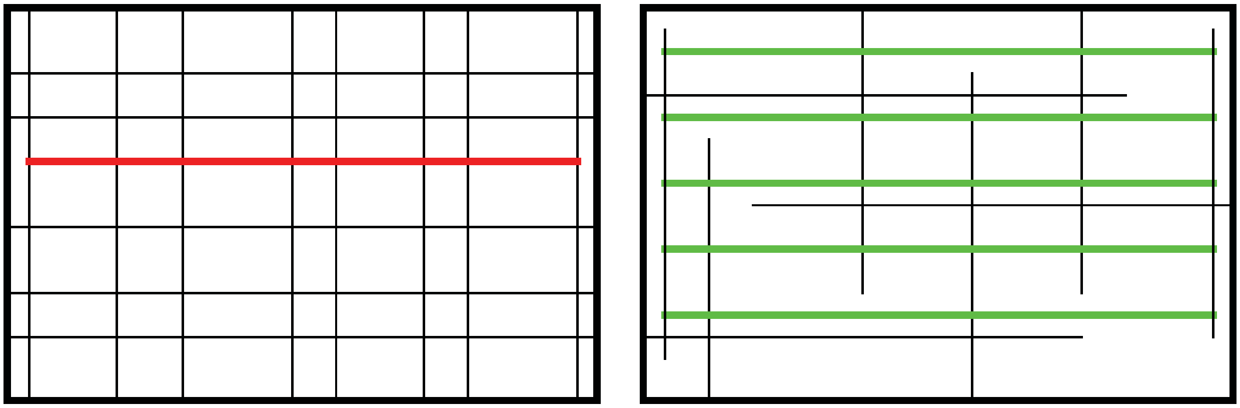


a) b)

Figure 10. Photo and Schematic. Information on fracture length and spacing can be extracted from both a) point clouds, and b) digital images.

Automatic trace delineation involves image processing algorithms called edge detectors (Gonzalez and Wintz, 1987). The development of edge detection algorithms for rock fractures are described in Hadjigeorgiou et al. (2003), Kemeny and Post (2003) and others. Even though automatic trace delineation algorithms are available in many image-processing programs (including Split FX), they are not recommended at this time for several reasons. First of all, they will delineate all the fractures in an image, which will undoubtedly come from several structural sets (as illustrate in Figure 10b). This means that in order to determine statistical parameters for each set, hand editing will still be necessary. Secondly, due to the complexity of images of rock outcrops, no automatic routine will do a perfect job of delineation and corrections will need to be made using hand editing tools. Thirdly, it does not take very long and does not require expertise to delineate fractures by hand. The traces in Figure 10b, for instance, took only several minutes to delineate.

Fracture length and spacing are interrelated, as illustrated in Figure 11. If the fractures are persistent (fractures long in relation to the spacing), then the measurement of fracture spacing for a given set is well defined and measured perpendicular to the average orientation of the set, as illustrated by the red "scanline" in Figure 11a. If the fractures are non-persistent (fractures short in relation to spacing), then the measurement of fracture spacing is not well defined by a single scanline, and several scanlines perpendicular the average orientation are needed, as illustrated by the green scanlines in Figure 11b. In either case, a histogram of fracture spacing is produced for each set.



a) b)

Figure 11. Schematic. Persistent vs. non-persistent discontinuities (black lines). a) persistent discontinuities, with a single scanline (red) to obtain fracture spacing information, b) non-persistent discontinuities, with multiple scanlines (green) used to obtain fracture spacing information.

In order to get accurate information on fracture length and spacing from digital images, proper images must be taken. Figure 12 shows two digital images of rock outcrops. In the first image the joint traces are clear and the scale of the image is appropriate for the density of joints. In the second image, the individual joint traces are difficult to see because the scale of the image is not appropriate for the density of joints at this site (close-up image needed to provide appropriate level of detail).

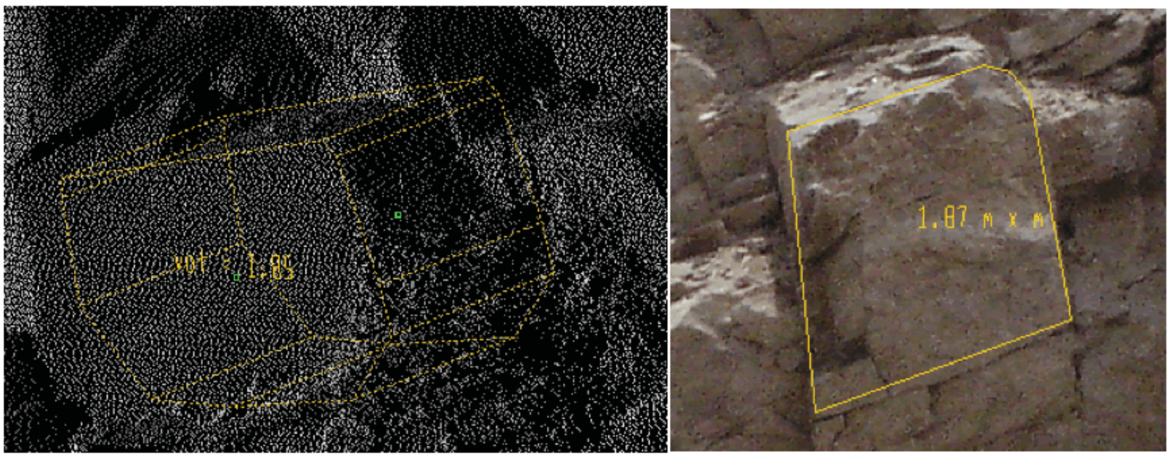
a) b)

Figure 12. Photos. a) digital image with the proper density of fracture information, b) figure cannot be analyzed at its current scale (close-up image needed to provide appropriate level of detail).

Block Size

Block size is a parameter that depends on the interaction of all the joint sets together, into a fracture network. In a similar fashion to fracture length and spacing, block size can be measured from either a digital image or a point cloud, and either manually or using edge detection algorithms.

Figure 13 illustrates block delineation using manual tools for both digital images and point clouds. In the case of a digital image, the block area is calculated and the area must be converted to volume using an assumed length in the third dimension. In the case of the point cloud, the block volume is measured directly.



a) b)

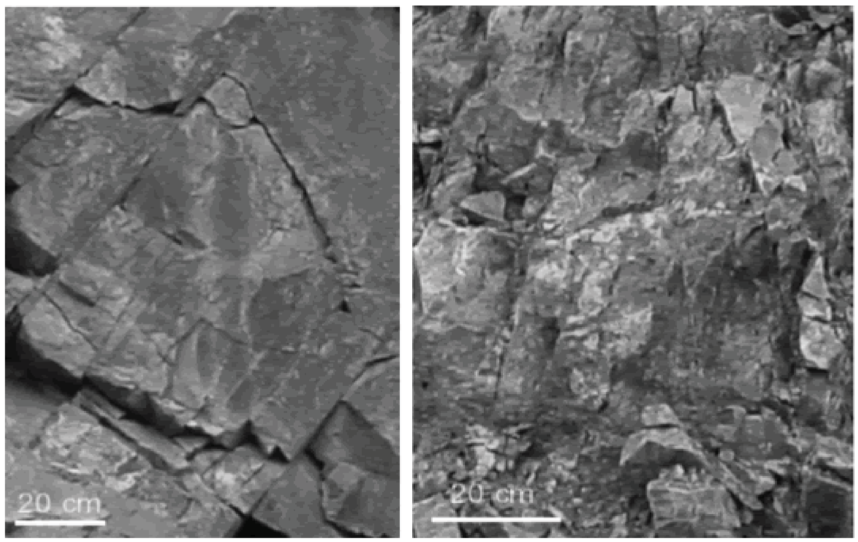
Figure 13. Photos. Manual methods of getting block size information, both from a) point cloud and from b) digital image.

In order to automatically delineate blocks and determine the distribution of block volumes at a site, the rock bridges must be first identified. Rock bridges are small sections of intact rock that separate coplanar or non-coplanar discontinuities, and prevent blocks from being "removable". Similar to the problem of trace delineation, the identification of rock bridges in a digital image of a rock outcrop is not a simple problem, and the use of hand-editing tools, such as those shown in Figure 13, is recommended at the present time.

Discontinuity Weathering and Fill

All of the discontinuity parameters described above (orientation, length and spacing, roughness, block size) relate to the geometry of the discontinuities and the fracture network, and it has been demonstrated that LiDAR and digital image processing do an excellent job of providing information on these parameters. Equally important, however, is the "condition" of the discontinuities, which include parameters such as weathering and fill. These parameters directly relate to the friction angle of the discontinuities, and highly weathered fractures or fractures containing very weak fill can have dangerously low friction angles. Also, weathering and fill make up a large component of rock mass classification systems. For instance, in the Rock Mass Rating (RMR, Bieniawski, 1989), Q (Barton et al., 1974), and Geologic Strength Index (GSI, Hoek, 2007) systems, weathering and fill account for about 12%, 25%, and 30% of the total rating, respectively.

LiDAR and digital image processing have the potential for providing information on discontinuity weathering and fill, and this is an area of current research. Some initial work on using texture algorithms to evaluate discontinuity weathering was investigated by Monte (2004). A comparison of the texture of a weathered and unweathered fracture is shown in Figure 14. Monte (2004) found that texture algorithms at a given site were able to differentiate discontinuities with different amounts of weathering after the parameters in the algorithms were properly adjusted. However, these parameters had to be readjusted for other locations and other rock types.



a) b)

Figure 14. Photos. Example of digital images of a) unweathered, and b) weathered discontinuities.

A more promising approach that is currently being investigated is using multi-spectral and hyper-spectral imaging to differentiate weathering and fill (Gupta et al., 1999). In particular, in many rock types weathering and fill is associated with clays, which can be identified with multi-spectral and hyper-spectral imaging. Determining the degree of weathering at a site at the present time is subjective because it is based primarily on visual inspection. However, the use of new techniques such as hyperspectral imaging could lead to more deterministic measures of weathering and discontinuity fill.

ROCKFALL CHARACTERIZATION

A second major highway application for LiDAR is rockfall characterization. This includes the characterization of rockfall source areas, the characterization of rockfall chutes, and monitoring rockfall occurrences by taking periodic scans of an area of interest.

Characterizing Rockfall Source Areas

Rockfall source areas can be characterized with LiDAR scans, to determine the risk for rockfall and slope instability. Characterization can include standard rock mass characterization as well as rockfall hazard ratings (e.g., Patterson et al., 2002). Rockfall source areas are often difficult to access and characterize using traditional methods. Figure 15 shows before and after pictures of the source area for the 2004 Thanksgiving day rockfall that occurred along Interstate 70 in Glenwood Canyon, just east of Glenwood, CO. It was a large volume rockfall and the source area was on the north side of the canyon about 400 m (1312 ft) above the highway. Traditional site characterization in steep remote areas such as this involve rappeling down the slope, which is costly and poses safety hazards. The LiDAR techniques described earlier in this chapter are ideal for characterizing rockfall source areas.

Another example of a potential use of LiDAR for rockfall characterization is shown in Figure 16. It shows a highway slope near Pine Valley, California that is weathering and exposing large boulders that pose a rockfall hazard. LiDAR scanning of this slope could be used to determine the number and sizes of the boulders. Repeated scans at this same site over time could also be used to monitor the weathering process.

a) b)

Figure 15. Photos. Section of Glenwood Canyon a) before, and b) after the 2004 Thanksgiving Day rockfall.

Figure 16. Photo. Weathering of a slope near Pine Valley, California, exposing boulders that pose a rockfall hazard.

Rockfall Chutes

The rockfall source area determines the size and initial location of rock blocks that could impact a highway. When a rock block dislodges from a source area, it often travels along a developed path or chute until it reaches the highway. Therefore, the characteristics of rockfall chutes often determine the location, velocity and other aspects of a rockfall event. In particular, the chute characteristics must be understood in order to design rockfall fences or other support measures. One important aspect of the rockfall chute is the topographic profile, which can be characterized with LiDAR using cross section tools. Figure 17 shows photos and profiles of a major rockfall chute on the north side of Interstate 70 near Georgetown, Colorado (scan taken from the Georgetown Interstate 70 overlook). Figure 17a shows a photo of the scan area, with the rockfall source area at the top of the photo, the chute in the middle and rockfall fences near the bottom of the photo. Figure 17b shows a side view of the point cloud, showing the scanner, scanner direction and Interstate 70 at the bottom right, and the rockfall source area at the upper left (horizontal scale reads 460 m, vertical scale reads 328 m). The rockfall source area is about 600 meters (1969 ft) from the scanner. Figure 17c is a plan view of the point cloud showing two cross-sections through the chute area; one to the right of the trees down the middle of the chute (Section A) and the other to the left of the trees (Section B). Figures 17d and 17e show the profiles from sections A and B, respectively. The sections are made through the triangulated mesh, and gaps in the sections are areas where the mesh was not constructed due to insufficient point cloud data). The two profiles are similar except for the steep section in the center of section A, due to a small rock outcrop that can be seen in the close up photo in Figure 17f. Figure 17g shows close ups of the point cloud near the rockfall fences.

Figure 17a. Photo. Rockfall chute, north side of Interstate 70 near Georgetown, Colorado.

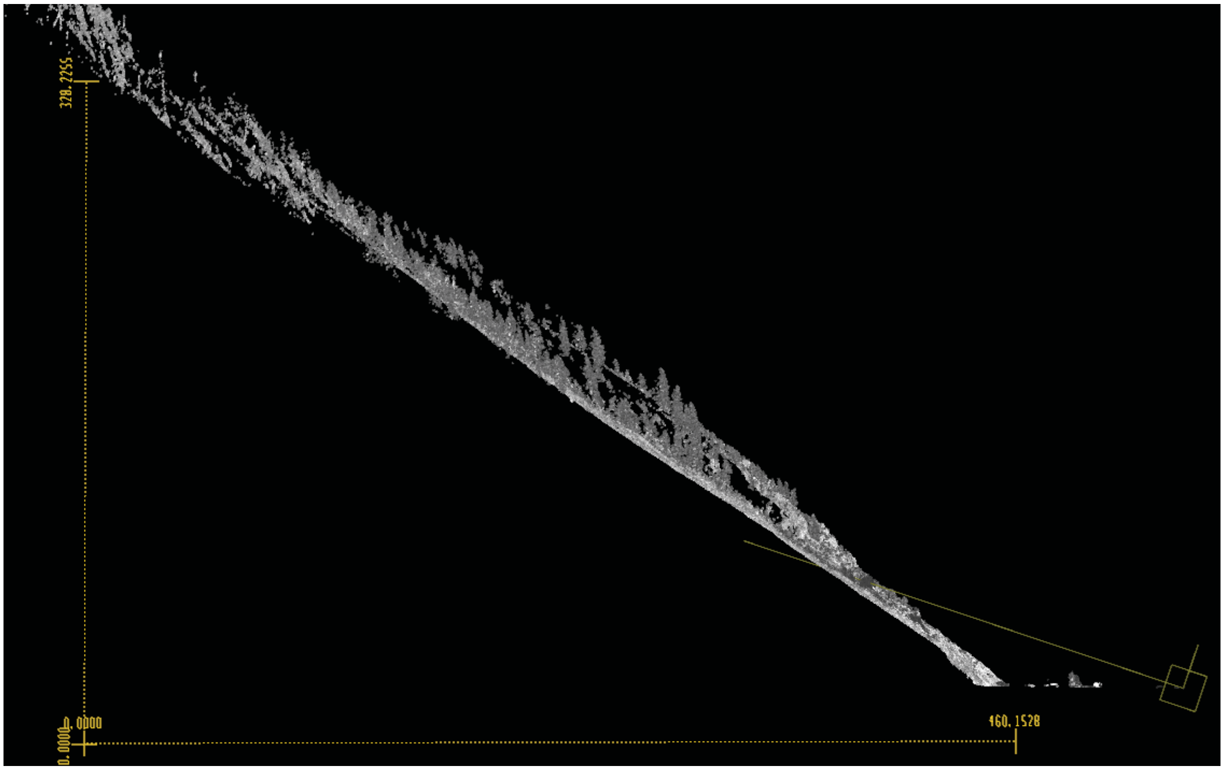


Figure 17b. Schematic. Side view of point cloud taken of site shown in Figure 17a.

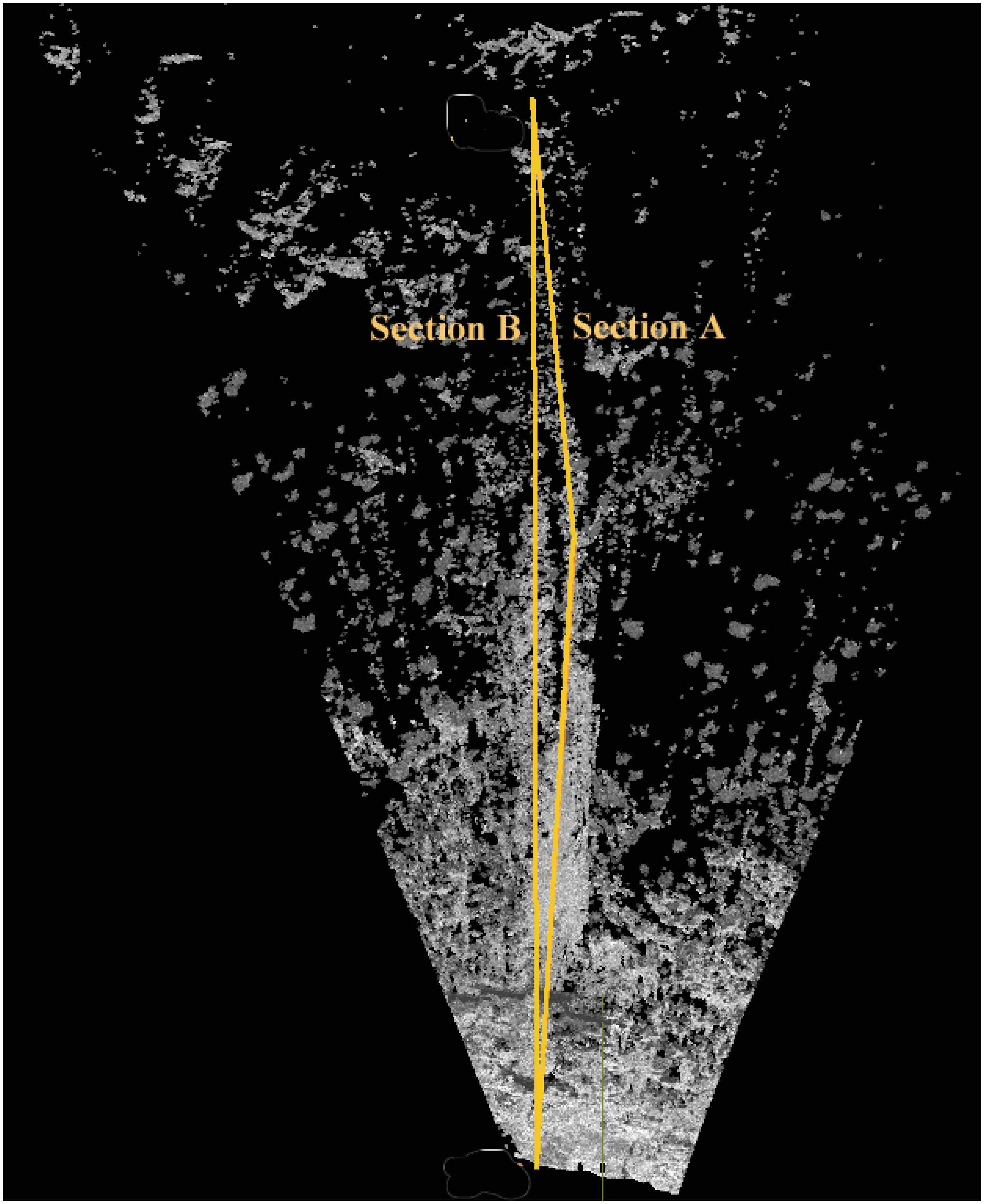


Figure 17c. Schematic. Plan view of point cloud showing the location of two cross sections.

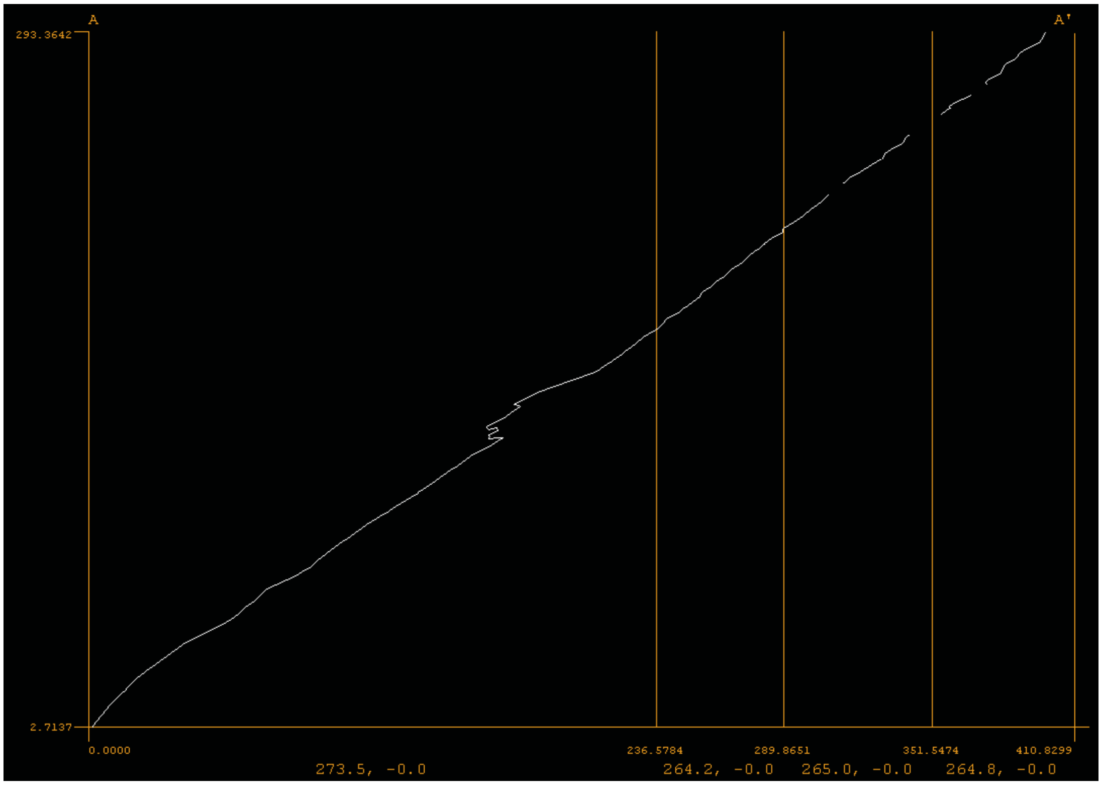


Figure 17d. Schematic. Section A (refer to Figure 17c).

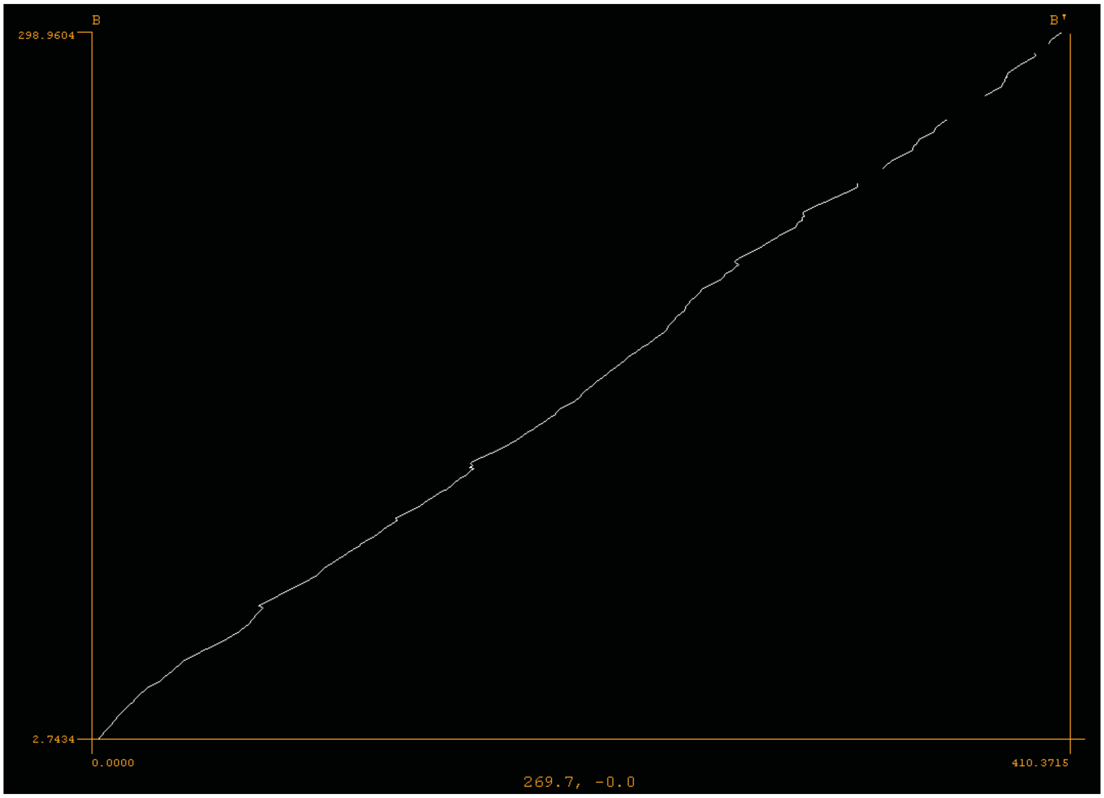


Figure 17e. Schematic. Section B (refer to Figure 17c).

Figure 17f. Photo. Close-up photo of center section of chute.

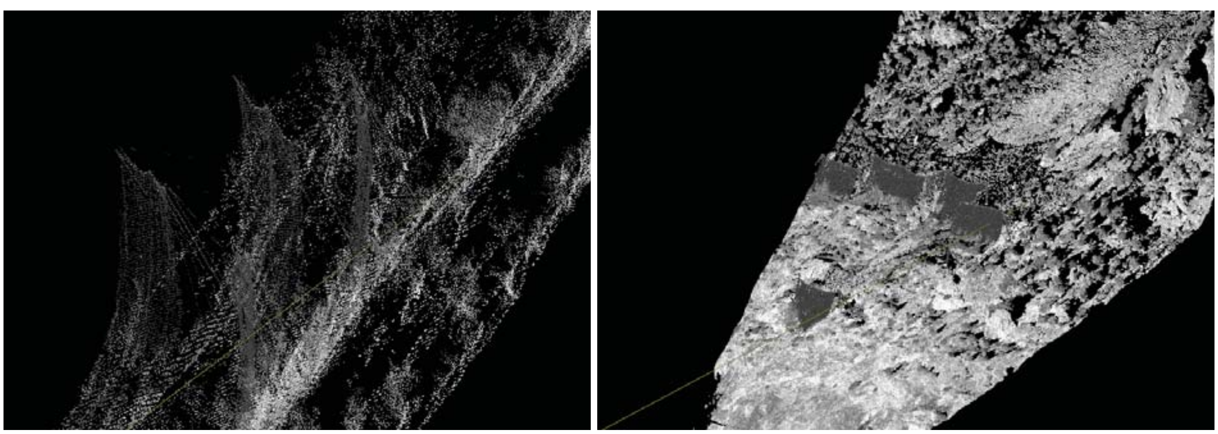


Figure 17g. Schematics. Close up views of point cloud showing rockfall fences.

Often a rock block does not travel to its final resting place once it dislodges from the source area. Rock blocks may slowly travel down a chute in a time-dependent fashion (during periods of rainfall, for example). Figure 18 is a photo of a small chute above Interstate 70 near Georgetown, Colorado (source area at the very top of the photo, Interstate 70 at the bottom of photo). It clearly shows several large blocks that have dislodged from the source area and are presumably moving down the slope in a time-dependent fashion. Rockfall monitoring with LiDAR can be used to understand this behavior, by taking scans at the same location but at different times (every 6 months or every month, for instance). Rockfall monitoring with LiDAR is discussed in more detail in the next section.

Figure 18. Photo. Slope above the north side of Interstate 70 near Georgetown showing a small rockfall chute containing several large rock blocks.

Rockfall Monitoring

A very important application of LiDAR is rockfall monitoring. Rockfall monitoring is conducted by taking LiDAR scans of the same scene at some interval of time, say once every six months (or more often in areas with high rockfall risk). Figure 19 shows a LiDAR rockfall monitoring site on Interstate 70 near Georgetown, Colorado. The top part of the figure shows mapping that was conducted by the Colorado Dept. of Transportation of rock fall source areas and rockfall chutes (CDOT, 2005). The highest risk rockfall source areas are striped areas shown in red and lesser risk areas are striped areas in yellow and orange. The chutes are shown in purple. Interstate 70 goes through the middle of the photo and the town of Georgetown is the right of the photo. Permanent benchmarks have been set up along the bike path next to the interstate, as shown in the lower right photo of Figure 19. In total there are 20 benchmarks covering about 3 km (1.9 m) of Interstate 70.

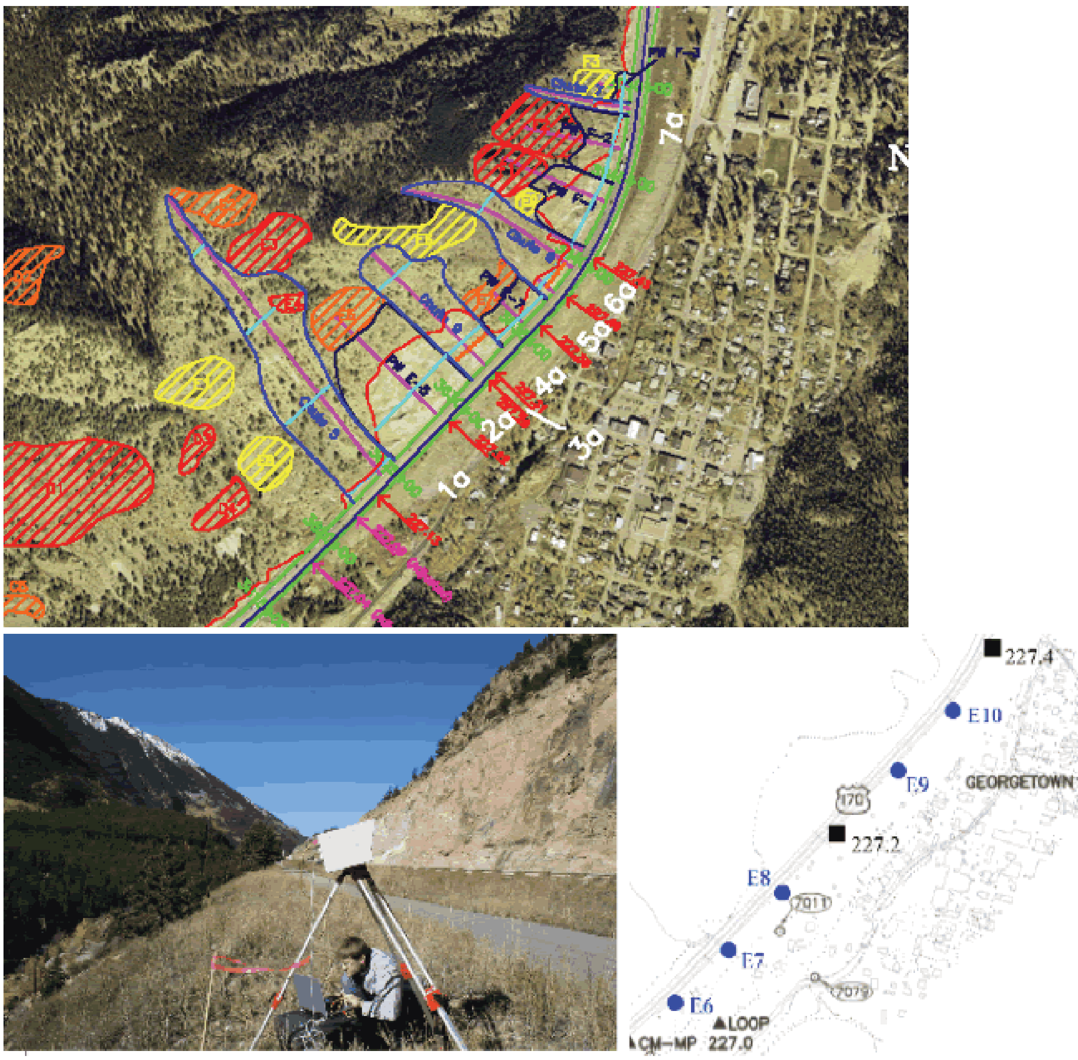


Figure 19. Photos and Schematic. Rockfall study area along Interstate 70 near Georgetown, Colorado. Top photo shows rockfall source and chute characterization, from CDOT (2007). Lower photo shows permanent benchmarks set up along bike path.

The periodic scans are processed to evaluate rockfall using “change algorithms”. Change algorithms can be found in a number of the point cloud processing software. The change algorithms subtract two point clouds and produce a “difference cloud”, which is a point cloud providing information on the relative difference between the two scans at points throughout the area that was scanned. From the change, the movement of a rock block can be tracked, or the size of a block that has move can be monitored. The total accumulated rockfall rate can also be calculated. Before the change algorithm can be applied, the two point clouds must be aligned as accurately as possible. In general, Iterative Closest Point (ICP) algorithms (Besl, 1992) are used to align the scans with the highest accuracy (higher than can be achieved by surveying alone).

A field site for testing change algorithms was set up at Milepost 2, Mt. Lemmon Highway, Arizona. A “rolling rock” experiment was conducted where 8 boulders with sizes from 10 to 100 cm were moved, as shown by the red circles in Figure 20a (larger circles represent larger boulders). Before and after scans were taken. The Iterative Closest Point (ICP) algorithm was applied and a difference point cloud was produced, as shown in Figure 20b. In Figure 20b, red indicates negative change (missing material compared with original scan), blue indicates positive change (new material). From this field site it was determined that the movement of boulders as small as 15 cm can be detected (the scans at this site were taken from a distance of about 60 m).

Figure 20a. Photo. Field site for testing change detection algorithms. Boulders marked with red circles were moved.

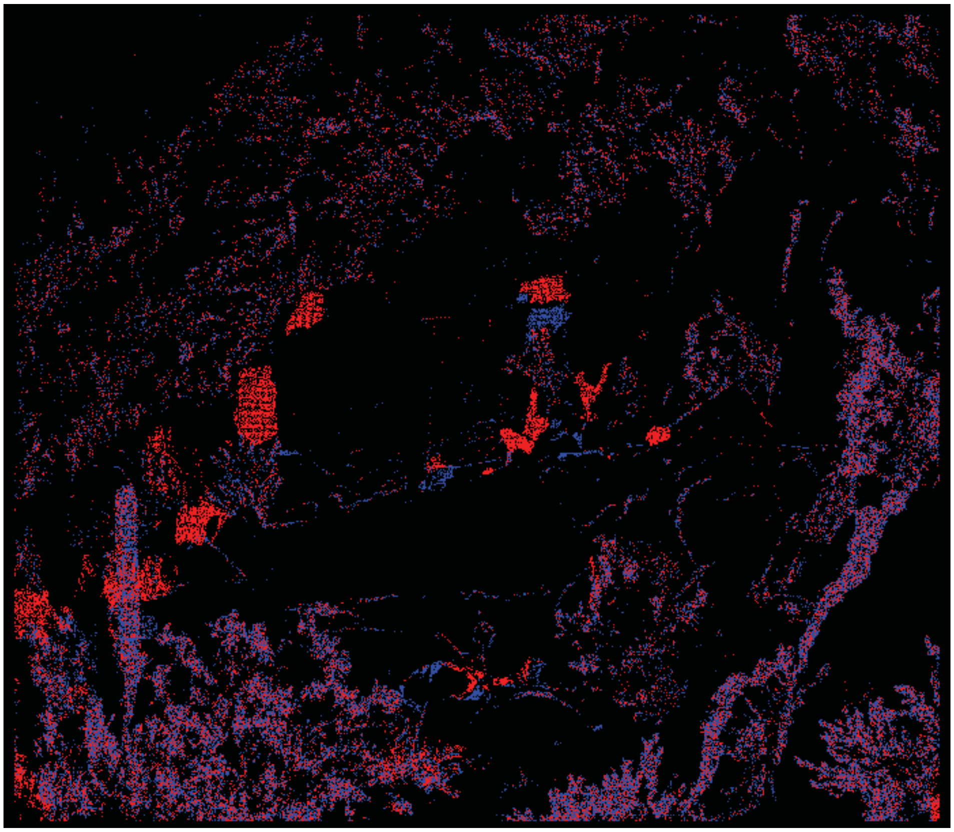


Figure 20b. Schematic. Difference point cloud. Red indicates negative change (missing material), blue indicates positive change (new material).

In addition to being used for safety purposes, the information from periodic scans can also be used to assist with rockfall maintenance. Figure 21 shows a rockfall fence filled with rock blocks. In order to work effectively, rockfall fences must be maintained, with a maintenance schedule dependent on the rockfall rate. Similar maintenance is required for rockfall ditches.

Figure 21. Photo. Rockfall Fence Containing an Overflow of Rock Fragments.

DETAILED 3D MEASUREMENTS

The last application of LiDAR for highway applications is the general area of detailed 3D measurements. LiDAR surveys provide a detailed "as built" that can be used for estimating various highway parameters, such as ditch width, slope height, roadway width, etc. These are parameters that are also used in estimating rockfall hazard ratings, as shown in Figure 22 (e.g., Patterson et al., 2002; Pack et al., 2002).

Before and after as-builts can also be used to verify the volume of a highway excavation, to accurately determine the shrink-swell behavior of particular rock type (Henwood et al., 2006), or to estimate stockpile volumes.

1. Slope height
2. Ditch effectiveness
3. Average vehicular risk
4. Sight distance
5. Roadway width
6. Structural condition (discontinuities)
7. Rock friction
8. Structural condition of eroded rock
9. Difference in erosion rates
10. Block size or volume of rockfall per event
11. Climate and presence of water on slope
12. Rockfall history.

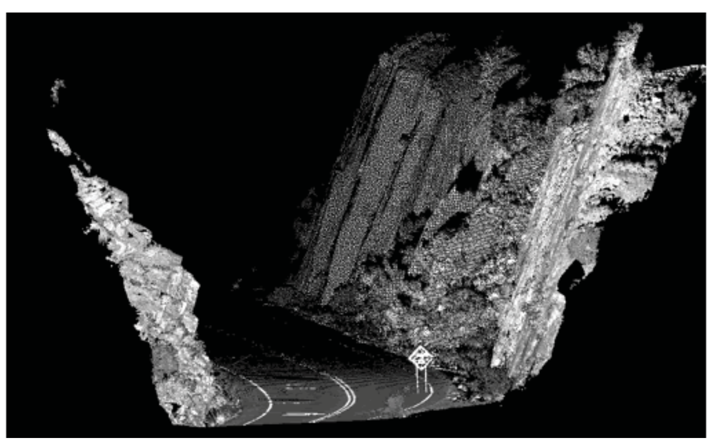


Figure 22. Schematic. Parameters used in many Rockfall Hazard Rating systems (left). Example of point cloud to estimate many of these parameters (right).

CHAPTER 5 – BEST PRACTICES

As hardware and software solutions are being developed for rock mass and rockfall characterization using LiDAR and digital image processing, guidance is needed on specific and appropriate procedures involved to conduct ground-based LiDAR surveys, as well as the appropriate data validation, processing and management procedures. In the field, appropriate procedures must be specified concerning a) the suitability of a site for LiDAR surveying, b) the procedures for scanning (number of scans, point spacing, resolution, etc.), c) establishing surveying control points, d) taking digital images, and e) collecting non-digital types of information. After a survey is conducted, data processing and management procedures include a) the specific steps that should be taken to process the data using various software packages for specific outcomes (i.e., calculate the slope hazard at a particular site), and b) the appropriate standards and formats for managing and archiving the various kinds of data from a LiDAR survey, including the raw scanner files, point cloud files, rendered surface files, and calculations and interpretations made on this data.

Based on a number of case studies that have been conducted in the past several years (some of which were described in Chapter 4), recommendations for best practices for the topics mentioned above are made, as discussed below. It should be noted that the development of best practices is an ongoing activity, and the recommendations made in this section will change with time. This chapter concludes with sections on the cost of a LiDAR survey, the accuracy of LiDAR generated data, and a brief comparison of LiDAR and photogrammetry for obtaining geotechnical data.

BEST PRACTICES IN THE FIELD

The basic procedure for scanning in the field was described in Chapter 2. Now some detailed recommended procedures are presented.

Deciding on Scanner Placement and Number of Scans

One of the first and most important steps is to spend a few minutes at the field site to determine where the scanner will be placed and how many scans will be made. For scans of a slope adjacent to a highway, scans will most likely be made on the opposite side of the highway, along a turn-out or shoulder. In general, it is best if the distance from the scanner to the slope is at least as great as the height of the slope of interest, as shown in Figure 23. This eliminates a sharp angle between the scanner field of view and the dip of the slope. If the height of the slope of interest is higher than approximately 30 m (98 ft), then the optimum location for the scanner will be farther away than the other side of the highway, which could present access and viewing problems depending on the topography and landowner issues. Another parameter is the distance between scans taken along the highway. In general it is best if the scanner horizontal field of view is 50 degrees or less, as shown in Figure 23. This eliminates a sharp angle between the scanner field of view and the strike of the slope. Also, at least a 20% overlap between scans should be maintained, as shown in Figure 23. The overlap is used to assist with the stitching together of point clouds.

A final decision is whether multiple scans of a face taken at different angles should be made. Depending on the orientation of discontinuities relative to the scanning direction, it is possible that a joint set will be obscured (in the scanner shadow zone, as discussed

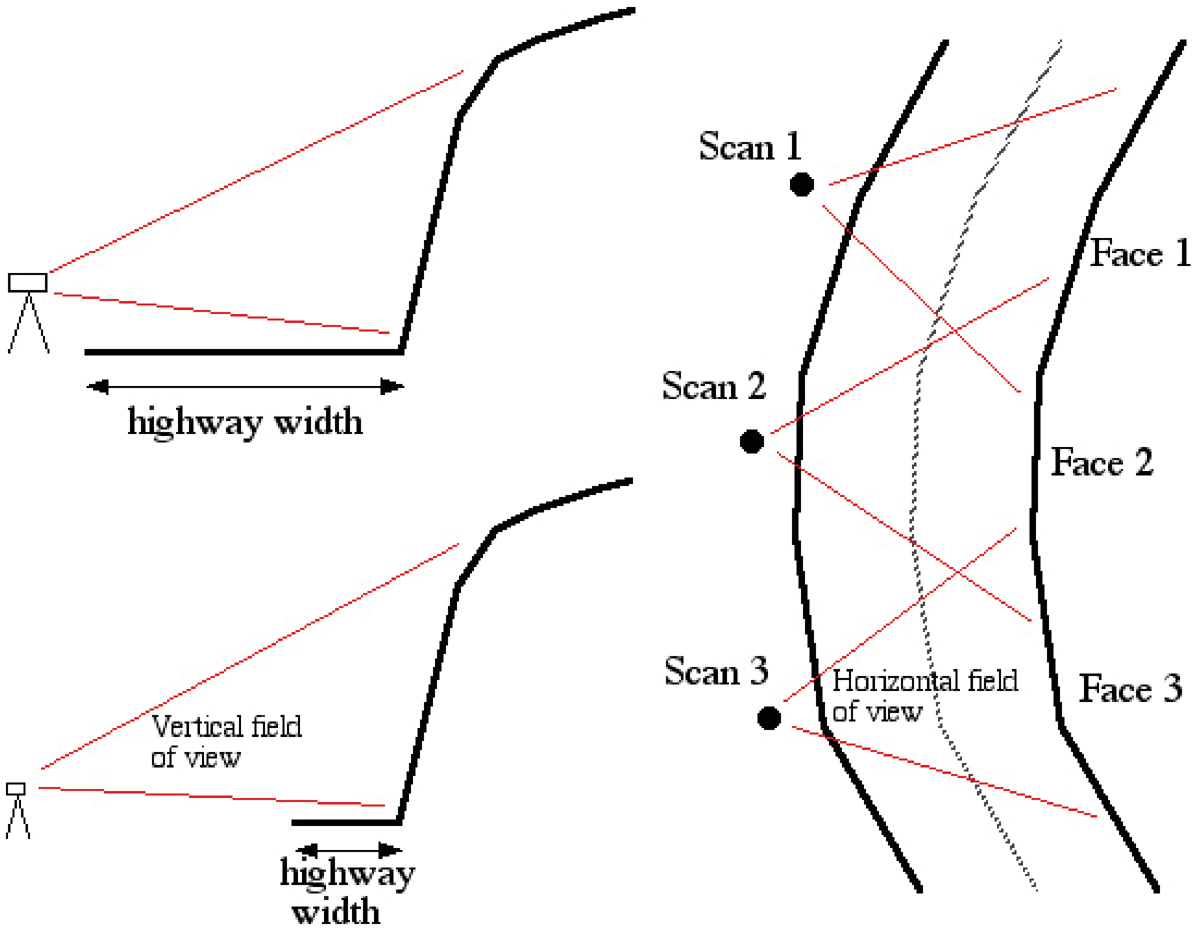


Figure 23. Schematic. Figures on left show cross sections with recommended scanning distances depending on the height of the slope of interest. Figure on right shows plan view with recommended distances between scanning locations.

in Chapter 4). If the guidelines given above are followed, the chance of significant scanner shadow zone is minimized. Also, a joint set that is subject to scanner shadow zone is likely to show traces, from which the orientation can be picked up with tracing on a draped photo as shown in Chapter 4. However, it is important to evaluate each scanner site for possible shadow zone, and take multiple images if necessary. For instance, referring to Figure 23, if Scan 2 has a potential problem with scanner shadow zone at Face 2, then either the locations of Scan 1 or Scan 3 can be used to take an additional scan of Face 2.

In most cases, multiple scans of a face at different angles will not be necessary, particularly with the use of photo draping to extract discontinuity orientation from fracture traces. However, if time warrants, and if the site conditions are complex and/or high risk, then taking multiple scans to eliminate potential scanner shadow zones is recommended.

Deciding on the Method for Scanner Registration

The next important step is to decide how scanner registration will be conducted. All scanners are able to register a point cloud by having at least three targets of known position in the scene. The three or more targets should not be in the same plane, and having targets across all areas of the scene produces the best results. Another procedure is to register some of the scans using targets, and register others by “stitching” them with those that have been registered (the stitching uses an Iterative Closest Point algorithm and is available in several of the point cloud processing programs). Some scanners can be registered by backsighting to known benchmarks along with surveying in the location of the scanner. Backsighting uses a built in optical telescope to site to known points so that the orientation of the scan can be determined. Finally, the orientation can be registered by carefully measuring the orientation of the scanner (if the scanner is leveled this only involves the measurement of scanner bearing). This last method, along with an accurate GPS of the scanner origin (sighting over a known benchmark, for instance), will also give the full registration. It should be noted that none of the above methods involve putting targets on the rock slope itself. Putting targets on the slope is a safety hazard and should be avoided, particularly on unstable slopes. However, depending on specific site conditions, putting targets on the slope may have advantages if it improves the accuracy of the registration and can be conducted in a safe manner.

At the present time, there are no recommendations on the preferred method for scanner registration. One reason is that the recommended method depends on the type and model of scanner. Backsighting, for instance, is only available in some of the scanners. Several publications are available looking in detail at the accuracy of various methods of scanner registration (Reshetyuk, 2006, for instance), the details of which are beyond the scope of this report. Several studies have been made by the author to compare different methods for scanner registration, but the results from these studies are not available at the present time.

Scanner Field of View and Point Spacing

In order to get a uniform point spacing in the point cloud, follow the guidelines as given in Figure 23 for the scanner field of view. Figure 24 shows a point cloud taken with a Riegl scanner, which has a 360-degree field of view. It shows a very high density of points near the scanner, with a much wider spacing farther away from the scanner. Shown in green is the only area of the point cloud that should be analyzed. It represents the rock face of interest (not things on the other side of the highway of no interest) with the field of view following the guidelines shown in Figure 23.

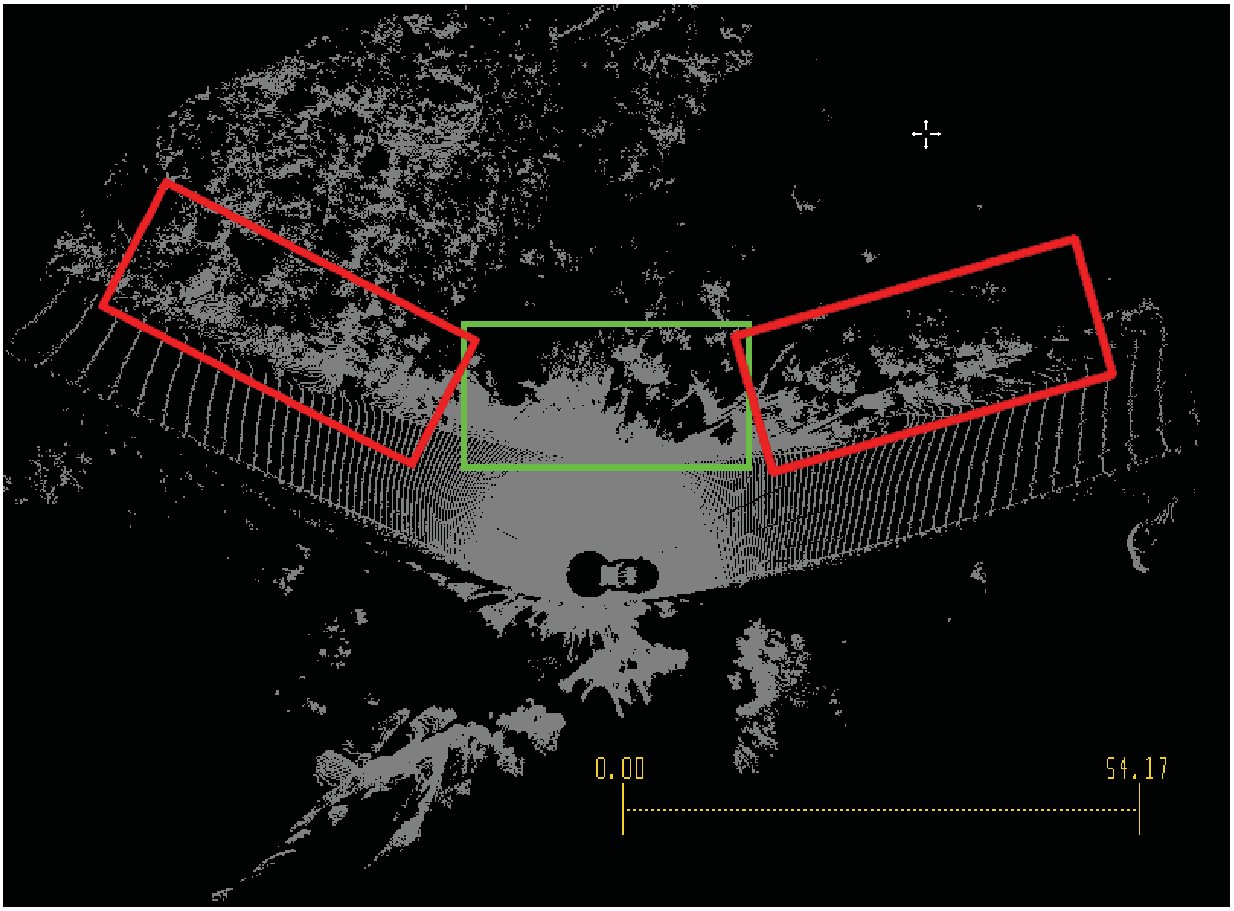


Figure 24. Schematic. Point cloud example. Plan view of scan of Mt. Lemmon Highway, Milepost 15. Proper scan window shown in green, unsuitable scanned highway slopes shown in red.

The areas shown in red are also of the rock face of interest, but these areas have two problems; 1) the point spacing will be much greater than that shown in the green region, and 2) the angle between the scanner and the face is too steep. It is recommended to always use the appropriate scanner field of view, to reduce the point cloud size and eliminate non-optimum scanner angles relative to the rock face. When taking multiple scans of a single face, as discussed in the text associated with Figure 23, a non-optimum scanner angle relative to the face is acceptable if the purpose is capture data on structural features that are hidden from one direction. In this case, even though the angle between scanner and rock face may be small, the angle between scanner and a particular structural feature of interest will still be satisfactory.

Average point spacing in the point cloud is a very important parameter that should be optimized for a particular application. In general, point spacings of 2 cm or less are optimum for most of the geotechnical applications discussed in Chapter 4 (rock mass characterization, rockfall chute characterization, rockfall change detection). Point cloud spacings up to 5 cm are acceptable for the scanning of high slopes (such as Glenwood Canyon), but point cloud spacings greater than 5 cm are not recommended for any geotechnical applications. For non-geotechnical applications involving the generation of a 3D digital terrain model, point cloud spacings up to 10 cm could be acceptable. Figure 25 shows an example of a point spacing of about 1.5 cm, allowing features less than 0.3 meters to be delineated clearly.

Figure 25. Schematic. Point cloud example. Ideal point cloud with a point spacing of about 1.5 cm (yellow ruler showing 1.85 meters).

Taking Digital Images

High-resolution digital images should always accompany each point cloud. The digital images can be used stand-alone for rock mass characterization and rockfall applications, or registered with the point cloud using photo draping techniques. All new scanners have high-resolution cameras built in (or mounted on top), and digital images are part of the "data package" that is produced from these scanners. However, older scanners may only have a low-resolution camera or no camera at all, so it is important to take digital images separately in these cases. Even with the newer scanners, it is good practice to take digital images separately to document the scanning and the overall site conditions. Separate digital images can also be used to take close-up images of rock features of interest. In general, image scale and camera calibration is not required for digital images taken separately, since this information can be extracted from the associated point cloud.

Field Notes

In addition to the data from the scanner, surveying, and any digital images taken separately, field notes should be taken (either by hand or using a laptop or handheld) and the field notes file should be placed in the same computer folder as the other data. Field notes can include the following:

- Location of site (from GPS or map)
- Site geology
- Rock mass information that cannot be extracted from point cloud (rock weathering, discontinuity fill, Schmidt hammer readings, small scale roughness, etc.) In order to associate this information with scan-derived information, the GPS coordinates of each piece of data collected can be recorded.
- Miscellaneous information such as details of benchmarks or other data collection activities in the area.

DATA PROCESSING BEST PRACTICES

A basic description of data processing using point cloud processing and CADD software was described in Chapter 3. Here we describe some specific recommended procedures.

Data Management

Data processing with point cloud processing and CADD software produces a number of very large files. For instance, a point cloud file containing one million points will take up about 30 Mbytes as an ASCII file and about 10 Mbytes as a binary file. The file will become larger as digital images and other kinds of information (such as stereonets and text) are added to the file. As discussed in Chapter 2, one million points might represent the scanning of a 30 meters high by 40 meters wide portion of a slope. If a number of scans along a highway are stitched together, then the size of the file goes up accordingly. It is important to store more than just the "finished" DTM files (data files that have been triangulated, stitched, photo draped, edited, etc.) or just the extracted geotechnical data. At a minimum, the original files from the scanner should be stored, as well as the point clouds once they have been registered (preferably in the xyz format given in Chapter 2 so that the data can be easily opened in any point cloud processing program). Each scan or set of scans should have a dedicated folder that contains the raw scanner files, registered point clouds, field notes, digital images, CADD files, etc.

Point Cloud Stitching

Individual point clouds usually have 1 to 3 million points (for 2 cm point spacing, that's a square areal coverage of approximately 25-45 m (82-148 ft) on a side). A site may consist of ten or more point clouds (sequentially down the highway as in Figure 23, for example). The point clouds can either be viewed and processed separately, or they can be stitched together into a single combined point cloud. For extracting geotechnical data, it is not necessary to stitch the point clouds together, and in general it is not recommended to do so. This is because the combined point cloud may have 20 million points or more, and will be very difficult to visualize and rotate in point cloud software. Point cloud software such as Split FX does allow the individual unstitched point clouds to be in the same file, and to combine the fracture orientation data on a single stereonet without having to stitch the point clouds together. For other purposes, such as viewing and making 3D measurements, it may be advantageous to have a single stitched DTM. In this case, it is recommended that a triangulated surface is made and only the merged triangulated surface is used for combined 3D measurements.

Extracting Rock Mass Characterization Information

At the present time, the only point cloud processing package that has a number of built-in features for extracting rock mass characterization information is Split FX. Based on using the software for a number of years, some best practices are given in Appendix C.

THE COST OF A LiDAR SURVEY

As described in this chapter, LiDAR can be used to collect important field data for the analysis of highway slope stability, and there are safety, access and other advantages of doing so. In many instances, the collection of this data using LiDAR could represent a cost savings compared with traditional methods. For example, the following numbers are based on the collection of discontinuity orientation measurements along a 300 meter section of Highway 93 in Arizona:

<u>Traditional data collection and analyses:</u>

- Cell mapping, 350 joint orientation measurements, 2 people for 2 days
- Processing and making graphs of the data, 1 person for 1 day
- Total 5 man days (with overhead, assume $1000 per day)
- Share of equipment and software costs $250
- Total cost - about $5250 (mostly manpower)

<u>LiDAR with automated fracture analysis software</u>

- Field scanning (six scans) and digital imaging, 1 person for 1 day
- Data processing, 1 day
- Scanner rental, $1500
- Share of other field equipment (camera, etc.), $200
- Share of software costs, $800 (assumes 10 projects covers software cost)
- Total cost - $4500 (less than 50% manpower)

This would be considered a typical example where the hand-measurements are made at the base of the slope, and it indicates slight cost savings with LiDAR. If repelling down the slope was involved to collect the discontinuity orientation measurements, then additional cost savings would be expected with LiDAR.

THE ACCURACY OF LiDAR-GENERATED DATA

For extracting fracture information from point clouds, a key measure of accuracy is the error in the estimation of a fracture's strike and dip (or dip and dip direction). As discussed earlier in this chapter, Figure 5 compares fracture orientation data measured by hand with LiDAR generated fracture orientation data (white vs black stereonets, respectively). Overall, the location of major structural features appear to differ by less than 5 degrees between hand-measurements and LiDAR generated data. Of course, the hand-measured results themselves have errors that could be as large as 5 degrees. Therefore, the discussion in this section focuses on errors in LiDAR-generated results alone.

Errors in the LiDAR results are due to three primary sources:

1. Instrument accuracy and field settings
2. Procedures and accuracy of point cloud registration
3. Software and procedures used for processing point clouds

Each of these errors are briefly discussed below:

Instrument accuracy and field settings

For a typical scan of a rock face, often over 1000 laser points will intersect large fracture surfaces, while less than 50 points may intersect smaller surfaces. It is important to understand how the number of laser points intersecting a fracture surface and the error of the laser impact the accuracy in the estimation of the strike and dip of the plane. For this purpose a Monte-Carlo based computer model has been developed to determine the error in the calculation of strike and dip, based on a 3D laser scanner with given distance and position accuracies and a fracture plane with a given size and distance from the scanner. Details of the model are described in Kemeny et al. (2003). Here we consider two fracture sizes, both with a point density of about 2 cm (the recommended point spacing described in Chapter 5). In the first case 724 laser points intersect a 0.5 x 0.5 m^2 fracture, and in the second case 100 laser points intersect a 0.2 x 0.2 m^2 fracture. Scanner position and distance accuracies of ± 1.5 cm are assumed. This is a large error, and most 3D laser scanners are capable of scan accuracies less that this (see Table 1 and Appendix A).

For the case of 724 laser points hitting the 0.5 x 0.5 m^2 fracture plane, the Monte-Carlo model showed a mean variation in dip from the actual dip of 0.19 degrees with a standard deviation of 0.03, and a mean variation in dip direction of 0.1 degrees with a standard deviation of 0.015. For the case of 100 laser points hitting the 0.2 x 0.2 m^2 fracture plane, it shows a mean variation in dip of 0.93 degrees with a standard deviation of 0.3, and a mean variation in dip direction of 1.0 degrees with a standard deviation of 0.33. Overall these results are very promising and indicate that errors in the strike and dip less than one degree should be able to be attained even with small fracture surfaces, using almost any of the 3D laser scanners available today. It should be noted that the model does not consider some other sources of possible error, including atmospheric and temperature errors, or the errors discussed in the next two sections below.

Point cloud registration errors

This is an important source of error, and this error affects the calculated fracture orientations for all fractures regardless of their size. The error in the estimation of fracture orientation will depend on the registration method that is used. For instance, if registration is based on Brunton measurements (measurements of objects in the scene or of the scan direction itself), then the error will be ± 2 degrees or more. The most common method of scanner registration is to use 3 or more surveyed points (3D similarity transform). If three points are used, and assuming a surveying error of ± 1.5 cm, 3D similarity transformation results indicate a maximum deviation in strike and dip of about ± 0.2 degrees for a typical scan taken at a distance of 30 meters. This is very reasonable, and if more targets are used the errors should be even smaller. The errors associated with other methods of scanner registration are discussed in Reshetyuk (2006).

Software and procedures used for processing point clouds

Differences in how the point cloud is analyzed to determine fracture orientation results in large differences in the estimation of the strike and dip of a fracture surface. One method is to pick three points on a fracture and determine the orientation of the plane made by these three points. Because actual rock fracture surfaces are not flat planes, this technique will show large variations depending on the roughness of the surface and which three points are selected. A better method is to select all the points that make up the fracture and calculate the best-fit plane through those points. This method will also show variations because "selecting all the points that make up a fracture" is not a straightforward task, particularly near the edge of the fracture. If an automated routine is used to select the points that make up the fractures (such as the automated routine in Split FX), then changing the parameters in the routine will result in differences in the calculated best-fit orientations.

A COMPARISON OF LiDAR AND PHOTOGRAMMETRY

LiDAR and photogrammetry both produce a high-resolution 3D rendering of a scene of interest, but they are based on very different principles. As described in Chapter 2, a LiDAR point cloud is based on the reflections of pulses of laser light that are emitted from a scanner. Also, photo draping techniques can then be used to drape a high-resolution digital image onto a point cloud, as described earlier in this chapter. Many types of analyses can be conducted with the point cloud alone, including the determination of discontinuity orientation, roughness, length and spacing and block size. The draped photo can be used to determining discontinuity orientations for structures that have no exposed surfaces (such as a joint set in the scanner shadow zone) as well as assisting with the interpretation of geology, major structures (such as faults), and other things.

In photogrammetry, the 3D coordinates of a scene are determined from digital images taken of the same scene from different directions. In particular, information on the 3D coordinates is determined from the parallax, which is the change of angular position of two observations of a single object relative to each other. Details on photogrammetry can be found in Faugeras (1996) and many others. In the field, special stereo cameras can be used that have two lenses at a fixed distance and orientation relative to each other. Today it is more common to use a standard digital camera and take multiple images of a scene from arbitrary directions and positions. The multiple camera positions are then determined using a technique called bundle adjustment that involves "feature matching" in overlapping areas of the images. Photogrammetry software specifically designed for extracting geotechnical information from digital images include 3G (www.3gsm.at), Siro Vison (www.csiro.au), and Adam Technology (www.adamtech.com.au). Photogrammetry software ranges in price from $5,000 to over $50,000. A standard high-resolution camera can be used for field surveys, which can range in price from $500 to over $5000, depending on resolution and features.

A brief description of some of the differences between LiDAR and photogrammetry and the impact of these differences on highway slope stability analyses are given below.

1. LiDAR emits its own light, as opposed to photogrammetry, where either natural lighting is used or an external light source (such as flash lighting) is used. This can result in some differences. First of all, when scanning a slope that has vegetation, the LiDAR light can penetrate through small openings between the vegetation to provide information on the soil or rock underneath. Photogrammetry, on the other hand, will only give this information if there is enough natural light available behind the vegetation. Secondly, because photogrammetry relies on multiple images of the same scene, lighting differences can occur due to changes in light in different directions or changes in lighting between the time the multiple images are taken. Thirdly, when imaging an underground excavation, LiDAR has the advantage that no external light source is required (LiDAR scans can be conducted in the dark).

2. Photogrammetry needs to view a portion of a scene from a least two directions in order to determine the 3D coordinates of that portion of the scene. LiDAR can determine 3D coordinates from a single viewing angle. This can pose problems with photogrammetry when there are large variations in topography over small areas, such as in areas of dense vegetation or rock rubble.

3. Because images are taken from different angles with photogrammetry, the 3D DTMs from photogrammetry may not have as many areas of no data (scanner shadow zones) compared with a LiDAR scan from a single viewing direction. To address this problem, LiDAR scans can also be taken from different viewing angles, as discussed earlier in this chapter.

4. In the field, a LiDAR survey takes about the same amount of time as a photogrammetry survey. Because registration is required for both methods, much of the time in the field is taken up with issues involved with 3D registration (placing and surveying of targets, for example). The automatic output from a LiDAR scan is a point cloud, and no processing is required in producing a point cloud file. To produce 3D information from photogrammetry, on the other hand, many steps are required that require time and expertise with photogrammetry software. Photogrammetry also requires camera calibration, a pre-field step not required for LiDAR surveys. Once a 3D model is produced, the analysis of the model to extract geotechnical information is very similar between LiDAR and photogrammetry. Overall, if photo draping is not used in the LiDAR analysis, then the LiDAR survey and processing will take less manhours and require less software training than the equivalent photogrammetry survey. If photo draping

is used as part of the LiDAR analysis, this will increase the manhours and amount of software training for using LiDAR for highway rock slope stability.

5. The hardware are significantly less expensive for photogrammetry, consisting of only a high resolution digital camera and associated field equipment (tripod, etc.). The software costs for photogrammetry can be either cheaper or more expensive than LiDAR, depending on the specific software packages that are used with each method. The total cost of LiDAR survey can be cheaper or more expensive than an equivalent photogrammetry survey depending on many factors, including total manhours, software costs, and how the cost of the LiDAR equipment is calculated (it may be shared with other purposes or rented, for example).

6. The final accuracy of a 3D model, whether it comes from photogrammetry or LiDAR, depends on many factors, including the specific hardware and software used, the method and accuracy of scanner registration, and the specific field procedures. Based on published accuracies by scanner manufacturers (Appendix A) and photogrammetry software companies (see web sites listed above), it should be possible to get the equivalent accuracy from both methods.

CHAPTER 6 – EXPECTED ADVANCES IN THE NEXT 5 YEARS

This section contains some discussion about expected future improvements to LiDAR hardware and software in the next few years. This is based on discussions and presentations that took place with hardware and software manufacturers at the following meetings and workshops:

- Workshop on Laser and Photogrammetric Methods for Rock Face Characterization, Golden, CO (June 17-18, 2006)
- 5th International Visualization in Transportation Symposium and Workshop, Denver, CO (October 23-26, 2006)
- LiDAR Spar Point Conference, Sugarland, TX (March 26-27, 2007)
- Workshop on LiDAR and Photogrammetry Methods for Rock Engineering, Vancouver, Canada (May 26-27, 2007).
- LiDAR Spar Point Conference, Houston, TX (March 3-5, 2008)

Overall, future improvements to LiDAR technologies fall into the following categories:

- Hardware improvements;
- Multi-sensor fusion;
- Mobile scanning;
- Improvements to point cloud processing software, including integration with CAD and GIS;
- 3D mashups; and
- Standards.

Each of these topics, as it relates to using LiDAR for highway rock slope stability, is discussed below.

HARDWARE IMPROVEMENTS

Recent improvements to LiDAR hardware include the following:

- Time-of-flight scanners with capture rates up to 50,000 pps
- Phase shift scanners with capture rates up to 1 million pps
- Increased range in time of flight scanners, up to 2 km
- Increased range in phase shift scanners, up to 50 meters
- Increased accuracies in time of flight and phase shift scanners

This trend is expected to continue in the future. The best information on recent hardware improvements is available from the scanner manufacturers web sites (see Chapter 2).

MULTI-SENSOR FUSION

LiDAR manufacturers are currently adding more and more useful features to the LiDAR units. These features include built in surveying capabilities, built in GPS, automated pan and tilt movement, built in tilt and compass bearing measurements, better onboard camera, built in motion compensators, etc. Already the fusion of ground-based LiDAR and high-resolution digital imaging has occurred, resulting in high-resolution, 3D, photo-quality digital terrain models. Also, the fusion of ground-based and airborne LiDAR is starting to take place. Future sensor fusion may include the integration of hyper-spectral imaging, radar and other sensor data.

MOBILE SCANNING

Mobile scanning (also referred to as dynamic scanning) includes the ability to scan from a moving ground-based vehicle or boat. Several of the scanner manufacturers are now involved with the production of mobile scanning units. From POB (2007):

> Several manufacturers, companies and agencies offer dynamic scanning solutions. Optech Inc. (Vaughan, Ontario, Canada) recently announced a dynamic scanner called the ILRIS-3Dmc. The Canadian manufacturer is promoting the use of its motion-compensated scanner for three common applications: stop-and-scan, mobile platform vertical scan (i.e., oil rig from a boat) and mobile platform horizontal scan (i.e., road surface survey from a vehicle). Riegl offers several scanners that can be deployed as dynamic scanners, and that have successfully been used on boats to inventory waterway assets and to geo-reference obstructions (such as semi-submerged rocks) that cannot be mapped directly from a boat. The Nottinghamshire, UK company 3D Laser Mapping has released a system called the StreetMapper Mobile LiDAR mapping system based on Riegl scanners. It offers a turnkey survey vehicle with all the necessary components mounted on it or as a combination of the sensor platform and the electronic rack. The overall weight of its system is about 150 kg (330 lb), which is small enough to operate from normal passenger cars.
>
> The Federal Highway Administration's Turner-Fairbank Highway Research Center is also using dynamic LiDAR. The agency has developed a system called the Digital Highway Measurement vehicle. This multi-sensor system uses laser scanners and Macrotexture lasers (lasers with a submillimeter beam diameter) to profile the texture of highway surfaces. It is also being used to explore the use of new 3D ground penetrating radar for subsurface evaluations down to 6 to 9 m (19.7 to 29.5 ft) for locating utilities and pavement thickness. Data collection like this would represent complete roadway cross-section and would be very valuable to highway designers.
>
> The accuracy of the final point cloud and subsequent drawings and models is dependent on many factors. One factor is the error from a single laser scanner measurement. This relative accuracy can be provided by the laser scanner manufacturer; for example, this can be as small as 10 mm for a Riegl scanner. The ability to accurately measure objects in the point cloud is also dependent on the point density, which is affected by vehicle and scanner speed. The slower the vehicle goes, the denser the point cloud will be. The absolute accuracy of the data in relation to a local coordinate system is dominated by the navigation system. This can be as low as 3 cm under favorable conditions and might be as high as 0.5 m under poor conditions.

3D MASHUPS

"Mashups" are new kinds of web-based applications that combine data from more than one source and provide an integrated tool for information searching, data retrieval and analysis (IBM, 2006). 3D mashups combine LiDAR or other 3D results with other types of information such as maps and 2D images. Google Maps, for example, could be combined with LiDAR scanning results and slope stability software to rapidly determine areas where slope problems are likely to occur. Repeated scans could be used to provide time-dependent maps of change and rockfall hazard. There are some technical challenges involved with mashups with integrating the different types of information.

IMPROVEMENTS IN POINT CLOUD PROCESSING SOFTWARE

Point cloud processing software has improved greatly in the past few years and is expected to continue to improve in the near future. More CADD tools are expected to be implemented into the point cloud processing software, and CADD software is now being developed that can integrate point clouds and CADD objects (Autodesk Navisworks, for example). Also, the ability to use smaller amounts of data in memory, either through compression or dynamic viewing windows, to allow large clouds to be viewed and processed on standard computers. Advanced filters is another area that needs to be developed, such as filters to automatically remove vegetation from rock slope point clouds.

STANDARDIZED DATA FORMATS

This is a major subject that needs to be tackled in the near future. The xyz ASCII format for point clouds as shown in Chapter 2 is widely used and accepted, but does not contain draped photo information, as well as other header information. Possible standard formats for ground-based LiDAR data include .LAS (used for airborne LiDAR), 3D TIFF, 3D JPEG, .AAF (advanced authoring format), .X3D, VRML and GeoVRML.

Other needs in terms of data standards include a highly compressed data format for efficient archiving, a standard terminology for ground-based LiDAR and the various kinds of output data, better integration between LiDAR point clouds and CADD software, better integration with mapping, geospatial applications (see Spar Point, 2007 for more details).

CHAPTER 7 – CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In this final report the use of ground-based LiDAR (also called 3D laser scanners) to obtain highway rock slope geotechnical information has been reviewed. This included discussions of currently available LiDAR hardware and software, the current state of LiDAR for highway geotechnical applications (rock mass characterization, rockfall characterization, as-built 3D measurements), best-practices for field scanning and for point cloud data processing, and expected trends in the industry in the near future.

At the beginning of this report a "wish list" was given of benefits that a new technology should possess in order to be useful to FHWA for highway rock slope stability studies. Conclusions are now made for each item on the list with regards to the use of ground-based LiDAR.

Automatic data acquisition over entire slope

It was demonstrated in Chapter 4 that some of the most important types of geotechnical information that is currently being collected by hand can be acquired from LiDAR point clouds and associated digital images. This includes detailed information about rock discontinuity orientation, roughness, length, spacing and block size. In many cases, this information can be automatically extracted from LiDAR point clouds using currently available point cloud processing software. For example, using the Split FX software, discontinuities in a point cloud can be automatically delineated and the orientations plotted on a stereonet. This information can then be exported to rock slope stability software. It was also demonstrated in Chapter 5 that fracture orientation errors of less than one degree could be achieved if at least three surveyed targets are used as part of the scanner registration. Currently, the determination of discontinuity roughness, length, spacing and block size is semi-automatic and involves the use of hand editing tools in the point cloud processing software.

Remote data acquisition for improved safety

Ground-based LiDAR collects data at a safe distance from the slope. Most of the ground-based LiDAR units now available have the ability to scan slopes from a distance of at least 50 meters, which is sufficient for many highway slope applications. Many scanners have a range of up to 200 meters and a few scanners have a range of 1 km or more. Details on scanner range are provided in Appendix A. Data collection for scanner registration (surveyed targets, backsighting, or scanner orientation measurements) can also be conducted at a safe distance from the slope.

Rapid data collection

A typical scan of a 20 m high by 30 m wide highway slope with a time-of-flight scanner takes about 10 minutes (assumes 2 cm point spacing and 2500 points per second). This same scan with a phase-shift scanner would take less than 20 seconds (assumes 2 cm spacing and 100,000 points per second). Additional time in the field is required to collect data for scanner registration. Depending on the method for scanner registration, this can take as little as a few extra minutes. Processing the data to extract geotechnical information can also be conducted very rapidly. It was shown in Chapter 4 that automatically delineating the fractures in a point cloud and plotting the orientations on a stereonet takes only a few minutes. A complete analysis, including the extraction of discontinuity roughness, fracture length and spacing, block size and photo draping can be conducted in several hours.

New technologies for data collection and processing easy to learn and operate

3D laser scanners are very easy to operate, as discussed in Chapters 2 and 5. Most scanners have a very user-friendly interface and only require a few settings before scanning, such as the scan region of interest, the point cloud spacing, and the camera exposure parameters. Appropriate personnel to conduct field LiDAR surveys could include field technicians, field surveyors, geologists and geotechnical personnel. Processing point clouds to extract geotechnical information using point cloud processing software is also fairly easy to learn but does require some geotechnical expertise. Users need to have a basic understanding of rock engineering principles associated with rock masses and rock discontinuities.

Able to provide a high-resolution 3D Digital Terrain Model (DTM) of a highway slope or rock outcrop that could be compared with future DTMs as the slope ages and deteriorates

An important feature of ground-based LiDAR is the ability to drape a high-resolution digital image onto a point cloud, producing a high resolution, 3D DTM of the scanned slope. This DTM represents a 3D snapshot of the slope at a particular time, which can be compared with DTMs taken a later time. Point clouds taken at different times, for instance, can be subtracted to produce a difference point cloud. As described in Chapter 4, the difference point cloud can be used to analyze rockfall, slope weathering, or the volume change after rock excavation.

Cost Effective

It was shown in Chapter 5 that 3D laser scanning can be very cost effective compared with traditional scanline mapping and photogrammetric surveys. Even though LiDAR hardware is expensive, the cost of the hardware can be shared between different uses and different offices. Scanner rental is also an option. Point cloud processing software is relatively inexpensive and in many instances is less expensive than photogrammetric software.

Overall Conclusions

It is concluded that there are many benefits to using ground-based LiDAR to assist with highway rock slope stability studies. Specific recommendations with regards to utilizing ground-based LiDAR for highway slope stability projects are given below.

RECOMMENDATIONS

Field Scanning

Field LiDAR surveys can be conducted by either FHWA personnel or outside surveying contractors. In either case, the best practices described in Chapter 5 should be followed closely, along with the documented procedures for the particular scanner that is used. With regard to scanner registration, there are three primary choices, as listed below:

1. Three or more surveyed targets in the scanned scene.
2. Backsighting to known benchmarks to establish the scanner position and and scan direction
3. Using a compass to establish the scan direction (normally by measuring the bearing and tilt of the scanner itself)

If established benchmarks are available at the location where scanning is to be conducted, then either method 1 or 2 is recommended, since they result in a more accurate registration than method 3. Method 3 only takes a few minutes and can be used as a backup registration method. Method 3 can be used as the primary method when benchmarks are not available, or when scanning and scanner registration must be conducted very quickly.

Point Cloud Processing Software

Data processing using point cloud software is relatively straightforward, however it is recommended that the personnel involved with LiDAR data analysis have training in rock engineering principles and design. Data processing using point cloud software can be conducted by either FHWA personnel or outside consultants. Either way, the best practices described in Chapter 5 should be followed. At the present time, only the Split FX software is designed specifically for extracting geotechnical information from LiDAR point clouds, and its use is recommended at this time. In the future, other software packages may also have these capabilities. Even though all examples shown in this report were conducted using the Split FX software, much of the analysis could be conducted with the more generic point cloud processing or CADD software. However, this is not recommended since it will involve significant manhours in software training and processing (finding hundreds of fracture planes in a point cloud by hand, for instance, could take an order of magnitude more time than utilizing automated methods).

Additional Recommended Studies

There are several areas that warrant additional research and case studies, as described below.

Comparing Scanner Registration Methods

As listed above, there are three primary methods for scanner registration, and each method has specific procedures and issues. A detailed case study should be conducted to determine the advantages and disadvantages of each method. Also, the specific accuracies of each method should be determined for a variety of field conditions, as well as determining best practices for each method to optimize accuracy and the time spent in the field.

"Start to Finish" Case Study for Rock Slope Stability

As a full assessment of the procedures described in this report, a "start-to-finish" slope stability case study should be conducted for a specific highway slope. This would include conducting a LiDAR survey of a slope, extracting geotechnical parameters, conducting a slope stability analysis, and writing a report on the results. Many case studies have been conducted using ground-based LiDAR in many different rock types. These case studies have evaluated different aspects of utilizing LiDAR for rock slope stability, but no single case study has evaluated all the field and processing procedures involved. Also, no case studies have been conducted with close collaboration with FHWA personnel and procedures.

Extracting Additional Information From LiDAR Point Clouds

There is the potential to extract additional information from LiDAR that would be useful for rock slope stability studies. This additional information includes:

- Degree of slope weathering (slight, moderate, significant)
- Discontinuity fill (mineral composition of fill and thickness of fill)
- Geology (mineral composition)
- Slope movement (slope displacement, velocity and acceleration)
- Incorporation of slope stability equations in point cloud processing software (allows slope stability visualization on point clouds)
- Automation of the extraction of information currently extracted using hand tools (roughness, length and spacing distributions, block size)

It is recommended that research be conducted in the areas described above.

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APPENDIX A – SPECIFICATIONS OF CURRENT LiDAR HARDWARE

Table 2. 2008 LiDAR Hardware Summary Sets 1 to 5 (*Point of Beginning* website).

Manufacturer	**3rdTech**	**FARO Technologies, Inc.**	**FARO Technologies, Inc.**	**FARO Technologies, Inc.**	**FARO Technologies, Inc.**
Product	**DeltaSphere-3000IR**	**Photon Laser Scanner**	**FARO Laser Scanner LS 840**	**FARO Laser Scanner LS 880**	**FARO Laser Scanner LS 420**
Performance					
Laser Wavelength (in nm)	780	785 nm	785nm	785nm	785nm
Laser Power (in W, mW)	8mW	20 mW	10mW	20mW	20mW
FDA Laser Classification (Class)	3R	3R	3R	3R	3R
Beam Diameter at Specified Distance from the Scanner (0.Y ft at X ft/Ymm at X m)	0.1 in. at 1 ft., 0.28 in. at 30 ft.	3.3 mm at exit, circular	3mm at exit	3mm at exit	3mm at exit
Measurement Technique	Modulated Beam TOF	Phase-shift	Phase shift	Phase shift	Phase shift
Average Data Acquisition Rate (pps)	15,000	120,000	120,000	120,000	120,000
Maximum Data Acquisition Rate (pps)	43,000	120,000	120,000	120,000	120,000
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	0.3 in at 40 ft	+/- 2mm at 25m	+/- 3mm at 25m	+/- 3mm at 25m	+/- 3mm at 25m
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	0.35 in at 40 ft		+/- 3mm at 25m	+/- 3mm at 25m	+/- 3mm at 25m
Angular Accuracy (degrees-min-sec)	0.015°		0.009°	0.009°	0.009°
Minimum Range (feet/m)	1 ft	10m	0.6m	0.6m	0.6m
Maximum Range (feet/m) at Specified Reflectivity (specify 4%, 10%, 30% or 80% targets)	54 ft at 85% reflectance; 35 ft at 30% reflectance	80M	40m at 90% reflectivity target	76m at 90% reflectivity target	20m
Field of View (vertical angle) (degrees-min-sec)	290°	320 degrees	320°	320°	320°
Field of View (horizontal angle) (degrees-min-sec)	360°	360 degrees	360°	360°	360°
Minimum Vertical Scan Increment (degrees-min-sec)	0.075°		0.009°	0.009°	0.009°
Minimum Horizontal Scan Increment (degrees-min-sec)	0.075°		0.00076°	0.00076°	0.00076°
Surface Reflectivity Range (%)	5 - 99%	.6/11.2 mm rms@ 90%	n/a	n/a	n/a
Onboard camera for aiming or for creating photomosaic, etc. (single image pixel resolution)	Yes. Optional - for creating full color, texture-mapped, computer graphics models and 360 degree panoramic images.	Yes	optional; resolution depends on used camera	optional; resolution depends on used camera	optional; resolution depends on used camera
Is hardware interoperable with optical total stations and GPS? If yes, how?	Yes. Compatible; aligned with tribrach mount.	No	Yes; by using fixed position methods and/or survedy referenc targets	Yes; by using fixed position methods and/or survedy referenc targets	Yes; by using fixed position methods and/or survedy referenc targets
Is the scanner better for scanning topography or for as-built surveys?	As-built surveys	As-Built	both	both	both
Is software technology for processing data from scanner manufacturer?	Yes, included.	Yes	yes	yes	yes
Can scanner be set up over a known point? (E.g., height of instrument, backsight point, etc.) If yes, can station information be entered?	Yes/No	Yes	yes; yes	yes; yes	yes;yes
Can the user specify the field of view and scan density?	Yes - both	Yes	yes	yes	yes
Maximum sample density (mm/ft)	15 points/degree		depends on object distance	depends on object distance	depends on object distance
Does the scanner support scan filters (e.g., range, intensity, area of interest)?	Yes - range, intensity, FOV	Yes	yes	yes	yes
Does the scanner have interchangable parts that allow for upgrades (e.g., the camera, other modular components, etc.)	Yes	Yes	yes; fully modular set up; distance sensor, PC module, mirror module, base module; color option; WiFi option	yes; fully modular set up; distance sensor, PC module, mirror module, base module; color option; WiFi option	yes; fully modular set up; distance sensor, PC module, mirror module, base module; color option; WiFi option
Communication Method (e.g., ethernet card, firewire, wireless)	Ethernet for range data / USB for color	Wireless, internal hard drive, ethernet	Ethernet; WiFi (wireless)	Ethernet; WiFi (wireless)	Ethernet; WiFi (wireless)
Does the scanner operate when out of level? Does it have compensators?	Yes / No	Yes	yes; yes	yes; yes	yes;yes

Table 2. 2008 LiDAR Hardware Summary Sets 1 to 5 (*Point of Beginning* website). - continued –

Manufacturer	3rdTech	FARO Technologies, Inc.	FARO Technologies, Inc.	FARO Technologies, Inc.	FARO Technologies, Inc.
Product	DeltaSphere-3000IR	Photon Laser Scanner	FARO Laser Scanner LS 840	FARO Laser Scanner LS 880	FARO Laser Scanner LS 420
Resolution and range of compensators	NA		resolution 0.001°; range +/- 15°	resolution 0.001°; range +/- 15°	resolution 0.001°; range +/- 15°
Environmental					
Storage Temperature Range (degrees F/C)	32 to 113°F		0°C to 60°C	0°C to 60°C	0°C to 60°C
Operating Temperature Range (degrees F/C)	32 to 113°F	5 degrees C to 40 degrees C	5°C to 40°C	5°C to 40°C	5°C to 40°C
Humidity (%)	Non-condensing	non condensing	non condensing	non condensing	non condensing
Ambient Light	Interior lighting or shade to total darkness. Direct sunlight reduces the range.		darkness until sunlight	darkness until sunlight	darkness until sunlight
General					
Scanner Dimensions (LxWxH) (inches/cm)	14 x 14 x 4 in	15.7	400mm x 160mm x 280mm	400mm x 160mm x 280mm	400mm x 160mm x 280mm
Scanner Weight (pounds/kg)	22 lbs	35lb	14.5kg	14.5kg	14.5kg
Is scanner recommended for mounting on standard survey tripod? If no, what is recommended stand?	Yes - or photographic tripod	Yes	yes	yes	yes
AC Power Requirements (volts/watts)	100-240 V (40 - 65 w)		90V to 280V; 60W	90V to 280V; 60W	90V to 280V; 60W
DC Power Requirements (volts/watts)	12 V (40 - 65 w)	24V	24V DC; 60W	24V DC; 60W	24V DC; 60W
Batteries	Standard 12 V battery	Nickel Metal Hydride	available	available	available
Battery Dimensions (LxWxH) (inches/cm)	Variable		110mm x 320mm x 420mm	110mm x 320mm x 420mm	110mm x 320mm x 420mm
Battery Weight (pounds/kg)	Variable		12.0kg	12.0kg	12.0kg
Battery Life (hours)	4 - 8 typical	6 hours	8 hrs.	8 hrs.	8 hrs.
Are batteries hot-swappable? (Y/N)	No		N	N	N
Computer Requirements for Control (handheld option?)	Standard PC/laptop, Win XP/Vista, ethernet, USB for color option.	Ethernet, WLAN, by PC or PDA	Standard Windows PC (or PDA with WiFi)	Standard Windows PC (or PDA with WiFi)	Standard Windows PC (or PDA with WiFi)
Computer Requirements for Data Processing	Standard PC/laptop,Win XP/Vista, 512 MB memory, 3D graphics card for display performance, 3-button mouse	Pentium III, 700 MHz, 256 MB RAM	OpenGL graphics card, 1GB RAM recomended	OpenGL graphics card, 1GB RAM recomended	OpenGL graphics card, 1GB RAM recomended
Standard Accessories (list)	Wheeled shipping crate with handle, external power supply, auxiliary auto power cable, quickrelease tripod mount, cables, SceneVision-3D software, safety glasses.	Power supply, connector box, LEMO cable, Ethernet cable, 2 laser protection glasses, FaroRecord software, FaroScene software, Inclination Sensor	Power supply, connector box, LEMO cable, Ethernet cable, 2 laser protection glasses, FaroRecord software, FaroScene software	Power supply, connector box, LEMO cable, Ethernet cable, 2 laser protection glasses, FaroRecord software, FaroScene software	Power supply, connector box, LEMO cable, Ethernet cable, 2 laser protection glasses, FaroRecord software, FaroScene software
Optional Accessories (list)	Calibrated professional digital camera and lens, camera mount, additional software, tripod, laptop stand, dolly, laptop, onsite training.	carbon fiber tripod, power base, ipod touch, nikon digital camera, backpack	Tripod, color option, reference spheres, software packages and many other accessories.	Tripod, color option, reference spheres, software packages and many other accessories.	Tripod, color option, reference spheres, software packages and many other accessories.
Warranty	12 months	1 year standard, optional additional 3yr	1yr	1yr	1yr

Table 3. 2008 LiDAR Hardware Summary Sets 6 to 10 (*Point of Beginning* website).

Manufacturer	**Leica Geosystems**	**Leica Geosystems**	**Maptek I-Site 3D Laser Imaging**	**Maptek I-Site 3D Laser Imaging**	**Measurement Devices Ltd**
Product	**HDS6000**	**Leica ScanStation 2**	**I-Site 4400LR Laser Scanner**	**I-Site 4400CR Laser Scanner**	**QuarrymanPro / LaserAce Scanner**
Performance					
Laser Wavelength (in nm)	650, 690 nm	532	905	905	905nm
Laser Power (in W, mW)	< 4.75mW	1 mW, avg.	10mW	10mW	
FDA Laser Classification (Class)	3R	3R	3R	3R	1M
Beam Diameter at Specified Distance from the Scanner (0.Y ft at X ft/Ymm at X m)	3mm at exit; 8mm @25m; 14mm @50m	6 mm at 50 m [1]	140mm at 100m	140mm at 100m	46mm at exit, 173mm at 50m
Measurement Technique	Phase shift	Pulsed laser; TOF	Time of flight	Time of flight	Time of flight
Average Data Acquisition Rate (pps)	125,000	Dependent on scan conditions	4400	4400	250pps
Maximum Data Acquisition Rate (pps)	up to 500,000	Up to 50,000 [2]	4400	4400	250pps
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	4mm at 90% albedo up to 25m; 5mm at 18% up to 25m; 5mm at 90% up to 50m; 6mm at 18% up to 50m	4 mm at 50 m [3]	20mm at 50 m (1), 50mm at 500m	20mm a 50m (1), 50mm at 500m	5cm
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	6mm, 1m to 25m range; 10mm to 50m range	6 mm at 50 m [4]	50mm at 100m (1)	50mm at 100m (1)	67mm at 50m
Angular Accuracy (degrees-min-sec)	0.0071 degree (25 seconds)	0.0034 degree (12 seconds)	0.04	0.04	0.02degrees
Minimum Range (feet/m)	0.1m	< 1 m	5m	2m	5m
Maximum Range (feet/m) at Specified Reflectivity (specify 4%, 10%, 30% or 80% targets)	79m @90%; 50m @18% albedo	300 m at 90%; 134 m at 18%	150m at 4%, 700m at 80%	500m at 80%	700m at 90%, 400m at 18%
Field of View (vertical angle) (degrees-min-sec)	310°	270 degree	80	80	-45 to +80 degrees
Field of View (horizontal angle) (degrees-min-sec)	360°	360 degree	360	360	0 to 360degrees
Minimum Vertical Scan Increment (degrees-min-sec)	0.009°	00-00-01 (1 arc second)	0.108 degrees	0.108 degrees	0.05degrees
Minimum Horizontal Scan Increment (degrees-min-sec)	0.009°	00-00-01 (1 arc second)	0.108 degrees	0.108 degrees	0.05degrees
Surface Reflectivity Range (%)	1%-100%	1 - 100%	1-95%	1-95%	1-100%
Onboard camera for aiming or for creating photomosaic, etc. (single image pixel resolution)	Any external digital camera can be used for photo-overlay using Leica Cyclone software	Yes [5]	Integral linear, 40 megapixel (16667x2520)	Integral linear 80 megapixel (16667X4200)	No
Is hardware interoperable with optical total stations and GPS? If yes, how?	Yes, via Leica's X-Function, LandXML and ASCII.	Yes [6]	Yes (2)	Yes (2)	Yes, via software
Is the scanner better for scanning topography or for as-built surveys?	As-built	Excellent for both	Topography	Topography	Topography
Is software technology for processing data from scanner manufacturer?	Yes, Cyclone and CloudWorx Suite	Yes, Cyclone, CloudWorx, Cyclone II TOPO	Yes	Yes	Yes, ModelAce and Face3DPro
Can scanner be set up over a known point? (E.g., height of instrument, backsight point, etc.) If yes, can station information be entered?	Yes, Yes	Yes; yes [7]	Yes/Yes	Yes/Yes	Yes and yes
Can the user specify the field of view and scan density?	Yes	Yes [14]	Yes/Yes	Yes/Yes	Yes
Maximum sample density (mm/ft)	1.6x1.6mm @ 10m, 7.9x7.9mm @ 50m	< 1 mm at 300 m range	190mm at 100m	190mm at 100m	10mm
Does the scanner support scan filters (e.g., range, intensity, area of interest)?	Yes: range, intensity, area	Yes, range, intensity, area	Yes	Yes	Polygon, rectangle, last hit
Does the scanner have interchangable parts that allow for upgrades (e.g., the camera, other modular components, etc.)	Yes: battery, user interface, reflector attachment	[8]	Battery may be upgraded for extreme weather conditions, otherwise no.	Battery may be upgraded for extreme weather conditions, otherwise no.	No
Communication Method (e.g., ethernet card, firewire, wireless)	on-board controls, ethernet, and bluetooth	Ethernet or wireless	Ethernet, Memory stick	Ethernet, Memory stick	Serial

Table 3. 2008 LiDAR Hardware Summary Sets 6 to 10 (*Point of Beginning* website). - continued –

Manufacturer	**Leica Geosystems**	**Leica Geosystems**	**Maptek I-Site 3D Laser Imaging**	**Maptek I-Site 3D Laser Imaging**	**Measurement Devices Ltd**
Product	**HDS6000**	**Leica ScanStation 2**	**I-Site 4400LR Laser Scanner**	**I-Site 4400CR Laser Scanner**	**QuarrymanPro / LaserAce Scanner**
Does the scanner operate when out of level? Does it have compensators?	Yes. Integrated tilt sensing and read-out.	Yes; yes, survey-grade [9]	Yes/Yes	Yes/Yes	Operates out of level, manual compensation
Resolution and range of compensators	Dual-axis tilt sensor: selectable on/off; 3.6" resolution	1 second resolution; 5minutes range	20	20	
Environmental					
Storage Temperature Range (degrees F/C)	-20°C to +50°C	+65 to -25 degrees Celsius	-40C to +60C	-40C to +60C	-20 to +70C
Operating Temperature Range (degrees F/C)	0° C to +40° C	+40 to 0 degrees Celsius	-40C (3) to +50C	-40C (3) to +50C	-10 to +45C
Humidity (%)	non-condensing atmosphere	Non-condensing	100% IP65	100% IP65	IP66
Ambient Light	any light conditions	Any light conditions	Any	Any	Any light conditions
General					
Scanner Dimensions (LxWxH) (inches/cm)	7.5?D x 11.5? W x 13.8? H, 190mm D x 244mm W x 351.5mm	370mm x 265 mm x 510 mm	430x250x360 mm	430x250x360 mm	20.9 x 24.3 x 42.0 cm
Scanner Weight (pounds/kg)	14 kg, nominal (includes integrated battery)	18.8 kg with carry handle	12kg	12kg	9.7kg
Is scanner recommended for mounting on standard survey tripod? If no, what is recommended stand?	Yes.	Yes	Yes	Yes	Yes
AC Power Requirements (volts/watts)	90 - 260V AC	100 - 240V; < 80W avg.	N/A (battery integral)	N/A (battery integral)	100-240VAC for battery charger
DC Power Requirements (volts/watts)	24V DC	36V; < 80W avg.	24V,1.6W (battery integral)	24V,1.6W (battery integral)	12VDC
Batteries	On-board: Li-ion, External (optional): lead acid	2 lead acid with System	24V 3800 mAh NiMh rechargeable	24V 3800 mAh NiMh rechargeable	7Ah 12VDC
Battery Dimensions (LxWxH) (inches/cm)	External: 9.5? x 10? x 12? ; 240mm x 260 mm x 300mm	236 mm x 165 mm x 215 mm	Included in scanner dimensions (battery is integral)	Included in scanner dimensions (battery is integral)	18 x 13 x 8 cm
Battery Weight (pounds/kg)	Internal: 1kg External: 16 kg,	12 kg	2kg	2kg	3.2kg
Battery Life (hours)	Internal: 1.5 hours External (optional): 4 hours	> 3 hrs	3	3	3hours for continuous fast scan
Are batteries hot-swappable? (Y/N)	No	Yes	No	No	No
Computer Requirements for Control (handheld option?)	1.4GHZ Pentium M or similar, 512MB SDRAM, Ethernet Card, SXGA+, Windows XP (Pro or Home Edition), Windows 2000; Handheld Tablet PC option; handheld PDA option	[10]	Hand held supplied	Hand held supplied	Optional ruggedised PC
Computer Requirements for Data Processing	2.0 GHz Pentium 4, 512 MB SDRAM, ethernet card, SXGA+, Win XP (Pro or Home Edition), Win 2000	[11]	PC or laptop (I-Site Studio? software supplied)	PC or laptop (I-Site Studio? Software supplied)	

Table 3. 2008 LiDAR Hardware Summary Sets 6 to 10 (*Point of Beginning* website). - continued –

Manufacturer	**Leica Geosystems**	**Leica Geosystems**	**Maptek I-Site 3D Laser Imaging**	**Maptek I-Site 3D Laser Imaging**	**Measurement Devices Ltd**
Product	**HDS6000**	**Leica ScanStation 2**	**I-Site 4400LR Laser Scanner**	**I-Site 4400CR Laser Scanner**	**QuarrymanPro / LaserAce Scanner**
Standard Accessories (list)	Scanner & accessories carrying case; additional internal battery; battery cradle for internal battery; battery charger/AC power supply; Cyclone-SCAN software; cleaning kit	[12]	Transport case, 2 Batteries, 110 VAC charger, Car charger, Tripod, Laser tribrach, Hand held computer, Remote control, Manual	Transport case, 2 Batteries, 110 VAC charger, Car charger, Tripod, Laser tribrach, Hand held computer, Remote control, Manual	Tribrach, 3x memory cards, card reader, battery, battery charger
Optional Accessories (list)	Notebook PC, tablet PC, PDA; scan targets; service agreement; extended warranty; tribrach (Leica Professional Series); tripod (Leica professional series); external battery	[13]	Underground photographic light, Cold weather jacket, Extreme environment and/or long life battery, Horizontal mount system, Low profile case.	Underground photographic light, Cold weather jacket, Extreme environment and/or long life battery, Horizontal mount system, Low profile case.	Tripod, traverse kit
Warranty	1 Year	1 year	12 months	12 months	12 month

Table 4. 2008 LiDAR Hardware Summary Sets 11 to 15 (*Point of Beginning* website).

Manufacturer	Measurement Devices Ltd	Optech Incorporated	Optech Incorporated	Riegl	Riegl
Product	**C-ALS Cavity Scanner**	**ILRIS-3D**	**ILRIS-3D-ER**	**LMS-Z210ii**	**LMS-Z390**
Performance					
Laser Wavelength (in nm)	905nm	1550	1550	Near infared	Near infared
Laser Power (in W, mW)		<10 mW	<20 mW	1mW	1mW
FDA Laser Classification (Class)	1	Class 1	Class 1M	1	1
Beam Diameter at Specified Distance from the Scanner (0.Y ft at X ft/Ymm at X m)	18mm at exit, 140mm at 50m	29 mm @ 100 m	29 mm @ 100 m	50 mm at 50 m	25 mm at 100 m
Measurement Technique	Time of flight	Time of Flight	Time of Flight	LIDAR	LIDAR
Average Data Acquisition Rate (pps)	200pps	2500	2500	8000	8000
Maximum Data Acquisition Rate (pps)	200pps	UP To 10 kHz	UP To 10 kHz	12000	12000
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)		7 mm @ 100 m See Note 1	7 mm @ 100 m See Note 1	15 mm at 400 m	2 mm at 50 m
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)		8 mm @ 100 m See Note 1	8 mm @ 100 m See Note 1	10 mm at 100 m	10 mm at 100 m
Angular Accuracy (degrees-min-sec)	0.2degrees	.00115° (20 microradians)	.00115° (20 microradians)	0.005	0.0005
Minimum Range (feet/m)	0.5m	3 m	3 m	4 m	1 m
Maximum Range (feet/m) at Specified Reflectivity (specify 4%, 10%, 30% or 80% targets)	150m at 90%, 70m at 18%	1500 m @ 80%	2100 m @ 80%	650 m	300 m
Field of View (vertical angle) (degrees-min-sec)	-90 to +90degrees	180°	180°	80	80
Field of View (horizontal angle) (degrees-min-sec)	0 to 360 degrees	360°	360°	360	360
Minimum Vertical Scan Increment (degrees-min-sec)	0.1degrees	.00115° (20 microradians)	.00115° (20 microradians)	0.005	0.001
Minimum Horizontal Scan Increment (degrees-min-sec)	0.1degrees	.00115° (20 microradians)	.00115° (20 microradians)	0.005	0.002
Surface Reflectivity Range (%)	1-100%	.1- 99%	.1- 99%	5-100%	5-100%
Onboard camera for aiming or for creating photomosaic, etc. (single image pixel resolution)	Yes with Red LED illumination	Yes (built-in camera)	Yes (built-in camera)	10 megapixel	10 megapixel
Is hardware interoperable with optical total stations and GPS? If yes, how?	Yes, via software	Yes, Post-Processing Software	Yes, Post-Processing Software	Yes	Yes
Is the scanner better for scanning topography or for as-built surveys?	Topography	Both	Both	Topography	As-Built
Is software technology for processing data from scanner manufacturer?	Yes, ModelAce and VoidWorks	Yes	Yes	Yes	Yes
Can scanner be set up over a known point? (E.g., height of instrument, backsight point, etc.) If yes, can station information be entered?	integrated pitch and roll sensors plus optional compass for position determination	Yes / Yes	Yes / Yes	Yes	Yes
Can the user specify the field of view and scan density?	Yes	Yes	Yes	Yes	Yes
Maximum sample density (mm/ft)		2 mm @ 100 m	2 mm @ 100 m	3.5 mm @ 50 m	3.5 mm @ 50 m
Does the scanner support scan filters (e.g., range, intensity, area of interest)?	Rectangle, last hit	Yes	Yes	Yes	Yes
Does the scanner have interchangable parts that allow for upgrades (e.g., the camera, other modular components, etc.)	Yes, optional internal compass	Yes	Yes	Yes	Yes
Communication Method (e.g., ethernet card, firewire, wireless)	Serial, TCP/IP, WiFi	Ethernet / Wireless	Ethernet / Wireless	TCP/IP	TCP/IP
Does the scanner operate when out of level? Does it have compensators?	Yes, integral pitch and roll sensors	Yes / Yes	Yes / Yes	Yes	Yes
Resolution and range of compensators		See Note 2	See Note 2	Yes	Yes
Environmental					
Storage Temperature Range (degrees F/C)	-20 to +70C	-20 to 50° C	-20 to 50° C	-20 to 60	-20 to 60
Operating Temperature Range (degrees F/C)	-10 to +45C	0 to 40° C	0 to 40° C	-10 to 50	-10 to 50
Humidity (%)	IP66	Sealed 100%	Sealed 100%	100%	100%
Ambient Light	Any light conditions	Yes (not affected)	Yes (not affected)	Not Affected	Not affected
General					
Scanner Dimensions (LxWxH) (inches/cm)	200.0 x 5.0 Diameter	32 x 32 x 22 cm	32 x 32 x 22 cm	44x21	49 x 21
Scanner Weight (pounds/kg)	9.4kg including extension piece	13 kg	13 kg	13kg	13 kg

Table 4. 2008 LiDAR Hardware Summary Sets 11 to 15 (*Point of Beginning* website). - continued –

Manufacturer	**Measurement Devices Ltd**	**Optech Incorporated**	**Optech Incorporated**	**Riegl**	**Riegl**
Product	**C-ALS Cavity Scanner**	**ILRIS-3D**	**ILRIS-3D-ER**	**LMS-Z210ii**	**LMS-Z390**
Is scanner recommended for mounting on standard survey tripod? If no, what is recommended stand?	No. Cable or rod deployment in up, down or horizontal borehole.	Yes	Yes	Tripod or Vehicle	Tripod or Vehicle
AC Power Requirements (volts/watts)	85-264VAC	90-260 VAC/3.2 VA	90-260 VAC/3.2 VA	No	No
DC Power Requirements (volts/watts)	10-15VDC	24 VDC/75 Watts	24 VDC/75 Watts	12-28 VDC	12-28 VDC
Batteries	12V	24 VDC Nominal	24 VDC Nominal	Marine Battery	Marine Battery
Battery Dimensions (LxWxH) (inches/cm)		9 x 13 x 5 cm	9 x 13 x 5 cm	12 x 11 x 8	12 x 11 x 8
Battery Weight (pounds/kg)		1 kg	1 kg	19	19
Battery Life (hours)		4 batteries = 5 hours	4 batteries = 5 hours	14	14
Are batteries hot-swappable? (Y/N)	No	Yes	Yes	No	No
Computer Requirements for Control (handheld option?)	Ruggedised PC	Pocket PC or Laptop	Pocket PC or Laptop	1024 MB RAM	1024 MB RAM
Computer Requirements for Data Processing		1024 MB Ram	1024 MB Ram	1024 MB RAM	2000 MB RAM
Standard Accessories (list)	50m cable, 50m rods, surface control box, transit cases, ModelAce software	Carry Case / AC Power Supply	Carry Case / AC Power Supply	Inclination Sensor	Inclination Sensor
Optional Accessories (list)	Internal 3 axis magnetometer and accelerometer	Batteries/Charger, PC, Camera Kit	Batteries/Charger, PC, Camera Kit	Internal Sync Timer for GPS/INS	Internal Sync Timer for GPS/INS
Warranty	12month	1 year	1 year	12 months	12 months

Table 5. 2008 LiDAR Hardware Summary Sets 16 to 20 (*Point of Beginning* website).

Manufacturer	**Riegl**	**Riegl USA, Inc**	**Riegl USA, Inc**	**Riegl USA, Inc.**	**Spatial Integrated Systems Inc**
Product	**LMS-Z420i**	**LMS-Z210ii**	**LMS-Z390i**	**LMS-Z420i**	**3 DIS - 3 Dimensional Imaging & Scanning**
Performance					
Laser Wavelength (in nm)	Near infared	Near infrared	Near Infrared	Near Infrared	780NM
Laser Power (in W, mW)	1mW	1mW	1mW	1mW	20 mW
FDA Laser Classification (Class)	1	Class 1 Eyesafe Invisible Beam	Class 1 Eyesafe Invisible Beam	Class 1 Eyesafe Invisible Beam	II B
Beam Diameter at Specified Distance from the Scanner (0.Y ft at X ft/Ymm at X m)	25 mm at 100 m	50 mm at 50 m	10 mm at 50 m	10 mm at 50 m	0.4 Inches @ 54 Ft
Measurement Technique	LIDAR	Lidar	LIDAR	Lidar	Modulated Beam TOF
Average Data Acquisition Rate (pps)	8000	8000pps	8000 pps	8000 pps	3300
Maximum Data Acquisition Rate (pps)	12000	10000pps	11000 pps	11000 pps	3300
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	5 mm at 1000 m	15 mm at 400 m	2 mm at 50 m	5 mm at 50 m	0.2 Inches @ 54 Feet
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	6 mm at 100 m	10 mm at 100 m	10 mm at 100 m	6 mm at 100 m	0.2 Inches @ 54 Feet
Angular Accuracy (degrees-min-sec)	0.0005	0.005	0.0005	0.0005	(55) Using Standard & Customized Catalogs
Minimum Range (feet/m)	2 m	4 m	1 m	2m	1 '
Maximum Range (feet/m) at Specified Reflectivity (specify 4%, 10%, 30% or 80% targets)	1000m	650 m	400 m	1000 m	54 '
Field of View (vertical angle) (degrees-min-sec)	80	0-80	0 - 80	0-80	320 Degrees
Field of View (horizontal angle) (degrees-min-sec)	360	0-360	0 - 360	0-360	360 Degrees
Minimum Vertical Scan Increment (degrees-min-sec)	0.002	0.005	.001	0.002	0.03 Degrees
Minimum Horizontal Scan Increment (degrees-min-sec)	0.002	0.005	.001	0.002	0.05 Degrees
Surface Reflectivity Range (%)	5-100%	5-100%	5-100%	5-100%	85%
Onboard camera for aiming or for creating photomosaic, etc. (single image pixel resolution)	10 megapixel	10 Megapixels	16.7 Megapixel	16.7 Megapixels	Yes - 2 Megapixels
Is hardware interoperable with optical total stations and GPS? If yes, how?	Yes	Yes	Yes	Yes	No
Is the scanner better for scanning topography or for as-built surveys?	As-built & Topography	Topography	As Built	As built & Topography	As-Built
Is software technology for processing data from scanner manufacturer?	Yes	Yes	Yes	Yes	Yes
Can scanner be set up over a known point? (E.g., height of instrument, backsight point, etc.) If yes, can station information be entered?	Yes	Yes	Yes	Yes	No
Can the user specify the field of view and scan density?	Yes	Yes	Yes	Yes	Yes
Maximum sample density (mm/ft)	3.5 mm @ 50 m	3.5 mm at 50 m	3.5 mm at 50m	3.5 mm at 50 m	14.36MM @ 16.46M
Does the scanner support scan filters (e.g., range, intensity, area of interest)?	Yes	Yes	Yes	Yes	No
Does the scanner have interchangable parts that allow for upgrades (e.g., the camera, other modular components, etc.)	Yes	Yes	Yes	Yes	No - All Included
Communication Method (e.g., ethernet card, firewire, wireless)	TCP/IP	TCP/IP	TCP/IP	TCP/IP	Ethernet
Does the scanner operate when out of level? Does it have compensators?	Yes	Yes	Yes	Yes	Yes - Compensators Not Necssary
Resolution and range of compensators	Yes	Yes	Yes	Yes	N/A
Environmental					
Storage Temperature Range (degrees F/C)	-20 to 60	-20c to 60c	-10c to 50c	-10c to 50c	32 - 104 Degrees F
Operating Temperature Range (degrees F/C)	-10 to 50	-10c to 50c	0c to 40c	0c to 40c	32 - 104 Degrees F
Humidity (%)	100%	100%	100%	100%	Non Condensing

Table 5. 2008 LiDAR Hardware Summary Sets 11 to 15 (*Point of Beginning* website). - continued –

Manufacturer	**Riegl**	**Riegl USA, Inc**	**Riegl USA, Inc**	**Riegl USA, Inc.**	**Spatial Integrated Systems Inc**
Product	**LMS-Z420i**	**LMS-Z210ii**	**LMS-Z390i**	**LMS-Z420i**	**3 DIS - 3 Dimensional Imaging & Scanning**
Ambient Light	Not Affected	Not Affected	Not Affected	Not Affected	Not Affected
General					
Scanner Dimensions (LxWxH) (inches/cm)	47 x 21	44 x 21	49 x 21	47 x 21	10
Scanner Weight (pounds/kg)	15 kg	13 kg	15kg	16 kg	22 Lbs - 10 Kg
Is scanner recommended for mounting on standard survey tripod? If no, what is recommended stand?	Tripod or Vehicle	Tripod or Vehicle	Tripod or Vehicle	Tripod or Vehicle	Yes
AC Power Requirements (volts/watts)	No	Yes	Yes	Yes	100-240V (50-70W)
DC Power Requirements (volts/watts)	12-28 VDC	12-28v DC	12-28v DC	12-28v DC	12V (50-70W)
Batteries	Marine Battery	NiMH	NiMH	NiMH	N/A
Battery Dimensions (LxWxH) (inches/cm)	12 x 11 x 8	14 x 4 x 4	14 x 4 x 4	14 x 4 x 4	N/a
Battery Weight (pounds/kg)	19	8 lbs	8 lbs	8 lbs	N/A
Battery Life (hours)	14	14 hours	14 hours	14 hours	N/A
Are batteries hot-swappable? (Y/N)	No	No	No	No	N/A
Computer Requirements for Control (handheld option?)	1024 MB RAM	1024 Mb Ram	1024 Mb Ram	1024 Mb Ram	Note (57)
Computer Requirements for Data Processing	2000 MB RAM	1024 Mb Ram	2000 Mb Ram	2000 Mb Ram	Note (57)
Standard Accessories (list)	Inclination Sensor	Inclination Sensor	Inclination Sensor	Inclination Sensor	Travel Case, Tripod & Computer
Optional Accessories (list)	Internal Sync Timer for GPS/INS	Internal Sync Timer for GPS/INS	Internal Sync Timer for GPS/INS	Internal Sync Timer for GPS/INS	N/A
Warranty	12 months	12 months	12 months	12 months	12 Months

Table 6. 2008 LiDAR Hardware Summary Sets 21 to 25 (*Point of Beginning* website).

Manufacturer	**Topcon**	**Trimble**	**Trimble**	**Z+F**	**Z+F / Z+F UK**
Product	**GLS-1000**	**Trimble GX 3D Scanner**	**Trimble VX Spatial Station**	**IMAGER 5006**	**IMAGER 5006**
Performance					
Laser Wavelength (in nm)	1535nm	532 nm	870 nm		Visible
Laser Power (in W, mW)	less than 25W	<1 mW	< 1 mW	29mW	See classification
FDA Laser Classification (Class)	1	Class 2	Distance meter class 1. Laser pointer class 2	3R	3R (ISO EN 60825-1)
Beam Diameter at Specified Distance from the Scanner (0.Y ft at X ft/Ymm at X m)	6mm @1-40m, 16mm @ 100m	3mm@50m (fixed focus); 0.3mm@5m; 0.9mm@15m; 1.5mm@25m (with autofocus)	Horizontal 4 cm/100 m (0.13 ft/328 ft). Vertical 8 cm/100 m (0.26 ft/328 ft)	0.14 at 3.3 (3.5mm at 1m)	3 mm at 1m
Measurement Technique	Time of Flight	Time of flight	Time of flight	Phase shift AMCW	phase based
Average Data Acquisition Rate (pps)		Depends on application	5 (1)	125,000	< 250 000 pxl/sec.
Maximum Data Acquisition Rate (pps)	3000	Up to 5000 pps	15	500,000	< 500 000 pxl/sec.
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	4mm @ 150m	7mm@100m (Uc); 2.5mm@100m (Std Dev)	3 mm @ ¡Ü150 m (0.011 ft @ ¡Ü492 ft)	+/- 1mm at 50m	1mm at 25 m rms 100% white reflectivity
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)		12mm@100m (Uc)	10 mm @ ¡Ü150 m (0.032 ft @ ¡Ü492 ft)	9mm at 50m	See Angular Accuracy
Angular Accuracy (degrees-min-sec)	6	Vt - 70µrad/14.5? (Uc); 17µrad/3.5? (Std Dev): Hz - 60µrad/12.4? (Uc); 30µrad/6.2? (Std Dev)	1 second	0.007°	0.007 degrees rms
Minimum Range (feet/m)	2m	2 m	2 m (6.56 ft)	0.3m	1.0 m
Maximum Range (feet/m) at Specified Reflectivity (specify 4%, 10%, 30% or 80% targets)	330m @ 90% reflectivity	200 m at 75% of points on 20% grey target ; up to 350 m with Overscan	Reflectorless >300 m (984 ft) to 18% reflective surface and >800+ m (2625 ft) to 90% reflective surface. Prism: 5500 m (18044 ft) (1)	79m	79 m
Field of View (vertical angle) (degrees-min-sec)	70 degrees	60 °	270 degrees	310°	310 degrees
Field of View (horizontal angle) (degrees-min-sec)	360 degrees	360 °	360 degrees	360°	360 degrees
Minimum Vertical Scan Increment (degrees-min-sec)		17 µrad (4.5?)	Minimum point spacing 10 mm (0.032 ft)	0.0018°	0.0018 degrees
Minimum Horizontal Scan Increment (degrees-min-sec)		27 µrad (5.5?)	Minimum point spacing 10 mm (0.032 ft)	0.0018°	0.0018 degrees
Surface Reflectivity Range (%)		1-99%	1-99% (1)	5-99%	upto 100%
Onboard camera for aiming or for creating photomosaic, etc. (single image pixel resolution)	2.0 MP	Yes	Yes, (2048 x 1536 pixels)	yes, optional	Yes
Is hardware interoperable with optical total stations and GPS? If yes, how?	Yes, optical tribrach and coordinate based	Yes, Through Trimble Connected Site	Yes, Through the Trimble Connected Site	yes, via custom survey targets	Yes, with software
Is the scanner better for scanning topography or for as-built surveys?	Good for both	Optimized for both	Optimized for both	both (within given max. range)	As-Built Surveys
Is software technology for processing data from scanner manufacturer?	Yes, Topcon ScanMaster	Yes, RealWorks Survey	Yes. RealWorks Survey	yes	Yes, LFM Software
Can scanner be set up over a known point? (E.g., height of instrument, backsight point, etc.) If yes, can station information be entered?	Yes, instrument panel input	Yes ; yes (dual axis compensator, height of instrument and PPM corrections)	Yes. Supports all survey workflows	yes	Not standard work pratice
Can the user specify the field of view and scan density?	Yes	Yes	Yes	yes	Yes
Maximum sample density (mm/ft)	1mm @ 100m	140 points/sq.inch @ 100 m	Minimum point spacing 10 mm (0.032 ft)	100,000 p per 360°	See Angular resolution

Table 6. 2008 LiDAR Hardware Summary Sets 21 to 25 (*Point of Beginning* website). - continued –

Manufacturer	Topcon	Trimble	Trimble	Z+F	Z+F / Z+F UK
Product	GLS-1000	Trimble GX 3D Scanner	Trimble VX Spatial Station	IMAGER 5006	IMAGER 5006
Does the scanner support scan filters (e.g., range, intensity, area of interest)?	No	Yes, range, intensity, area of interest	Yes	yes	Yes
Does the scanner have interchangable parts that allow for upgrades (e.g., the camera, other modular components, etc.)	Tilting tribrach assembly	Yes ; all included but Trimble GX includes a standard 5/8 11 hole for accessories	No hardware upgrades. Software is upgradable.	yes	Yes
Communication Method (e.g., ethernet card, firewire, wireless)	Built-in WLAN (802.11g)	Ethernet or Wireless	USB, 2.4 GHz radio and Bluetooth to the Controller	ethernet, USB, bluetooth	ethernet, bluetooth
Does the scanner operate when out of level? Does it have compensators?	Yes, compensated On/Off	Yes / Yes (dual axis compensator)	Yes. Yes (dual-axis compensator)	yes; tilt sensor	Yes. Compensators can be overridden.
Resolution and range of compensators	1 second incremented to 6 minute max	Range: 6 min	Accuracy 0.5 seconds. Range 6 minutes	resolution: 1/1,000°; range: 2°	1/1000 degrees
Environmental					
Storage Temperature Range (degrees F/C)	-10C - +60C	-20° to 50° C	Contact Trimble for more information	-20°C - 50°C	-20C - +50C
Operating Temperature Range (degrees F/C)	0C - +40C	0° to 40° C	¯C20 ¡ãC to +50 ¡ãC (¯C4 ¡ãF to +122 ¡ãF)	0°C - 40°C	0C - +40 C
Humidity (%)	IP-52	Non-condensing	IP55. Contact Trimble for more information	non-condensing	non-condensing
Ambient Light		Any light conditions	Any light conditions (1)	all conditions from darkness to daylight	all conditions from darkness to daylight
General					
Scanner Dimensions (LxWxH) (inches/cm)	240mm x 240mm x 566mm	323 mm x 343 mm x 404 mm	352 x 209 x 196 mm (1.16 x 0.69 x 0.64 ft)	286mm x 190mm x 372mm (w x d x h)	286 X 190 X 732 mm
Scanner Weight (pounds/kg)	16kg	13.6 kg	5.25 kg (11.57 lb)	14kg	14kgs
Is scanner recommended for mounting on standard survey tripod? If no, what is recommended stand?	Standard tribrach and tripod	Yes	Yes	yes	Yes. Alternatives also available
AC Power Requirements (volts/watts)	100-240V w/Adapter	90-240 V, 50-60 Hz	100-240 V, 50-60 Hz	90 - 260V AC (power supply)	90-260 Volts
DC Power Requirements (volts/watts)	7.4VDC	24 V nominal	12 V nominal	24V DC (scanner)	24 Volts
Batteries	(4) on-board	Yes	Yes, one internal and/or three external (via battery holder)	Sealed lead acid battery + Licium Ion	Supplied with 2 off internal batteries
Battery Dimensions (LxWxH) (inches/cm)		80 mm x 80 mm x 230 mm	126 x 74 x 24 mm (0.41 x 0.24 x 0.08 ft)	acid battery: 32 x 24 x 26cm; Li-Ion: integrated in scanner	?
Battery Weight (pounds/kg)	.4 lbs	3.1 kg	0.35 kg (0.77 lb)	acid battery: 15kg; Li Ion: integrated in scanner	?
Battery Life (hours)	4 hours	3.5 hours (Average, depending on environmental conditions)	One battery approx. 5 hours, three batteries approx. 15 hours	acid battery: 4h; Li-Ion: 1,5h	2 Hours. External battery also available 4 hours
Are batteries hot-swappable? (Y/N)	Yes	No	Yes, when using external 3-battery holder	yes	No
Computer Requirements for Control (handheld option?)	PC optional	Laptop PC or Trimble TSC2 handheld controllers	Trimble TSC2 or Trimble CU Controllers	1.2GHz, 512MB RAM (Win 2000, XP)	Internal harddisk or PDA or Laptop.
Computer Requirements for Data Processing	2Ghz CPU 1GB RAM	Ask Trimble dealer, depends on application	Windows PC. Contact Trimble for more information	1024 MB RAM	Laptop

Table 6. 2008 LiDAR Hardware Summary Sets 21 to 25 (*Point of Beginning* website). - continued –

Manufacturer	**Topcon**	**Trimble**	**Trimble**	**Z+F**	**Z+F / Z+F UK**
Product	**GLS-1000**	**Trimble GX 3D Scanner**	**Trimble VX Spatial Station**	**IMAGER 5006**	**IMAGER 5006**
Standard Accessories (list)	Case, cover,	Transportation case; compact power supply with AC cables; Trimble tribach; ethernet cable for connection of scanner to data collector; 50 adhesive flat targets; Trimble 3D Scanner Field software	Large range of accessories. Contact Trimble for more information	power supply, exchangable battery, charger	Carry cases, power supply, batteries, ethernet cable
Optional Accessories (list)	Tilting tribrach mount	Trimble TSC2 controller with PocketScape field software; Trimble 3D scanner backpack; car battery cable kit; target kits (planar, circular, traverse kit); batteries	Large range of accessories. Contact Trimble for more information	camera, dolly, tripod, laptop tray for tripod	tripod, external batteries
Warranty	12 months	1 year - extendable	Two years standard. Extendable.	Limited 1 year	12 Months. Extented warranty available

Table 7. 2008 LiDAR Hardware Summary Set 26 (*Point of Beginning* website).

Manufacturer	**Zoller + Frohlich**
Product	**IMAGER 5006**
Performance	
Laser Wavelength (in nm)	650 nm
Laser Power (in W, mW)	19 / 29 mW
FDA Laser Classification (Class)	3 R
Beam Diameter at Specified Distance from the Scanner (0.Y ft at X ft/Ymm at X m)	3 mm in 1m distance
Measurement Technique	phase shift
Average Data Acquisition Rate (pps)	250.000 pps
Maximum Data Acquisition Rate (pps)	500.000 pps
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	Linearity error up to 50 m < 1mm
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	
Angular Accuracy (degrees-min-sec)	0.007°
Minimum Range (feet/m)	1.0 m
Maximum Range (feet/m) at Specified Reflectivity (specify 4%, 10%, 30% or 80% targets)	Ambiguity interval 79 m
Field of View (vertical angle) (degrees-min-sec)	310 °
Field of View (horizontal angle) (degrees-min-sec)	360 °
Minimum Vertical Scan Increment (degrees-min-sec)	0.0018°
Minimum Horizontal Scan Increment (degrees-min-sec)	0.0018°
Surface Reflectivity Range (%)	0 - 100 %
Onboard camera for aiming or for creating photomosaic, etc. (single image pixel resolution)	no, external camera optional
Is hardware interoperable with optical total stations and GPS? If yes, how?	GPS, RS232, NMEA
Is the scanner better for scanning topography or for as-built surveys?	as-built
Is software technology for processing data from scanner manufacturer?	yes
Can scanner be set up over a known point? (E.g., height of instrument, backsight point, etc.) If yes, can station information be entered?	mounted prism can be surveyed for the scannerposition
Can the user specify the field of view and scan density?	yes
Maximum sample density (mm/ft)	1.57 mm @ 10 m
Does the scanner support scan filters (e.g., range, intensity, area of interest)?	yes, in postprocessing
Does the scanner have interchangable parts that allow for upgrades (e.g., the camera, other modular components, etc.)	yes, camera
Communication Method (e.g., ethernet card, firewire, wireless)	ethernet, wireless, USB
Does the scanner operate when out of level? Does it have compensators?	yes, tilt sensor
Resolution and range of compensators	+/- 2 ° / 0.001° resolution
Environmental	
Storage Temperature Range (degrees F/C)	- 20° C - 50°C
Operating Temperature Range (degrees F/C)	0°C - 40°C
Humidity (%)	non-condensing
Ambient Light	from darkness to daylight
General	
Scanner Dimensions (LxWxH) (inches/cm)	28.6 cm x 19.0 cm x 37.2 cm
Scanner Weight (pounds/kg)	13.8 kg

Table 7. 2008 LiDAR Hardware Summary Set 26 (*Point of Beginning* website). - continued –

Manufacturer	**Zoller + Frohlich**
Product	**IMAGER 5006**
Is scanner recommended for mounting on standard survey tripod? If no, what is recommended stand?	yes
AC Power Requirements (volts/watts)	
DC Power Requirements (volts/watts)	
Batteries	changeable (intern) / external
Battery Dimensions (LxWxH) (inches/cm)	19.0 cm x 8.8 cm x 5.5 cm / 26.0 cm x 24.0 cm x 30.0 cm
Battery Weight (pounds/kg)	1.5 kg / 16 kg
Battery Life (hours)	2.5 h / 6 h
Are batteries hot-swappable? (Y/N)	yes
Computer Requirements for Control (handheld option?)	no computer (internal PC)
Computer Requirements for Data Processing	Windows 2000, XP; Pentium III min 1 GHz recommended Pentium IV 1.8GHz; 512 MB RAM or more; 3D Graphic card (OpenGL support)
Standard Accessories (list)	Li-Ion battery pack; Power supply KNL-24; Power cable; Li-Ion charging cradle; Power supply cable; Ethernet cable; Software Z+F LaserControl ?Advanced?; Transport box IMAGER 5006; Transport box acces
Optional Accessories (list)	Transportable rechargeable battery pack Power Pack TRAPP-15-24; Charging cable; Cross-Ethernet cable; Laptop/PDA; Tripod; Tribrach; Dolly; Mounting for Laptop; Targets; Transport box for tripod
Warranty	12 month

Table 8. 2008 LiDAR Hardware Summary Survey Notes (*Point of Beginning* website).

Survey Notes			
1	Leica Geosystems	Leica ScanStation 2	[1] There are two common methods of reporting spot size. The 'Gaussian' diameter is: 6 mm at 50 m; 4 mm at 25 m; and 6 mm at < 1m; the 'FWHM' method of reporting spot size results in values of 3 mm at 50 m; 2 mm at 25 m; 3 mm at < 1 m. [2] Maximum instantaneous data acquisition rate. [3] Accuracy for a single pulsed range measurement (not averaged). [4] Accuracy of a single pulsed position measurement; 2.0 mm target center point accuracy (based on averaging technique) [5] 1 megapixel for 24x24 degree; 64 megapixels rectified for full scan; can also be used with external camera. [6] Via Leica's X-Function, LandXML and ASCII. [7] Instrument height, backsight, traversing, resectioning and stakeout fully supported. [8] Fully integrated for highest system accuracy and minimized calibration frequency. Upgradeabililty is dependent on specific feature(s). [9] On/off dual axis compensator [10] 1.4 GHz Pentium M or similar, 512 MB SDRAM, ethernet card, SXGA+, Win XP (Pro or Home Edition), Win 2000; handheld tablet PC option. [11] 2.0 GHz Pentium 4, 512 MB SDRAM, ethernet card, SXGA+, Win XP (Pro or Home Edition), Win 2000 [12] Instrument shipping case, tribrach (Leica Professional Series), tripod, ethernet cable, two power supplies, cables, power supply charger, cleaning kit, Cyclone-SCAN software. [13] HDS scan targets and target accessories, customer care package (CCP), extended warranty, tablet PC or laptop [14] Vertical and horizontal FOV are fully independently adjustable; vert and horiz point spacings are fully independently adjustable to a minimum of < 1mm point spacing at 300m range.
2	Maptek I-Site 3D Laser Imaging	I-Site 4400LR Laser Scanner	(1) As measured on factory test range. (2) Set-up over known point using laser plummet, backsight with integral telescope and level via compensation is standard procedure. Total station measurement on same set-up may be made before or after if required. Alternatively, a GPS receiver can be fitted directly to the scanner via a standard 5/8" UNC thread, with automatic offsets to the center of the scanner made for GPS readings. Coordinates can be transferred in the field or back at the office in desktop software. (3) Extreme environment battery required.
3	Maptek I-Site 3D Laser Imaging	I-Site 4400CR Laser Scanner	(1) As measured on factory test range. (2) Set-up over known point using laser plummet, backsight with integral telescope and level via compensation is standard procedure. Total station measurement on same set-up may be made before or after if required. Alternatively, a GPS receiver can be fitted directly to the scanner via a standard 5/8" UNC thread, with automatic offsets to the center of the scanner made for GPS readings. Coordinates can be transferred in the field or back at the office in desktop software. (3) Extreme environment battery required.
4	Measurement Devices Ltd	QuarrymanPro / LaserAce Scanner	Ruggedised scanner designed for Stockpile surveys, Quarrying and face profiling. Simple onboard user interface.
5	Measurement Devices Ltd	C-ALS Cavity Scanner	Ruggedised scanner for borehole deployment to survey inaccesible natural or man-made voids either underground or surface.
6	Optech Incorporated	ILRIS-3D	Note 1: Accuracies are based on single shot measurements. No averaging of multiple shots is used to determine system performance. Note 2: Optional compensators for level, orientation, motion, direction, etc., are available, depending on the compensation required.
7	Optech Incorporated	ILRIS-3D-ER	Note 1: Accuracies are based on single shot measurements. No averaging of multiple shots is used to determine system performance. Note 2: Optional compensators for level, orientation, motion, direction, etc., are available, depending on the compensation required.
8	Trimble	Trimble VX Spatial Station	1. Performance depends on environmental conditions, range, surface texture, colour, angle etc.
9	Z+F / Z+F UK	IMAGER 5006	...the worlds fastest, and most flexible Laser Scanner. ?the first real "stand alone" scanner without any cable connection. For further information please go to our website www.zf-uk.com.

APPENDIX B - SPECIFICATIONS OF CURRENT LiDAR SOFTWARE

Table 9. 2008 LiDAR Software Summary Sets 1 to 5 (*Point of Beginning* website).

Manufacturer	3rdTech	InnovMetric Software Inc	kubit USA	Leica Geosystems	Leica Geosystems
Product	**SceneVision-3D**	**PolyWorks V10**	**PointCloud 3.2 / PointCloud Pro 3.2**	**Leica Cyclone Family of Software [1]**	**Leica CloudWorx for AutoCAD (Basic and Pro versions)**
Price (list by modules or components)	Included with DeltaSphere; contact 3rdTech for additional pricing information.	On demand	starts from $1.000	[2]	[2]
Laser scanner brands and models from which data can be imported directly	DeltaSphere-3000IR, also Polhemus, Riegl	All brands	All (ASCII or PTC format)	All [3]	All [3]
Operating systems supported (if one is preferred, please state)	Windows XP/Vista	XP/2000/Vista	AutoCAD application (e.g. ADT, Civil. Map)	Win 200, XP 32 and 64 , Vista 32 and 64	Win 200, XP 32 and 64 , Vista 32 and 64
Minimum CPU requirement	Pentium 4	1 GH	Like AutoCAD	Pentium 4 2GHz	Pentium 4 2GHz
Minimum RAM required	512 MB (1GB recommended)	2 GB	Like AutoCAD (recommended 1 GB or more)	Pentium 4 2GHz	Pentium 4 2GHz
Space required on hard disk to properly run application, including swap space, etc. (list in Mb)	50 MB (512 MB swap)	2GB	Like AutoCAD	[8]	[8]
Other hardware requirements	3D graphics card	Nvidia Quadro FX graphic board	Like AutoCAD	[4]	[4]
Cloud Editing/Analysis					
Can features be defined with user-created code libraries?	Planes, contours, lines, points	Yes	Yes	Yes, Import codes from CAiCE, etc.	Yes [9]
Feature codes exportable to CAD software? (specify which software)	VRML models, lines	MicroStation/AutoCAD	N/A (already in CAD)	Yes, LandXML, ASCII	No, runs in CAD
Can user compare cloud or shapes fitted to clouds to plan or perform theoretical shape and interference checking? (State which, all or none.)	None	All	Clash Detection module (PointCloud Pro)	Yes, all	Yes [9]
Ability to make measurements such as distances, angles, areas, volumes, of lines, planes, shapes and other surfaces from cloud? (State which, all or none.)	Distances between points, lines, planes, perpendiculars; angles between lines and planes.	All	All	Yes, all	Yes [9]
Can user overlay or drape a photograph from an external source (e.g., digital camera) on cloud or elements extracted from cloud?	Yes, fully automatic	No	Yes	Yes, [5]	Yes, [10]
Ability to register scans without the use of targets?	Yes, fully automatic	Yes, using geometry	No (only post-processing software)	Yes [17]	NA
Ability to place several clouds from different scans in coordinated 3D space using total station or GPS survey data that has been used to determine positions of scanner and alignment of scans?	No	Yes	Yes	Yes	NA
Analyze points in a cloud representing shapes such as planes, cylinders and spheres to detect measurement outliers?	Planes only	Yes	Yes	Yes	Yes (Pro planes and cylinders)
Ability to integrate scans with floor plans, engineering drawings of objects and surveyed information? (State which, all or none.)	None	Engineering drawings and surveyed information.	Yes	Yes, all	Yes, all
Automate decimation of points in selectable areas to make data files as compact as possible?	Yes, FA	Yes	Yes	Yes	NA
Is fitting of lines, planes and shapes to cloud done manually or automatically, or both?	Automatic plane fitting. Also automatic intersection of planes to determine lines or contours.	Both	both (planes, pipes)	Both	Both

Table 9. 2008 LiDAR Software Summary Sets 1 to 5 (*Point of Beginning* website). - continued –

Manufacturer	3rdTech	InnovMetric Software Inc	kubit USA	Leica Geosystems	Leica Geosystems
Product	SceneVision-3D	PolyWorks V10	PointCloud 3.2 / PointCloud Pro 3.2	Leica Cyclone Family of Software [1]	Leica CloudWorx for AutoCAD (Basic and Pro versions)
- For automatic and manual fitting, what techniques are used or available (e.g. least squares, taking average, etc.)?	Least squares	Least squares, minimum circumscribed, maximum circumscribing, orientation-constrained, position constrained.	least square	Least squares; catalog	Least squares
Ability to automatically track lines or limits of areas by color or texture discrimination?	No	Yes	No	Yes, segment by intensity	No
Ability to automatically calculate and list alignment of center line of shapes (such as a pipe) containing straight and curved segments such as elbows?	No	Yes		Yes, calculate	Yes, straight (Pro)
Maximum number of points that can be loaded	100 million	100 million WinXP32 and 200 million WinXP64.	30 Million in one reference, multiple references are possible	N/A [13]	N/A [13]
Automatic removal of noise (e.g., cars on road, vegetation, etc.)?	No	Yes	No	Yes	Yes
Rendering/CAD Model Generation/Viewing					
Does software automatically or manually generate or create CAD models or model segments from point clouds and other known information? (Specify level of automation and intelligence.)	Automatic VRML models from point clouds or color point clouds.	Automatic and Interactive methods	semi-automatic	Yes, [6]	Yes, [11]
Are items (CAD models such as pipes, steel, flanges, elbow) fit to the point cloud using standard object tables/catalogs?	No	Using primitives	No	Yes	No
Create statistical quality assurance reports on the modeled objects?	No	No	Yes	Yes	Yes
Automatically compute, without user interaction, a full 3D polygonal mesh (not view-based) from a point cloud?	Yes, FA	Yes	No	Automatic	No
Perform contour generation?	No	Yes	No	Yes	No
Perform volume calculation capabilities?	No	Yes	No (is a AutoCAD feature)	Yes	No
Perform solid modeling (volume generation) based on user-defined lines, planes and other surfaces as bounds?	No	No	Yes	Yes, volumes	No
Perform profile and cross-section generation along any cutting plane, family of planes or road alignment?	Yes	Yes	Yes	Yes	No
Have edge detection technology to determine boundaries of solids, planes and other shapes?	No	Yes	No	Yes	No
Perform automatic extraction of standard shapes from cloud (e.g. pipe fittings, structural steel members, etc.)?	No	Pipe center-line	No	Yes	Yes {14]
Can user view cloud or generated shapes or models from any viewpoint in 3D?	Yes	Yes	Yes	Yes	Yes
Are fly-throughs or walk-throughs supported?	Yes	Yes (Video generation)	Yes (is a AutoCAD feature)	Yes	Yes
Have intelligent display of detail depending on scale of the view?	No	No	Yes	Yes	Yes
Can user select transparent/opaque surface for cloud and CAD shapes?	Yes	Yes	Like AutoCAD	Yes	No
Which export formats are supported?	RTPI,VRML, ASCI XYZ, OBJ	TXT, IGES,DXF,STL,OBJ, VRML.Microstation plug-ins	Like AutoCAD	11 Formats, [7]	As AutoCAD

Table 9. 2008 LiDAR Software Summary Sets 1 to 5 (*Point of Beginning* website). - continued –

Manufacturer	**3rdTech**	**InnovMetric Software Inc**	**kubit USA**	**Leica Geosystems**	**Leica Geosystems**
Product	**SceneVision-3D**	**PolyWorks V10**	**PointCloud 3.2 / PointCloud Pro 3.2**	**Leica Cyclone Family of Software [1]**	**Leica CloudWorx for AutoCAD (Basic and Pro versions)**
Specify other measurement tools (e.g., clearance, cut/fill, table of elevation differences)	Perpendicular point to plane	Heights, lengths, angles, radii, volume.		All	None
Can the pointcloud be rendered with visualization effects (e.g., intensity mapping, elevation mapping, shading, silhouette)?	Yes; laser intensity, range, full color.	Yes	Like AutoCAD	Yes, all and more	No
Can the software automatically detect scan targets?	No	Yes	No	Yes, spherical & planar	N/A
Miscellaneous					
Provide high-speed thumbnail views of scans, clouds, photographic images and generated shapes?	No	No	No	No	No
Can client/server system support multiple users?	No	Yes	Yes	Yes	Yes
Is client/server system supported to enable several clients contributing to a single project?	No, but system includes multiple licenses.	No	Yes	Yes, simultaneously	Yes, simultaneously
Other Features					
Describe	Auto intersection of planes to determine lines or contours. Create full-color, texture-mapped, photo-realistic CG models. Produce panoramic images. Create high-res, photo close-ups in the model.	Grid cell manager to split huge data sets	Image extension: combined evaluation of point cloud and orientated images	[15]	[15]

Table 10. 2008 LiDAR Software Summary Sets 6 to 10 (*Point of Beginning* website).

Manufacturer	Leica Geosystems	Leica Geosystems	Leica Geosystems	Leica Geosystems	Leica Geosystems
Product	**Leica CloudWorx for MicroStation**	**Leica CloudWorx for PDMS**	**Leica CloudWorx for Intergraph SmartPlant Review**	**Leica TruView FREE Web Viewer**	**Leica Cyclone II TOPO**
Price (list by modules or components)	[2]	[2]	[2]	Free	[2]
Laser scanner brands and models from which data can be imported directly	All [3]	All [3]	All [3]	All [3]	All [3]
Operating systems supported (if one is preferred, please state)	Win 200, XP 32 and 64 , Vista 32 and 64	Win 200, XP 32 and 64 , Vista 32 and 64	Win 200, XP 32 and 64 , Vista 32 and 64	Win 200, XP 32 and 64 , Vista 32 and 64	Win XP 32 and 64 , Vista 32 and 64
Minimum CPU requirement	Pentium 4 2GHz	Pentium 4 2GHz	Pentium 4 2GHz	Pentium 4 2GHz	Pentium 4 2GHz
Minimum RAM required	Pentium 4 2GHz	Pentium 4 2GHz	Pentium 4 2GHz	Pentium 4 2GHz	Pentium 4 2GHz
Space required on hard disk to properly run application, including swap space, etc. (list in Mb)	[8]	[8]	[8]	12 mb	45 mb
Other hardware requirements	[4]	[4]	[4]	OpenGL Graphics	OpenGL Graphics
Cloud Editing/Analysis					
Can features be defined with user-created code libraries?	Yes [9]	Yes [9]	N/A	N/A	Yes
Feature codes exportable to CAD software? (specify which software)	No, runs in CAD	N/A	N/A	N/A	Yes
Can user compare cloud or shapes fitted to clouds to plan or perform theoretical shape and interference checking? (State which, all or none.)	Yes [9]	Yes, all	Yes, all	No	No
Ability to make measurements such as distances, angles, areas, volumes, of lines, planes, shapes and other surfaces from cloud? (State which, all or none.)	Yes [9]	Yes [9]	Yes [9]	Yes, linear only	Yes, linear only
Can user overlay or drape a photograph from an external source (e.g., digital camera) on cloud or elements extracted from cloud?	Yes, [10]	Yes, [10]	Yes, [10]	No	No
Ability to register scans without the use of targets?	NA	NA	NA	No	No
Ability to place several clouds from different scans in coordinated 3D space using total station or GPS survey data that has been used to determine positions of scanner and alignment of scans?	NA	NA	NA	No	No
Analyze points in a cloud representing shapes such as planes, cylinders and spheres to detect measurement outliers?	Yes (planes and cylinders)	No	No	No	No
Ability to integrate scans with floor plans, engineering drawings of objects and surveyed information? (State which, all or none.)	Yes, all	Yes, all	Yes, all	No	No
Automate decimation of points in selectable areas to make data files as compact as possible?	NA	NA	NA	No	No
Is fitting of lines, planes and shapes to cloud done manually or automatically, or both?	Both	N/A	N/A	No	No
- For automatic and manual fitting, what techniques are used or available (e.g. least squares, taking average, etc.)?	Least squares	N/A	N/A	No	No
Ability to automatically track lines or limits of areas by color or texture discrimination?	No	No	No	No	No
Ability to automatically calculate and list alignment of center line of shapes (such as a pipe) containing straight and curved segments such as elbows?	Yes, straight	No	No	No	No
Maximum number of points that can be loaded	N/A [13]	N/A [13]	N/A [13]	N/A	N/A [13]
Automatic removal of noise (e.g., cars on road, vegetation, etc.)?	Yes	Yes	No	No	No

Table 10. 2008 LiDAR Software Summary Sets 6 to 10 (*Point of Beginning* website). - continued –

Manufacturer	**Leica Geosystems**	**Leica Geosystems**	**Leica Geosystems**	**Leica Geosystems**	**Leica Geosystems**
Product	**Leica CloudWorx for MicroStation**	**Leica CloudWorx for PDMS**	**Leica CloudWorx for Intergraph SmartPlant Review**	**Leica TruView FREE Web Viewer**	**Leica Cyclone II TOPO**
Rendering/CAD Model Generation/Viewing					
Does software automatically or manually generate or create CAD models or model segments from point clouds and other known information? (Specify level of automation and intelligence.)	Yes, [11]	Yes, [9]	No	No	No
Are items (CAD models such as pipes, steel, flanges, elbow) fit to the point cloud using standard object tables/catalogs?	No	No [9]	No	No	No
Create statistical quality assurance reports on the modeled objects?	Yes	Yes	Yes	No	No
Automatically compute, without user interaction, a full 3D polygonal mesh (not view-based) from a point cloud?	No	No	No	No	No
Perform contour generation?	No	No	No	No	No
Perform volume calculation capabilities?	No	No	No	No	No
Perform solid modeling (volume generation) based on user-defined lines, planes and other surfaces as bounds?	No	No	No	No	No
Perform profile and cross-section generation along any cutting plane, family of planes or road alignment?	No	No	No	No	Yes, via feature coding
Have edge detection technology to determine boundaries of solids, planes and other shapes?	No	No	No	No	Yes, edges, planes, low, high, painted and flow line
Perform automatic extraction of standard shapes from cloud (e.g. pipe fittings, structural steel members, etc.)?	Yes {14]	Yes	Yes	No	No
Can user view cloud or generated shapes or models from any viewpoint in 3D?	Yes	Yes	Yes	No	Yes
Are fly-throughs or walk-throughs supported?	Yes	Yes	Yes	No	Yes
Have intelligent display of detail depending on scale of the view?	Yes	Yes	Yes	Yes	Yes
Can user select transparent/opaque surface for cloud and CAD shapes?	No	No	No	No	No
Which export formats are supported?	As MicroStation	As PDMS	As SmartPlant	N/A	LandXML, Leica DBX, Custom ASCII
Specify other measurement tools (e.g., clearance, cut/fill, table of elevation differences)	None	None	None	Delta from X,Y or Z	None
Can the pointcloud be rendered with visualization effects (e.g., intensity mapping, elevation mapping, shading, silhouette)?	No	No	No	Yes	Yes
Can the software automatically detect scan targets?	N/A	N/A	N/A	N/A	N/A
Miscellaneous					
Provide high-speed thumbnail views of scans, clouds, photographic images and generated shapes?	No	No	No	No	No
Can client/server system support multiple users?	Yes	Yes	Yes	Yes	No
Is client/server system supported to enable several clients contributing to a single project?	Yes, simultaneously	Yes, simultaneously	Yes, simultaneously	No	No

Table 10. 2008 LiDAR Software Summary Sets 6 to 10 (*Point of Beginning* website). - continued –

Manufacturer	Leica Geosystems	Leica Geosystems	Leica Geosystems	Leica Geosystems	Leica Geosystems
Product	Leica CloudWorx for MicroStation	Leica CloudWorx for PDMS	Leica CloudWorx for Intergraph SmartPlant Review	Leica TruView FREE Web Viewer	Leica Cyclone II TOPO
Other Features					
Describe	[15]	[16]	[16]	TruView is an easy to use, free web based point cloud viewer intended for non-sophisticated and occasional users to have easy access to point cloud data withouth the need for training	Cyclone II TOPO is an easy to learn and use application for CAD techs to feature code topographic maps from 3D point cloud data

Table 11. 2008 LiDAR Software Summary Sets 11 to 15 (*Point of Beginning* website).

Manufacturer	**Maptek I-Site 3D Laser Imaging**	**Maptek I-Site 3D Laser Imaging**	**Maptek I-Site 3D Laser Imaging**	**Riegl**	**Riegl USA**
Product	**I-Site Studio 3.1**	**I-Site Forensic 2.0**	**I-Site Voidworks 2.0**	**RiSCAN PRO**	**Phidias**
Price (list by modules or components)	Contact Maptek I-Site representative	Contact Maptek I-Site representative	Contact Maptek I-Site representative	$8,750	$7,500
Laser scanner brands and models from which data can be imported directly	Maptek I-Site/Riegl/Optech/Leica/Z+F/MDL	Maptek I-Site/Riegl/Optech/Leica/Z+F/MDL	Maptek I-Site/MDL/Optech	All	All
Operating systems supported (if one is preferred, please state)	Windows Vista 64, Windows XP x64, Windows Vista, Windows XP, Windows 2000, Linux	Windows Vista 64, WIndows XP 64, Windows Vista, Windows XP, Windows 2000	Windows XP, Windows 2000	Windows XP Professional, Windows 2000 SP2	MicroStation
Minimum CPU requirement	2GHz	2GHz	2GHz	1.5ghz Pentium 4	2.5 ghz
Minimum RAM required	1024 MB	512 MB	512 MB	256mb Minimum; 1024mb Maximum	2000 MB
Space required on hard disk to properly run application, including swap space, etc. (list in Mb)	2048 MB	1024 MB	512 MB	700mb project example; 40gb projects	5 GB
Other hardware requirements	Accelerated 3D graphics, 3 button mouse	Accelerated 3D graphics, 3 button mouse	Accelerated 3D graphics, 3 button mouse		No
Cloud Editing/Analysis					
Can features be defined with user-created code libraries?	Yes	No	No	Yes	Yes
Feature codes exportable to CAD software? (specify which software)	Yes (DXF,DWG)	Yes (DXF,DWG)	Yes (DXF,DWG)	Yes	Yes
Can user compare cloud or shapes fitted to clouds to plan or perform theoretical shape and interference checking? (State which, all or none.)	All	All	All	Yes	Yes
Ability to make measurements such as distances, angles, areas, volumes, of lines, planes, shapes and other surfaces from cloud? (State which, all or none.)	Distances, angles, areas, volumes (cut, fill, 2.5D, 3D, 3D differential).	Distances, angles, areas	Distances, angles, areas, volumes (cut, fill, 2.5D, 3D, 3D differential).	Yes	All
Can user overlay or drape a photograph from an external source (e.g., digital camera) on cloud or elements extracted from cloud?	Yes, 4400 series scanner only.	Yes, 4400 series scanner only.	No	Yes	Yes
Ability to register scans without the use of targets?	Yes	Yes	Yes	Yes	Yes
Ability to place several clouds from different scans in coordinated 3D space using total station or GPS survey data that has been used to determine positions of scanner and alignment of scans?	Yes	Yes	Yes	Yes	Yes
Analyze points in a cloud representing shapes such as planes, cylinders and spheres to detect measurement outliers?	Yes	Yes	No	Yes	Yes
Ability to integrate scans with floor plans, engineering drawings of objects and surveyed information? (State which, all or none.)	All (2D plans, 3D CAD models)	All (2D plans, 3D CAD models)	No	Yes	All
Automate decimation of points in selectable areas to make data files as compact as possible?	Yes	Yes	No (manual only)	Yes	Yes
Is fitting of lines, planes and shapes to cloud done manually or automatically, or both?	Both	Both	Manually	Yes	Both
- For automatic and manual fitting, what techniques are used or available (e.g. least squares, taking average, etc.)?	Least squares distance, least median distance, ICP	Least squares distance, least median distance, ICP	Least squares distance, ICP	Yes	Least Squares
Ability to automatically track lines or limits of areas by color or texture discrimination?	Yes	Yes	No	Yes	Yes
Ability to automatically calculate and list alignment of center line of shapes (such as a pipe) containing straight and curved segments such as elbows?	No	No	No	Yes	Yes

Table 11. 2008 LiDAR Software Summary Sets 11 to 15 (*Point of Beginning* website). - continued –

Manufacturer	**Maptek I-Site 3D Laser Imaging**	**Maptek I-Site 3D Laser Imaging**	**Maptek I-Site 3D Laser Imaging**	**Riegl**	**Riegl USA**
Product	**I-Site Studio 3.1**	**I-Site Forensic 2.0**	**I-Site Voidworks 2.0**	**RiSCAN PRO**	**Phidias**
Maximum number of points that can be loaded	200 million	200 million	20 million	200,000,000	No limit
Automatic removal of noise (e.g., cars on road, vegetation, etc.)?	Yes	Yes	Yes	Yes	Yes
Rendering/CAD Model Generation/Viewing					
Does software automatically or manually generate or create CAD models or model segments from point clouds and other known information? (Specify level of automation and intelligence.)	Yes, level of automation is high for topographic and irregular 3D surfaces	Yes, level of automation is high for topographic and irregular 3D surfaces.	Yes, level of automation is high for irregular 3D surfaces.	Yes	Yes
Are items (CAD models such as pipes, steel, flanges, elbow) fit to the point cloud using standard object tables/catalogs?	No	No	No	Yes	Yes
Create statistical quality assurance reports on the modeled objects?	Yes	Yes	Yes	Yes	Yes
Automatically compute, without user interaction, a full 3D polygonal mesh (not view-based) from a point cloud?	Yes	Yes	No	Yes	No
Perform contour generation?	Yes	Yes	No	Yes	Yes
Perform volume calculation capabilities?	Yes	Yes	Yes	Yes	Yes
Perform solid modeling (volume generation) based on user-defined lines, planes and other surfaces as bounds?	All	All	All	Yes	Yes
Perform profile and cross-section generation along any cutting plane, family of planes or road alignment?	Yes	Yes	Yes	Yes	Yes
Have edge detection technology to determine boundaries of solids, planes and other shapes?	Yes	Yes	No	Yes	Yes
Perform automatic extraction of standard shapes from cloud (e.g. pipe fittings, structural steel members, etc.)?	No	No	No	Yes	Yes
Can user view cloud or generated shapes or models from any viewpoint in 3D?	Yes	Yes	Yes	Yes	Yes
Are fly-throughs or walk-throughs supported?	Yes	Yes	Yes	Yes	Yes
Have intelligent display of detail depending on scale of the view?	Yes	Yes	Yes	Yes	Yes
Can user select transparent/opaque surface for cloud and CAD shapes?	Yes	Yes	Yes	Yes	yes
Which export formats are supported?	3dp, 3dv, ma, vrml, dxf, dwg, dxb, obj, 00t, dgd, txt, 3di, arch_d, jpg, ireg	3dp, 3dv, ma, vrml, dxf, dwg, dxb, obj, 00t, dgd, txt, 3di, arch_d, jpg, ireg	vrml, dxf, dwg, dxb, obj, 00t, dgd, txt, arch_d	Ascii, Crystalix, 3DD with SOP, Point Cloud, Autocad, Polyworks, Wavefront, VRML, PLY, STL, LAS, Pointcloud for Autocad, XYZ.	Multiple
Specify other measurement tools (e.g., clearance, cut/fill, table of elevation differences)	Many (1)	Many (1)	Many (1)	Point Readout; Altitude Read, Color & Intensity Read	Multiple
Can the pointcloud be rendered with visualization effects (e.g., intensity mapping, elevation mapping, shading, silhouette)?	Yes	Yes	Yes	Yes	Yes
Can the software automatically detect scan targets?	Yes	Yes	No	Yes	No
Miscellaneous					
Provide high-speed thumbnail views of scans, clouds, photographic images and generated shapes?	No	No	No	Yes	Yes
Can client/server system support multiple users?	Yes	No	No	Yes	No

Table 11. 2008 LiDAR Software Summary Sets 11 to 15 (*Point of Beginning* website). - continued –

Manufacturer	Riegl USA	Riegl USA/Phoscan	Spatial Integrated Systems Inc	Topcon Positioning Systems	Trimble
Product	RiScan PRO	Riegl Tool Suite	3 DIS - 3 Dimensional Imaging & Scanning	ScanMaster	RealWorks Survey
Miscellaneous					
Provide high-speed thumbnail views of scans, clouds, photographic images and generated shapes?	Yes	Yes	No	No	Yes
Can client/server system support multiple users?	Yes	Yes	No	No	No
Is client/server system supported to enable several clients contributing to a single project?	Yes	Yes	No	No	No
Other Features					
Describe	Yes			Integrated WiFi control	Station-based navigation - Image-based drawing and modeling - EasyProfile - Google Earth exports

Table 12. 2008 LiDAR Software Summary Sets 16 to 20 (*Point of Beginning* website).

Manufacturer	**Riegl USA**	**Riegl USA/Phoscan**	**Spatial Integrated Systems Inc**	**Topcon Positioning Systems**	**Trimble**
Product	**RiScan PRO**	**Riegl Tool Suite**	**3 DIS - 3 Dimensional Imaging & Scanning**	**ScanMaster**	**RealWorks Survey**
Price (list by modules or components)	Included with the Scanner	$9,750	Consult SIS	Contact local Topcon dealer	Contact Trimble dealer
Laser scanner brands and models from which data can be imported directly	Riegl	All	3 DIS 1500	Topcon	All (all brands can be imported via ASCII-based formats; Optimized for Trimble 3D scanners and Survey Equipments
Operating systems supported (if one is preferred, please state)	Microsoft	Windows XP Professional, Windows 2000 SP2	Windows XP	Windows XP	Windows 2000 / XP
Minimum CPU requirement	2.5 ghz	1.5ghz Pentium 4	Pentium 1.6 GH	2GHz	Pentium 4 2 Giga Hertz
Minimum RAM required	2000 MB	256mb Minimum; 1024mb Maximum	512 MB	1GB	1 GB
Space required on hard disk to properly run application, including swap space, etc. (list in Mb)	5 GB	700mb project example; 40gb projects	512 MB	Sufficient to store raw data	2 GB
Other hardware requirements	No		3D Graphic Card Recommended	Video Card w/DirectX 9.0c support	graphic card (minimum 128 MB)
Cloud Editing/Analysis					
Can features be defined with user-created code libraries?	No	Yes	No	Only individual coding	Yes
Feature codes exportable to CAD software? (specify which software)	Yes	Yes	AutoCad/Imageware	Yes via DXF format	Yes
Can user compare cloud or shapes fitted to clouds to plan or perform theoretical shape and interference checking? (State which, all or none.)	Yes	Yes	None	No	All
Ability to make measurements such as distances, angles, areas, volumes, of lines, planes, shapes and other surfaces from cloud? (State which, all or none.)	Yes	Yes	Yes	distances, angles, areas	All
Can user overlay or drape a photograph from an external source (e.g., digital camera) on cloud or elements extracted from cloud?	Yes	Yes	No	No	Yes (from internal scanner camera and external source - digital camera)
Ability to register scans without the use of targets?	Yes	Yes	Yes	Yes	Yes
Ability to place several clouds from different scans in coordinated 3D space using total station or GPS survey data that has been used to determine positions of scanner and alignment of scans?	Yes	Yes	Yes	Yes	Yes
Analyze points in a cloud representing shapes such as planes, cylinders and spheres to detect measurement outliers?	Yes	Yes	None	No	Yes
Ability to integrate scans with floor plans, engineering drawings of objects and surveyed information? (State which, all or none.)	Yes	Yes	None	Yes, all	All
Automate decimation of points in selectable areas to make data files as compact as possible?	Yes	Yes	No	Yes	Yes
Is fitting of lines, planes and shapes to cloud done manually or automatically, or both?	Manually	Yes	Both	Both	Both
- For automatic and manual fitting, what techniques are used or available (e.g. least squares, taking average, etc.)?	Least Squares and others	Yes	Least Squares	Least squares, best fit	Least squares
Ability to automatically track lines or limits of areas by color or texture discrimination?	Yes	Yes	No	No	Yes

Table 12. 2008 LiDAR Software Summary Sets 16 to 20 (*Point of Beginning* website). - continued –

Manufacturer	**Riegl USA**	**Riegl USA/Phoscan**	**Spatial Integrated Systems Inc**	**Topcon Positioning Systems**	**Trimble**
Product	**RiScan PRO**	**Riegl Tool Suite**	**3 DIS - 3 Dimensional Imaging & Scanning**	**ScanMaster**	**RealWorks Survey**
Ability to automatically calculate and list alignment of center line of shapes (such as a pipe) containing straight and curved segments such as elbows?	Yes	Yes	No	No	No (see 3Dipsos)
Maximum number of points that can be loaded	No limit	200,000,000	CPU & RAM Dependent	128 million on 32 bit PC	depends on system limits
Automatic removal of noise (e.g., cars on road, vegetation, etc.)?	Yes	Yes	No	No	Yes
Rendering/CAD Model Generation/Viewing					
Does software automatically or manually generate or create CAD models or model segments from point clouds and other known information? (Specify level of automation and intelligence.)	No	Yes	No	No	Yes
Are items (CAD models such as pipes, steel, flanges, elbow) fit to the point cloud using standard object tables/catalogs?	No	Yes	No	No	No (see 3Dipsos)
Create statistical quality assurance reports on the modeled objects?	Yes	Yes	No	No	Yes
Automatically compute, without user interaction, a full 3D polygonal mesh (not view-based) from a point cloud?	Yes	Yes	No	No	Yes
Perform contour generation?	Yes	Yes	No	Yes	Yes
Perform volume calculation capabilities?	Yes	Yes	No	No	Yes
Perform solid modeling (volume generation) based on user-defined lines, planes and other surfaces as bounds?	No	Yes	No	Yes	Yes
Perform profile and cross-section generation along any cutting plane, family of planes or road alignment?	Yes	Yes	No	Yes	Yes
Have edge detection technology to determine boundaries of solids, planes and other shapes?	Yes	Yes	No	No	Yes
Perform automatic extraction of standard shapes from cloud (e.g. pipe fittings, structural steel members, etc.)?	No	Yes	No	No	Yes
Can user view cloud or generated shapes or models from any viewpoint in 3D?	Yes	Yes	Yes	Yes	Yes
Are fly-throughs or walk-throughs supported?	Yes	Yes	Yes	No recording	Yes
Have intelligent display of detail depending on scale of the view?	Yes	Yes	Yes	Yes	Yes (images)
Can user select transparent/opaque surface for cloud and CAD shapes?	No	Yes	Yes	Yes	No
Which export formats are supported?	Multiple	DGN, DWG, DXG, IGES, ACIS SAT, Parasolids, CGM, Step AP203/AP214, VRML World, STL, U3D	ASCII	DXF, CSV, PXA	dxf, dgn, asc, obj, kml, ptc etc.
Specify other measurement tools (e.g., clearance, cut/fill, table of elevation differences)	Multiple		Multiple Inspection Tools Available		Full inspection tools available
Can the pointcloud be rendered with visualization effects (e.g., intensity mapping, elevation mapping, shading, silhouette)?	Yes	Yes	Yes	Yes	Yes, all
Can the software automatically detect scan targets?	Yes	Yes	Yes	No	Yes

Table 12. 2008 LiDAR Software Summary Sets 16 to 20 (*Point of Beginning* website). - continued –

Manufacturer	**Riegl USA**	**Riegl USA/Phoscan**	**Spatial Integrated Systems Inc**	**Topcon Positioning Systems**	**Trimble**
Product	**RiScan PRO**	**Riegl Tool Suite**	**3 DIS - 3 Dimensional Imaging & Scanning**	**ScanMaster**	**RealWorks Survey**
Miscellaneous					
Provide high-speed thumbnail views of scans, clouds, photographic images and generated shapes?	Yes	Yes	No	No	Yes
Can client/server system support multiple users?	Yes	Yes	No	No	No
Is client/server system supported to enable several clients contributing to a single project?	Yes	Yes	No	No	No
Other Features					
Describe	Yes			Integrated WiFi control	Station-based navigation - Image-based drawing and modeling - EasyProfile - Google Earth exports

Table 13. 2008 LiDAR Software Summary Sets 21 to 22 (*Point of Beginning* website).

Manufacturer	**Trimble**	**Z+F UK LTD**
Product	**LASERGen**	**LFM Software**
Price (list by modules or components)	$9000 Subscription Plan	POA
Laser scanner brands and models from which data can be imported directly	All	IMAGER 5003 & IMAGER 5006 & All scanners via ascii
Operating systems supported (if one is preferred, please state)	Windows NT - XPPro	Windows 2000, NT, XP
Minimum CPU requirement	1 gig	2.5GHz processor
Minimum RAM required	512	1GB RAM
Space required on hard disk to properly run application, including swap space, etc. (list in Mb)	Based on project	A small 30-60GByte
Other hardware requirements		GeForce graphics card 128M memory
Cloud Editing/Analysis		
Can features be defined with user-created code libraries?	Yes	No
Feature codes exportable to CAD software? (specify which software)	Yes	Direct pointcloud links to: AutoCAD, Smart Plant Review, PDS, PDMS, Microstation
Can user compare cloud or shapes fitted to clouds to plan or perform theoretical shape and interference checking? (State which, all or none.)	Yes	Yes, interference checking
Ability to make measurements such as distances, angles, areas, volumes, of lines, planes, shapes and other surfaces from cloud? (State which, all or none.)	Yes	Yes, distances and 3D model generation
Can user overlay or drape a photograph from an external source (e.g., digital camera) on cloud or elements extracted from cloud?	Yes	Yes
Ability to register scans without the use of targets?	Yes	Yes
Ability to place several clouds from different scans in coordinated 3D space using total station or GPS survey data that has been used to determine positions of scanner and alignment of scans?	Yes	Yes
Analyze points in a cloud representing shapes such as planes, cylinders and spheres to detect measurement outliers?	Yes	Yes
Ability to integrate scans with floor plans, engineering drawings of objects and surveyed information? (State which, all or none.)	Yes	Yes
Automate decimation of points in selectable areas to make data files as compact as possible?	Yes	Yes
Is fitting of lines, planes and shapes to cloud done manually or automatically, or both?	Both	Both
- For automatic and manual fitting, what techniques are used or available (e.g. least squares, taking average, etc.)?	least squares & Orthoganl Regression	Best fit
Ability to automatically track lines or limits of areas by color or texture discrimination?	Yes	No
Ability to automatically calculate and list alignment of center line of shapes (such as a pipe) containing straight and curved segments such as elbows?	Yes	Yes
Maximum number of points that can be loaded	Unlimited	limited by PC memory
Automatic removal of noise (e.g., cars on road, vegetation, etc.)?	Yes - Rules based	Yes

Table 13. 2008 LiDAR Software Summary Sets 21 to 22 (*Point of Beginning* website). - continued –

Manufacturer	**Trimble**	**Z+F UK LTD**
Product	**LASERGen**	**LFM Software**
Rendering/CAD Model Generation/Viewing		
Does software automatically or manually generate or create CAD models or model segments from point clouds and other known information? (Specify level of automation and intelligence.)	Automated	Yes, semi/automatic. Level of intelligence depends on target CAD package
Are items (CAD models such as pipes, steel, flanges, elbow) fit to the point cloud using standard object tables/catalogs?	Yes	Yes
Create statistical quality assurance reports on the modeled objects?	Yes	Yes
Automatically compute, without user interaction, a full 3D polygonal mesh (not view-based) from a point cloud?	No	Yes
Perform contour generation?	Yes	No
Perform volume calculation capabilities?	Yes	No
Perform solid modeling (volume generation) based on user-defined lines, planes and other surfaces as bounds?	Yes	Yes
Perform profile and cross-section generation along any cutting plane, family of planes or road alignment?	Yes	Yes
Have edge detection technology to determine boundaries of solids, planes and other shapes?	Yes	No
Perform automatic extraction of standard shapes from cloud (e.g. pipe fittings, structural steel members, etc.)?	Yes	Yes
Can user view cloud or generated shapes or models from any viewpoint in 3D?	Yes	Yes
Are fly-throughs or walk-throughs supported?	Yes	Yes
Have intelligent display of detail depending on scale of the view?	Yes	Yes
Can user select transparent/opaque surface for cloud and CAD shapes?	Yes	Yes
Which export formats are supported?	All standard formats	acis rendering
Specify other measurement tools (e.g., clearance, cut/fill, table of elevation differences)	Too many to list	
Can the pointcloud be rendered with visualization effects (e.g., intensity mapping, elevation mapping, shading, silhouette)?	Yes	Yes
Can the software automatically detect scan targets?	Yes	Yes
Miscellaneous		
Provide high-speed thumbnail views of scans, clouds, photographic images and generated shapes?	Yes	Yes
Can client/server system support multiple users?	yes	Yes
Is client/server system supported to enable several clients contributing to a single project?	Yes	Yes
Other Features		
Describe	Multi-Platform	Bubble view support

Table 14. 2008 LiDAR Software Summary Survey Notes (*Point of Beginning* website).

Survey Notes			
1	3rdTech	SceneVision-3D	Includes additional features for forensics - "Viewpoints", blood spatter trajectory calculation, hi-resolution insets.
2	kubit USA	PointCloud 3.2 / PointCloud Pro 3.2	trial version is available
3	Leica Geosystems	Leica Cyclone Family of Software [1]	1. Suite of 7 modules: Cyclone-SCAN; -REGISTER; -MODEL; -SURVEY; -SERVER, PUBLISHER, VIEWER Pro 2. Contact Leica Representative 3. All brands/makes can be imported via ASCII-based formats; these brands/makes can be imported natively: Leica HDS2500/HDS3000/HDS4500/ScanStation; Z+F - Imager; Riegl; 5003 (ZFS,ZFC); Riegl (3DD). 4. Ethernet adapter for licensing; keyboard; mouse or other pointing device 5. Can use images from internal camera on Leica scanners or any external camera 6. Automatic: Region Grow modeling tools; manual modeling tools; ability to apply attributes to modeled elements. 7. DXF, COE (DWG, DGN), ASCII (XYZ, SVY, PTS, PTX, TXT, Customized format) 8. 130 MB static footprint; swap dependent on size of point cloud and operation. 9. Using CAD tools. 10. From Cyclone 11. Automatic: Region Grow modeling tools; manual modeling tools; ability to use intelligent CAD tools. 12. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors.Has 64-bit data engine and virtual 64-bit graphics engine.Data stored in databases. 13. Cyclone based applications could load approx 40 million points at a time if required but the management system dynamically loads all necessary points real-time and never approaches that max 14. Semi-automatic; cylinders,planes. 15. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors. Has 64-bit data engine and virtual 64-bit graphics engine. Data stored in databases. 16. Users can place D-Points along pipe run defined by cloud and model pipes in place via D-Points inside PDMS 17. Using cloud-to-cloud registration on data from any scanner and/or via "free stationing" and traversing using scan data from Leica ScanStation
4	Leica Geosystems	Leica CloudWorx for AutoCAD (Basic and Pro versions)	1. Suite of 7 modules: Cyclone-SCAN; -REGISTER; -MODEL; -SURVEY; -SERVER, PUBLISHER, VIEWER Pro 2. Contact Leica Representative 3. All brands/makes can be imported via ASCII-based formats; these brands/makes can be imported natively: Leica HDS2500/HDS3000/HDS4500/ScanStation; Z+F - Imager; Riegl; 5003 (ZFS,ZFC); Riegl (3DD). 4. Ethernet adapter for licensing; keyboard; mouse or other pointing device 5. Can use images from internal camera on Leica scanners or any external camera 6. Automatic: Region Grow modeling tools; manual modeling tools; ability to apply attributes to modeled elements. 7. DXF, COE (DWG, DGN), ASCII (XYZ, SVY, PTS, PTX, TXT, Customized format) 8. 130 MB static footprint; swap dependent on size of point cloud and operation. 9. Using CAD tools. 10. From Cyclone 11. Automatic: Region Grow modeling tools; manual modeling tools; ability to use intelligent CAD tools. 12. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors.Has 64-bit data engine and virtual 64-bit graphics engine.Data stored in databases. 13. Cyclone based applications could load approx 40 million points at a time if required but the management system dynamically loads all necessary points real-time and never approaches that max 14. Semi-automatic; cylinders,planes. 15. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors. Has 64-bit data engine and virtual 64-bit graphics engine. Data stored in databases. 16. Users can place D-Points along pipe run defined by cloud and model pipes in place via D-Points inside PDMS 17. Using cloud-to-cloud registration on data from any scanner and/or via "free stationing" and traversing using scan data from Leica ScanStation
5	Leica Geosystems	Leica CloudWorx for MicroStation	1. Suite of 7 modules: Cyclone-SCAN; -REGISTER; -MODEL; -SURVEY; -SERVER, PUBLISHER, VIEWER Pro 2. Contact Leica Representative 3. All brands/makes can be imported via ASCII-based formats; these brands/makes can be imported natively: Leica HDS2500/HDS3000/HDS4500/ScanStation; Z+F - Imager; Riegl; 5003 (ZFS,ZFC); Riegl (3DD). 4. Ethernet adapter for licensing; keyboard; mouse or other pointing device 5. Can use images from internal camera on Leica scanners or any external camera 6. Automatic: Region Grow modeling tools; manual modeling tools; ability to apply attributes to modeled elements. 7. DXF, COE (DWG, DGN), ASCII (XYZ, SVY, PTS, PTX, TXT, Customized format) 8. 130 MB static footprint; swap dependent on size of point cloud and operation. 9. Using CAD tools. 10. From Cyclone 11. Automatic: Region Grow modeling tools; manual modeling tools; ability to use intelligent CAD tools. 12. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors.Has 64-bit data engine and virtual 64-bit graphics engine.Data stored in databases. 13. Cyclone based applications could load approx 40 million points at a time if required but the management system dynamically loads all necessary points real-time and never approaches that max 14. Semi-automatic; cylinders,planes. 15. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors. Has 64-bit data engine and virtual 64-bit graphics engine. Data stored in databases. 16. Users can place D-Points along pipe run defined by cloud and model pipes in place via D-Points inside PDMS 17. Using cloud-to-cloud registration on data from any scanner and/or via "free stationing" and traversing using scan data from Leica ScanStation

Table 14. 2008 LiDAR Software Summary Survey Notes (*Point of Beginning* website). - continued –

Survey Notes			
6	Leica Geosystems	Leica CloudWorx for PDMS	1. Suite of 7 modules: Cyclone-SCAN; -REGISTER; -MODEL; -SURVEY; -SERVER, PUBLISHER, VIEWER Pro 2. Contact Leica Representative 3. All brands/makes can be imported via ASCII-based formats; these brands/makes can be imported natively: Leica HDS2500/HDS3000/HDS4500/ScanStation; Z+F - Imager; Riegl; 5003 (ZFS,ZFC); Riegl (3DD). 4. Ethernet adapter for licensing; keyboard; mouse or other pointing device 5. Can use images from internal camera on Leica scanners or any external camera 6. Automatic: Region Grow modeling tools; manual modeling tools; ability to apply attributes to modeled elements. 7. DXF, COE (DWG, DGN), ASCII (XYZ, SVY, PTS, PTX, TXT, Customized format) 8. 130 MB static footprint; swap dependent on size of point cloud and operation. 9. Using CAD tools. 10. From Cyclone 11. Automatic: Region Grow modeling tools; manual modeling tools; ability to use intelligent CAD tools. 12. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors.Has 64-bit data engine and virtual 64-bit graphics engine.Data stored in databases. 13. Cyclone based applications could load approx 40 million points at a time if required but the management system dynamically loads all necessary points real-time and never approaches that max 14. Semi-automatic; cylinders,planes. 15. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors. Has 64-bit data engine and virtual 64-bit graphics engine. Data stored in databases. 16. Users can place D-Points along pipe run defined by cloud and model pipes in place via D-Points inside PDMS 17. Using cloud-to-cloud registration on data from any scanner and/or via "free stationing" and traversing using scan data from Leica ScanStation
7	Leica Geosystems	Leica CloudWorx for Intergraph SmartPlant Review	1. Suite of 7 modules: Cyclone-SCAN; -REGISTER; -MODEL; -SURVEY; -SERVER, PUBLISHER, VIEWER Pro 2. Contact Leica Representative 3. All brands/makes can be imported via ASCII-based formats; these brands/makes can be imported natively: Leica HDS2500/HDS3000/HDS4500/ScanStation; Z+F - Imager; Riegl; 5003 (ZFS,ZFC); Riegl (3DD). 4. Ethernet adapter for licensing; keyboard; mouse or other pointing device 5. Can use images from internal camera on Leica scanners or any external camera 6. Automatic: Region Grow modeling tools; manual modeling tools; ability to apply attributes to modeled elements. 7. DXF, COE (DWG, DGN), ASCII (XYZ, SVY, PTS, PTX, TXT, Customized format) 8. 130 MB static footprint; swap dependent on size of point cloud and operation. 9. Using CAD tools. 10. From Cyclone 11. Automatic: Region Grow modeling tools; manual modeling tools; ability to use intelligent CAD tools. 12. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors.Has 64-bit data engine and virtual 64-bit graphics engine.Data stored in databases. 13. Cyclone based applications could load approx 40 million points at a time if required but the management system dynamically loads all necessary points real-time and never approaches that max 14. Semi-automatic; cylinders,planes. 15. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors. Has 64-bit data engine and virtual 64-bit graphics engine. Data stored in databases. 16. Users can place D-Points along pipe run defined by cloud and model pipes in place via D-Points inside PDMS 17. Using cloud-to-cloud registration on data from any scanner and/or via "free stationing" and traversing using scan data from Leica ScanStation
8	Leica Geosystems	Leica TruView FREE Web Viewer	1. Suite of 7 modules: Cyclone-SCAN; -REGISTER; -MODEL; -SURVEY; -SERVER, PUBLISHER, VIEWER Pro 2. Contact Leica Representative 3. All brands/makes can be imported via ASCII-based formats; these brands/makes can be imported natively: Leica HDS2500/HDS3000/HDS4500/ScanStation; Z+F - Imager; Riegl; 5003 (ZFS,ZFC); Riegl (3DD). 4. Ethernet adapter for licensing; keyboard; mouse or other pointing device 5. Can use images from internal camera on Leica scanners or any external camera 6. Automatic: Region Grow modeling tools; manual modeling tools; ability to apply attributes to modeled elements. 7. DXF, COE (DWG, DGN), ASCII (XYZ, SVY, PTS, PTX, TXT, Customized format) 8. 130 MB static footprint; swap dependent on size of point cloud and operation. 9. Using CAD tools. 10. From Cyclone 11. Automatic: Region Grow modeling tools; manual modeling tools; ability to use intelligent CAD tools. 12. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors.Has 64-bit data engine and virtual 64-bit graphics engine.Data stored in databases. 13. Cyclone based applications could load approx 40 million points at a time if required but the management system dynamically loads all necessary points real-time and never approaches that max 14. Semi-automatic; cylinders,planes. 15. Clouds are not confined/restricted on a per-scan basis. Engine supports billions of points in a single dataset with interactive performance. Limit box can be changed on-the-fly. Supports multiple windows. Multi-threaded; supports multiple processors. Has 64-bit data engine and virtual 64-bit graphics engine. Data stored in databases. 16. Users can place D-Points along pipe run defined by cloud and model pipes in place via D-Points inside PDMS 17. Using cloud-to-cloud registration on data from any scanner and/or via "free stationing" and traversing using scan data from Leica ScanStation
9	Maptek I-Site 3D Laser Imaging	I-Site Studio 3.1	(1) Distance from surface, surface areas, 3D extents, angular extents, chained linear distance, point to line/plane distance, line to line/plane angle, cut/fill volumes in 2.5D and 3D, centroids (geometric and intensity weighted), alignment residual errors (plane and feature fitting). (2) Media quality AVI generation, ultra high resolution screen capture, powerful easy-to-use survey location features, instant photo-rendering (4400 series scanners), advanced surface generation and update tools, utilizes x64 processors and multi-core systems, intuitive 3D environment, easy to set-up, learn and use.
10	Maptek I-Site 3D Laser Imaging	I-Site Forensic 2.0	(1) Surface areas, 3D extents, angular extents, chained linear distance, point to line/plane distance, line to line/plane angle, centroids (geometric and intensity weighted), alignment residual errors (plane and feature fitting). (2) Standard crime scene mark-up and analysis tools, scan authenticity verification, media quality AVI generation, ultra high resolution screen capture, powerful easy-to-use survey location features, instant photo-rendering (4400 series scanners), intuitive 3D environment, simple installation.

Table 14. 2008 LiDAR Software Summary Survey Notes (*Point of Beginning* website). - continued –

Survey Notes			
11	Maptek I-Site 3D Laser Imaging	I-Site Voidworks 2.0	(1) Surface areas, 3D extents, chained linear distance, point to line/plane distance, line to line/plane angle, cut/fill volumes in 2.5D and 3D, centroids (geometric and intensity weighted), alignment residual errors (feature fitting). (2) Easy to install and upgrade, easy to learn and use, intuitive 3D environment.
12	Riegl USA	Phidias	This also operates as a close range photogrammetry software
13	Trimble	RealWorks Survey	Station-based navigation provides new productive opportunities to exploit overlaid image and point cloud data. Drawing and modeling can now be performed using image data directly. EasyProfile automatically extracts natural features in a point cloud and generates associated profiles/lines to be exported in CAD packages. KML file generation allows locating of models directly in Google Earth.
14	Trimble	LASERGen	AVEVA PDMS AVEVA Review Autodesk AutoCAD 2002 - 2007 Bentley Systems, Inc. SE/J/V8/XM Intergraph PDS Intergraph SmartPlant Review LASERGen Viewer - 3D and Image viewer
15	Z+F UK LTD	LFM Software	LFM Server supports import of point cloud into standard CAD Packages, to allow users to work in their most familiar environment.

APPENDIX C – SPLIT FX BEST PRACTICES

EXTRACTING ROCK MASS CHARACTERIZATION INFORMATION (SPLIT FX TIPS)

At the present time, the only point cloud processing package that has a number of built-in features for extracting rock mass characterization information is Split FX. Based on using the software for a number of years, some best practices are given below.

Automatic Extraction of Fracture Planes.

In general, the automatic fracture finder (find patches menu item) can do a better job of finding fractures than going through the point cloud by hand (and much faster). However, the settings should be optimized so that 1) a large number of fractures are extracted, and 2) at least initially, only fractures with a high degree of planarity (R^2 of best-fit plane through the points greater than about 0.9) are extracted. Typical settings to achieve this are shown in Figure 26. Requiring initially that the automatically extracted fractures have a high degree of planarity eliminates unwanted patches, such as patches formed from part of an excavated slope, due to a portion of the rock face coincidentally satisfying the flatness criterion. In particular, for a trim blasted slope, not requiring a high degree of planarity can cause the entire slope to be selected as a fracture.

Extracting Rough Fractures

To delineate rough fractures, the recommended approach is change the filter settings to allow fractures with a lower best-fit R^2 to be accepted, and to pick out these fracture manually (after finding all the smooth fractures automatically).

Stereonet Plotting

It is recommended that when plotting fracture poles extracted from LiDAR data, always weight by fracture area. Traditionally this is not done, because fracture area is typically not measured along with orientation in traditional site characterization. Also, in traditional site characterization, strike and dips are generally only taken on large fractures to begin with (area greater than 1 m^3). An example of stereonets with and without weighting, including data collected with a traditional scanline, is shown in Figure 27.

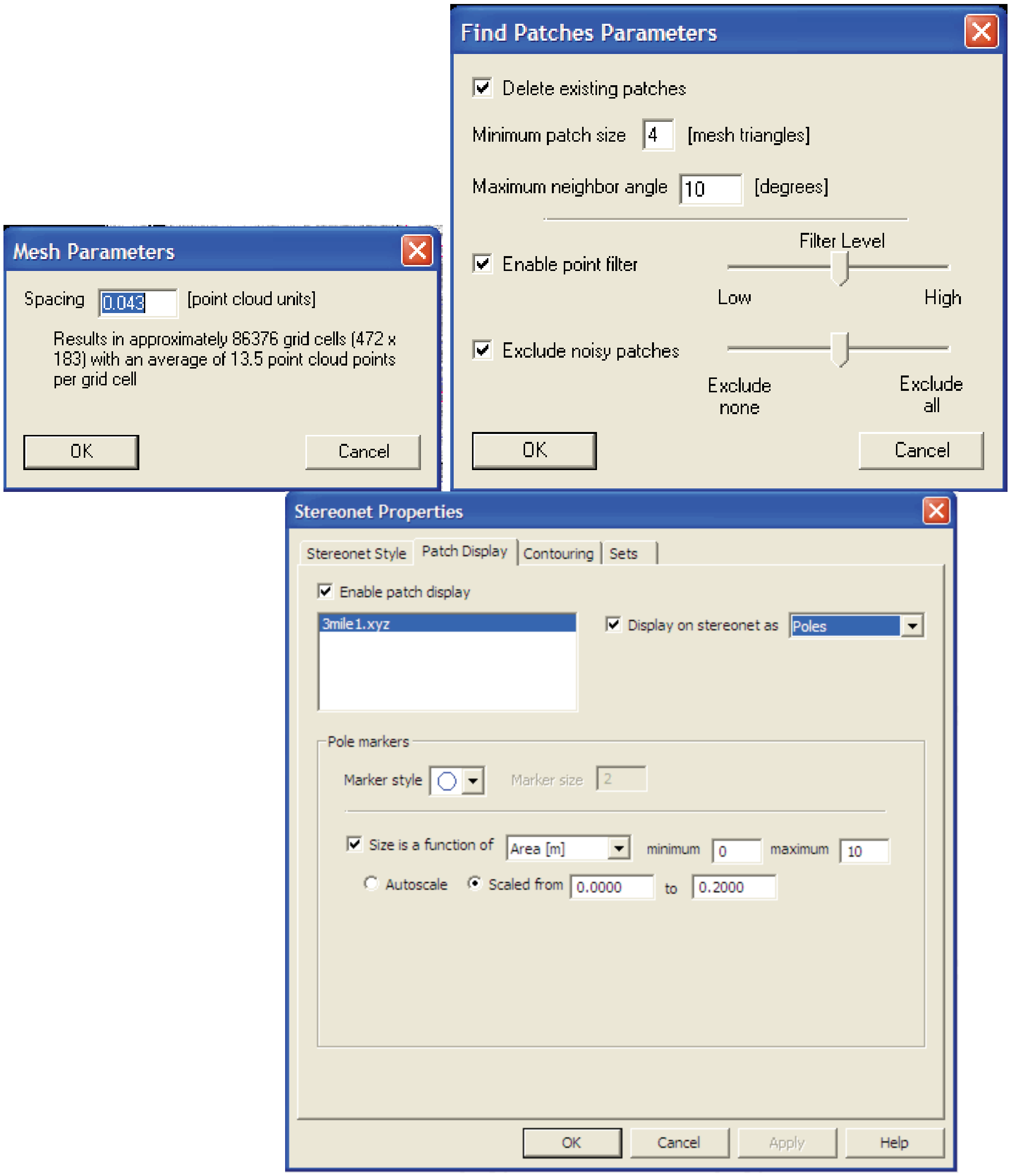

Figure 26. Screen Capture. Recommended Split FX settings for mesh generator, patch finder, and stereonet plotting, for a scan of Mt. Lemmon Highway near Milepost 8.

Fracture Tracing on Digital Images (Including Draped Photos)

At the present time, most automatic edge detectors are not able to properly delineate fracture traces, at least without extensive parameter "tuning" or post editing. Therefore, it is recommended to trace the fractures by hand. This only takes a few minutes for each digital image of interest.

Complete .FX File For Each Site

A Split FX file (.fx file format) can store multiple point clouds, draped or undraped digital images, difference point clouds, joint set information, field notes, etc. It is a complete data base

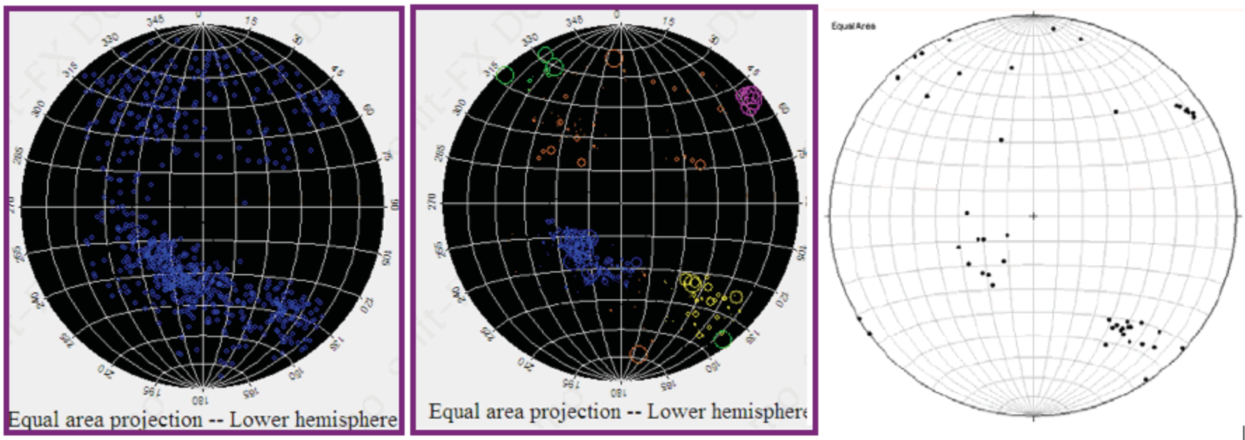

Figure 27. Schematics. Comparison between plotting poles with (left) and without (center) "weight-by-area". Weighting by area results in a much better comparison with standard fracture mapping (right).

for a site that can be updated as additional scans are made (to look at rockfall, for example). It is recommended that an .fx file containing all this information is made for each site, as it is a good way to organize the data.