U.S. Bureau of Reclamation Digital Photogrammetry Research Report

Dam Safety Office

Report No. DSO-04-01
Department of the Interior
Bureau of Reclamation
January 2004

MARCH 3, 1849

U.S. Bureau of Reclamation
Digital Photogrammetry Research Report

DSO-04-01

By:
Peter Shaffner, Photogrammetry Research Manager, Geologist
Lisa Krosley, Principal Investigator, Geologist
Joseph Kottenstette, Civil Engineer

Peer Reviewed By:
Steve Beason, Geologist
Gregg Scott, Civil Engineer

January 2004

Table of Contents

Page

Appendices

Research Goals

The primary goal of this research was to evaluate close range terrestrial photogrammetry software packages and high-resolution digital cameras in order to establish a system capable of remotely measuring the orientation, location, and spacing of discontinuities within the rock abutments at concrete dam sites.

Considerable costs are typically associated with geologic mapping of steep rock abutments because access generally requires ropes, specialized equipment, and trained climbers. Photogrammetry would not necessarily eliminate the need for rope-access mapping, but it would serve as an initial phase of geologic mapping that would allow major features to be delineated and understood so that further investigations could be carefully focused on specific features most critical to stability analyses.

The research goals included selecting and purchasing appropriate software and associated hardware and evaluating the capabilities of the photogrammetry systems at a local test site and at a dam site. Of particular interest was evaluating the accuracy of photogrammetry for measuring the location and the orientation of geologic features in comparison to traditional field methods.

Executive Summary

Based on this completed phase of the research program, the Bureau of Reclamation (Reclamation) now has the capability to use digital photographs to map geologic discontinuities at dam sites. Several computer software programs and digital cameras were evaluated. Software designed specifically for mapping geologic features was purchased from the Commonwealth Scientific Industrial and Research Organization (CSIRO) in Australia. The SiroVision software consists of two integrated components: Siro3D, which allows for the creation of a three-dimensional image; and SiroJoint, which allows users to measure mapped parameters defining discontinuities using 3D images. The selection of this particular software over several more robust programs available on the market was based on several variables, including cost, ability to map geologic features directly within the program, and ease of use. There are several software products on the market that may produce higher accuracy and may be more useful for other applications, but SiroVision was a logical first choice for geologic mapping because the product is much faster to learn and does not require additional software to produce stereonets to display discontinuity orientations. Coupled with a Nikon D100 digital camera, SiroVision was used to map the discontinuity orientations at three locations, including East Canyon Dam. Initial problems with accuracy and processing were reduced significantly following separate field measurements at test sites. This testing allowed corrections to the data acquisition process as more was learned about the sensitivity of the software to various camera parameters, such as tilt

and convergence, and more was learned to improve computer processing. The research testing allowed many iterations of the data processing during this learning period, with accuracy improvements each time.

With the existing SiroVision system that Reclamation now owns, two people in 1 day can obtain field data that would normally require at least a week of field work using a three-person climb team. For an average dam site, the computer processing and geologic mapping in the office can be completed with one person in several days. This significant time-saving technology greatly expands Reclamation's capabilities for mapping steep abutments, but it is probably not cost effective if only a handful of orientations or spatial locations are required.

The geologic report recently completed for East Canyon Dam serves as an example of the quality of product possible using photogrammetry. Even if photogrammetry is not the primary source for providing discontinuity and spatial data, it can be used along with traditional methods to increase the confidence in the data, especially until more case histories are developed to provide statistical verification of the accuracies of this technique.

The photogrammetric system Reclamation now operates is capable of mapping geologic discontinuities and meets the intent of the research program. The orientation accuracy is very good, and it is reasonable to believe that the spatial accuracy will improve as the photogrammetry team gains experience and the new camera and survey tripod system is implemented. In comparison to other photogrammetry software systems reviewed (Foto-G and ShapeCapture), SiroVision has more constraints in gathering images. The terrain of some sites may require the camera freedom provided by Foto-G and ShapeCapture. On the other hand, the data processing with SiroVision appears easier than with the other two photogrammetry systems, and SiroVision provides analysis tools unlike the others. Foto-G is the photogrammetry software used by Vexcel (www.vexcel.com). Vexcel is an international remote sensing company providing engineering services, products, and systems to commercial and government customers. ShapeCapture is the software used by ShapeQuest, Inc. (www.shapecapture.com). This company provides software sales support and distribution for ShapeCapture and ShapeMonitor software. Additionally, they provide full system integration, which includes hardware, software, training, and custom programming for clients. The following website provides information for SiroVision: <http://www.em.csiro.au/mine_environment_imaging/capabilities/imaginganddata/index.html>. All 3D systems can be integrated with CADD systems for design and project modifications if needed.

Evaluations will continue as work is completed at project and test sites. Also, collaboration with other groups using photogrammetry for geotechnical data collecting will be continued (e.g., Colorado School of Mines). Networking with research partners is a way to find quick solutions to problems.

This research clearly demonstrates that the pursuit of photogrammetry as a viable data collection method requires a small, dedicated team of specialists in order to maximize effectiveness and accuracy. Most of the accuracy problems are directly related to human error, which decreases with experience.

Based upon this research, several items have been identified as needing further investigation. These items are discussed in the Recommendations section. In general, they include improving the results of SiroVision and learning to use the Foto-G and ShapeCapture software.

Background

In this section, several topics have been selected to impart information about photogrammetry in a very general manner. These topics are:

- History of photogrammetry
- Definition of photogrammetry
- Obtaining a 3D image from an image set
- Calculating orientations from trace and plane points

History of Photogrammetry

The first photogrammetrically obtained topographic map made its debut in 1849 when Aimé Laussedat used a string of kites to capture the image pairs required to derive 3D measurements. The technique of combining left and right film image pairs underwent minor processing changes over the next 100 years, but it wasn't until 1958 that digital images began replacing film. Until recently, the most common method used to collect the images was aerial photography (Burtch).

Aerial photogrammetry is ideal for large-scale areas but fails when nearly vertical slopes or overhangs are mapped, and it is not suitable for detailed geologic mapping. When digital cameras and desktop computers became available, photogrammetrists began toying with the idea of creating software that would produce the 3D images, but the programs required more user interaction than most users were comfortable providing. The significance of this step is that the use of cameras permitted the mapping of vertical and overhanging slopes with the new image collection technique that was called close-range, or terrestrial, photogrammetry. During the last few years, high-resolution cameras, high-speed computers, and time-saving photogrammetry software programs have become significantly more affordable and available. Today, digital photogrammetry is a cost-effective method for obtaining spatial information.

Definition of Photogrammetry

A definition of photogrammetry in the mapping sciences is provided by the American Society for Photogrammetry and Remote Sensing at the following web site: <http://www.123photogrammetry.com/photogrammetry.html>.

> *Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment through the processes of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena.*

It is the present state of art, science, and technology that will determine how accurately the physical object will be recorded for measurement. Collectively, science and technology set the limit for the potential accuracy. The actual accuracy attained (the fraction of the potential) is entirely controlled by the art. The amount of artistic knowledge the user must possess to run the software depends upon the software, but the knowledge demanded seems to be decreasing. As software versions improve, the need for users to be experts in the mathematics of photogrammetry decreases dramatically. As science and technology make advances, the photogrammetric artistic eye, or user knowledge, has fewer and fewer demands upon it. Thus, the dependency upon user knowledge for reaching the output object of the application is less and less.

Potential Accuracy

Science, or the software algorithm methodology that produces 3D data from the two-dimensional image pairs, is equal in importance to the current state of affordable technology. The resolution of the digital camera, the lens distortion, and survey accuracy are the technology that, with the science, will determine the accuracy potential. Given the current state of science and technology, a common accuracy achievable using photogrammetry is about 1:10,000. For example, if the camera locations are 10,000 millimeters (mm) from the object of interest, or 10 meters (m), the measured position of a single point on this object will be within 1 mm of its actual position. This ratio is also attainable using LIght Detection And Ranging (LIDAR) systems as long as the laser travel distance is within the specification of the particular piece of hardware.

Actual Accuracy

The final accuracy obtained in defining the physical shape of the object can vary significantly. This variance in the precision of the data is difficult to quantify because it relates to human error. An example of human error is failing to obtain two photographs that meet the needs of the software to develop a 3D image. This can occur when:

- The distance between the left and right images is not optimum.
- Images are taken either too far from the object or with insufficient lens magnification.
- Survey coordinates of the cameras and/or control points are not accurate.
- The camera line of sight to the object is not perpendicular to the rock face.

Generally, the actual accuracy will be directly related to the experience of the user. During the first attempts, it would not be unusual to produce data that are several orders of magnitude short of the potential accuracy. This should improve quickly with experience. The accuracy required for geologic mapping can be quickly achieved by following some basic guidelines.

Obtaining a 3D Image from an Image Set

Collecting Images

There are some parameters common to all photogrammetry techniques for obtaining high-quality 3D spatial information:

- Two images are required at a minimum.
- The objects for which 3D data are desired must be in both images (referred to as image overlap).
- Ground and/or camera control point locations of easting, northing, and elevation must be obtained using survey equipment.
- The camera must be calibrated.

A major distinction between aerial and terrestrial photogrammetry parameters exists. In comparing these two parameters, there are significant differences in the distance between the camera and object and the convergence angle between the cameras' lines of sight of two image pairs. In aerial photogrammetry, the aircraft collects images high above the ground and there is typically no convergence between the two lines of sight. In terrestrial photogrammetry, the distance between the cameras and the face are usually within several hundred feet, and the camera lines of sight converge. The left diagram of figure 1 shows a front view of a typical aerial photography setup. The two camera positions are at the top, and the resulting overlap, or image common to both photos, is the mapable area. Objects in the overlap can produce 3D data. The right diagram of figure 1 is a plan view of a generalized terrestrial photogrammetry setup. By converging the line of sight of the two cameras, the amount of overlap can increase and the distance to the object can be decreased.

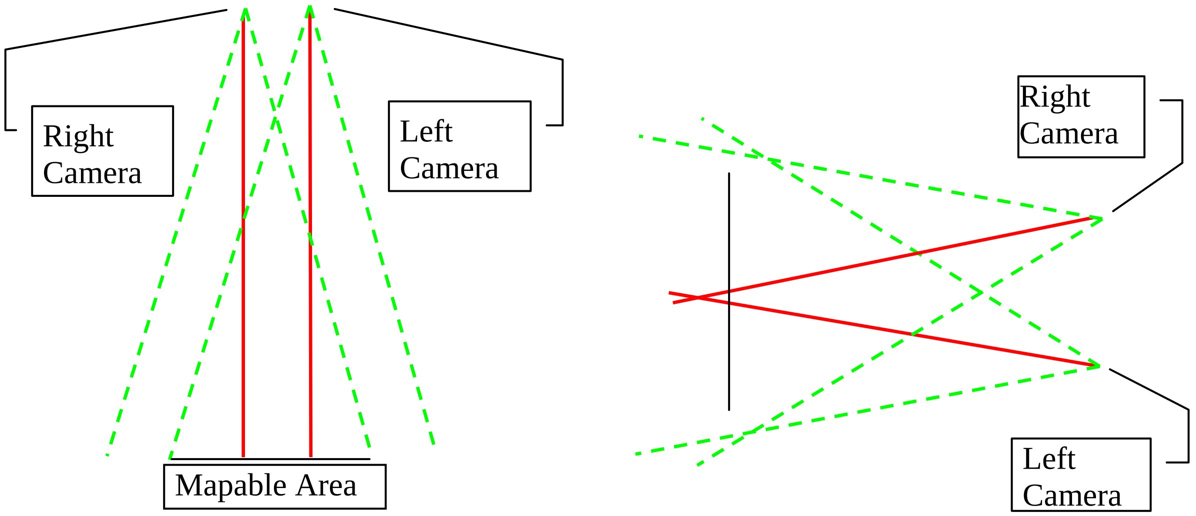


Figure 1.—Aerial (left) and terrestrial (right) image capture setup.

The problem with a low to nonexistent convergence angle is that the required image overlap is difficult to obtain at close ranges.

Each software product has unique characteristics and features. The following description attempts to contrast the most notable differences of the three photogrammetry systems examined by Reclamation. Major characteristics of Foto-G and ShapeCapture are that they do not require the locations of the cameras to be known, but they do require three well-distributed control points. The control does not have to be on the face but must be in both images. If camera locations are not required, images can be obtained while moving, such as in a boat or aircraft. Other benefits of not requiring camera locations are that any arrangement of fixed telephoto lenses can be used, and the camera can be hand held; no tripod setup is needed. This software group can process more than two images to develop a 3D image. This allows the user to develop panoramic 3D images and 3D images with zones of variable detail.

SiroVision, in the other group of terrestrial photogrammetry, needs one control point near the center of the face and two known camera locations. Additionally, the camera cannot have any tilt (the base of the camera is horizontal). While these constraints limit the use of this software in some applications, they provide the benefit of requiring less user interaction during the image processing step. For most tasks, this software would provide high-quality information suitable for geologic mapping. SiroVision is discussed in detail in a later section.

Processing Data

The data processing methods appear to vary widely among the Foto-G, ShapeCapture, and SiroVision photogrammetry software systems. Only some of the processing of Foto-G, ShapeCapture, and LIDAR was observed during this research, so specifics cannot be provided. SiroVision was selected as the main focus of this geologic research. It contains two software programs: Siro3D and SiroJoint. Because SiroVision has been used at three sites, more detail can be provided.

Not only was SiroVision found to be quite helpful in providing lens and camera setup positions to obtain the required accuracies, it also directs the user through the processing steps and provides useful pieces of information on the various options. Processing the images to the point of producing a 3D image takes less than 2 hours in most cases, but it could take all day for a difficult site. Siro3D is the program used to find the 3D points, commonly referred to as point cloud data, and the 3D surface or Triangulated Irregular Network (TIN). Siro3D also registers the image pixels and associated RGB colors to the 3D surface to make the 3D image. Figure 2 is an example of point cloud data. The point cloud is the most basic form of data. With the processing complete, the point, or TIN, data (figure 3) can either be exported into a CADD program or exported into SiroJoint. The point cloud image and 3D image (figure 4) are viewable and rotatable in SiroJoint.

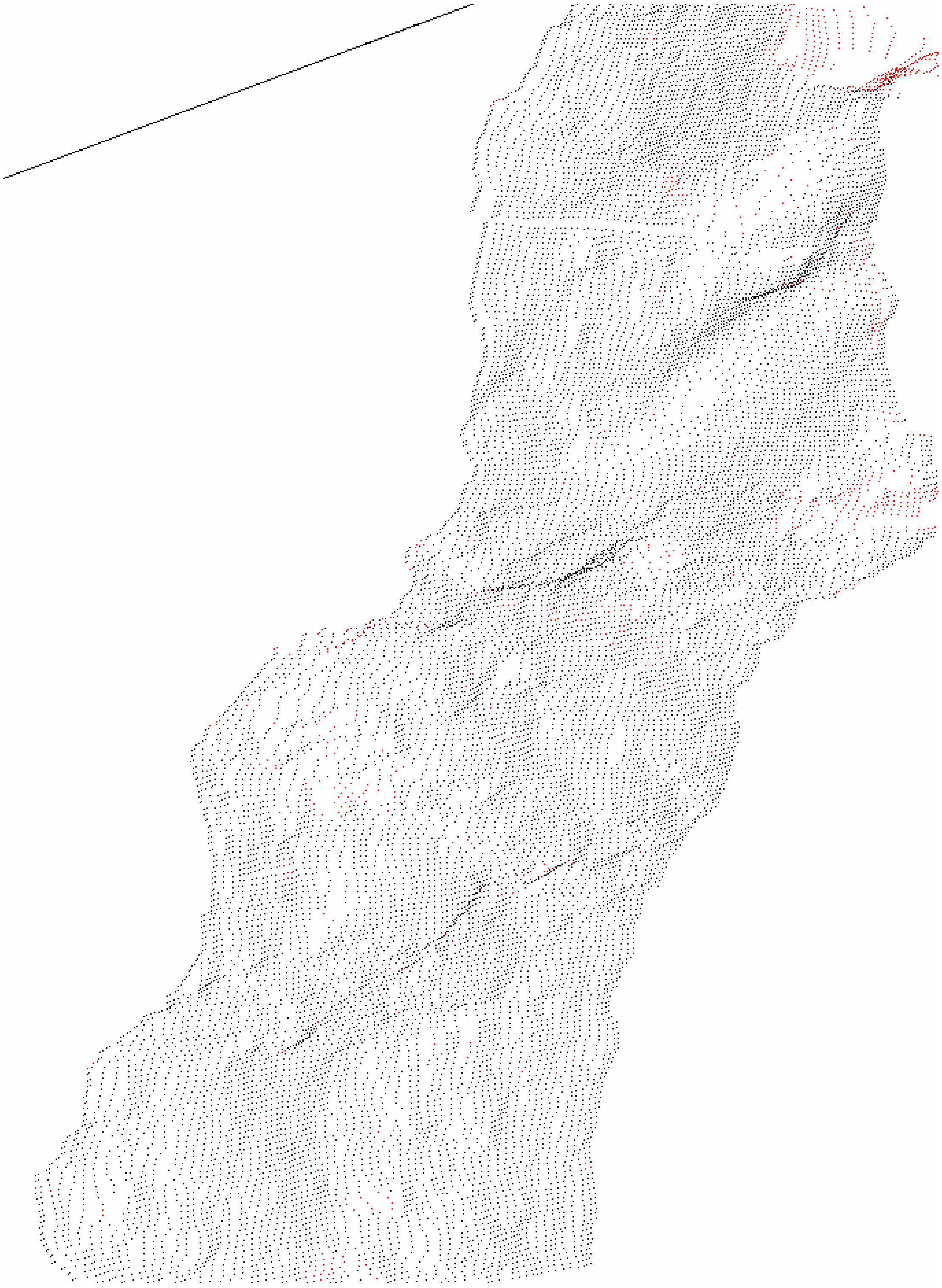


Figure 2.—Point cloud data using SiroVision visualization tool.

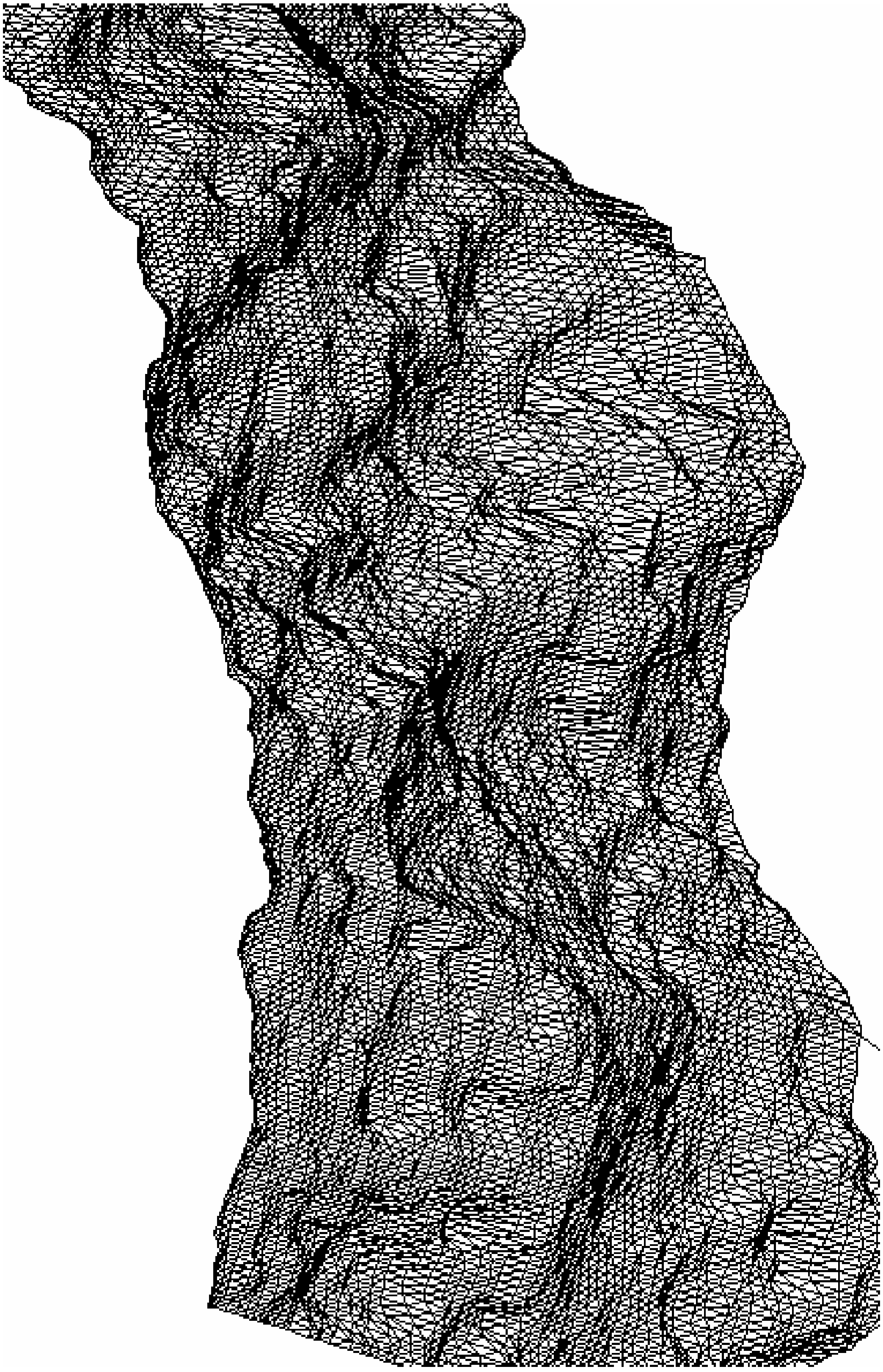


Figure 3.—Triangulated Irregular Network (TIN) of rock face surface using SiroVision visualization tool.

Figure 4.—Color registration of image RGB data onto a TIN surface to produce a three-dimensional image using SiroVision visualization tools. This image can be rotated to facilitate mapping.

Data Types

In SiroJoint, a second level of data may be derived, which includes distance between two points (crack mapping) and plane orientations (discontinuity mapping). How SiroVision obtains these orientations is discussed in the following section, "Calculating Orientations from Polygon and Trace Drawing Objects." By exporting the point cloud into CADD, intersections (catch lines), area (for design), and volume (borrow pits) can also be determined. By adding the dimension of time, the resulting data could be used as a monitoring tool, such as for slope deformations, volume changes, and appurtenance movements. It is uncertain how well any of the photogrammetry programs will model a borrow pile. It may depend on the size of materials in the pile, the texture of the soil, and the available survey control. This will require further testing.

For the Foto-G, ShapeCapture, and LIDAR software programs, the 3D point data must be exported to an external CADD application to map the features. Selection of points for plane definitions in CADD is fairly well understood. However, the procedure for mapping edges or cracks using the Foto-G, ShapeCapture, and LIDAR point data in the CADD system was not presented by the vendors. One known difference is that direct links to stereonet tools and direct geologic mapping are not features provided by these programs. Therefore, only SiroVision techniques and screen captures are described in this section.

Calculating Orientations from Polygon and Trace Drawing Objects

On a rock surface, not all the discontinuity sets are visible as a surface. When faces are visible, a polygon may be drawn that outlines the edges of the exposed face. When the discontinuity surface is not visible and only an edge or fracture is exposed, a line is drawn along the feature to define the discontinuity plane. Figure 5 shows a polygon and trace feature using SiroVision.

Polygon Drawing Feature

In SiroVision, when a discontinuity face is fully exposed (like that shown in figure 6), a polygon can be drawn that defines the area that would best define the plane. The reliability of the mapped planes can be visually checked, one at a time, immediately after construction (as shown in figure 7). The point cloud data set, or 3D points, that reside within this polygon are applied to an internal least-squares-best-fit routine, and the plane orientation is immediately calculated. The plane attributes window, shown in figure 7, is useful for immediately checking orientation, geometry, and accuracy information of the plane object. This allows one to ascertain that reasonable, expected results are attained.

Figure 8 is another example of the SiroVision 3D point data screen. In this example, all points internal to the polygon are used to derive the plane that best fits this data set.

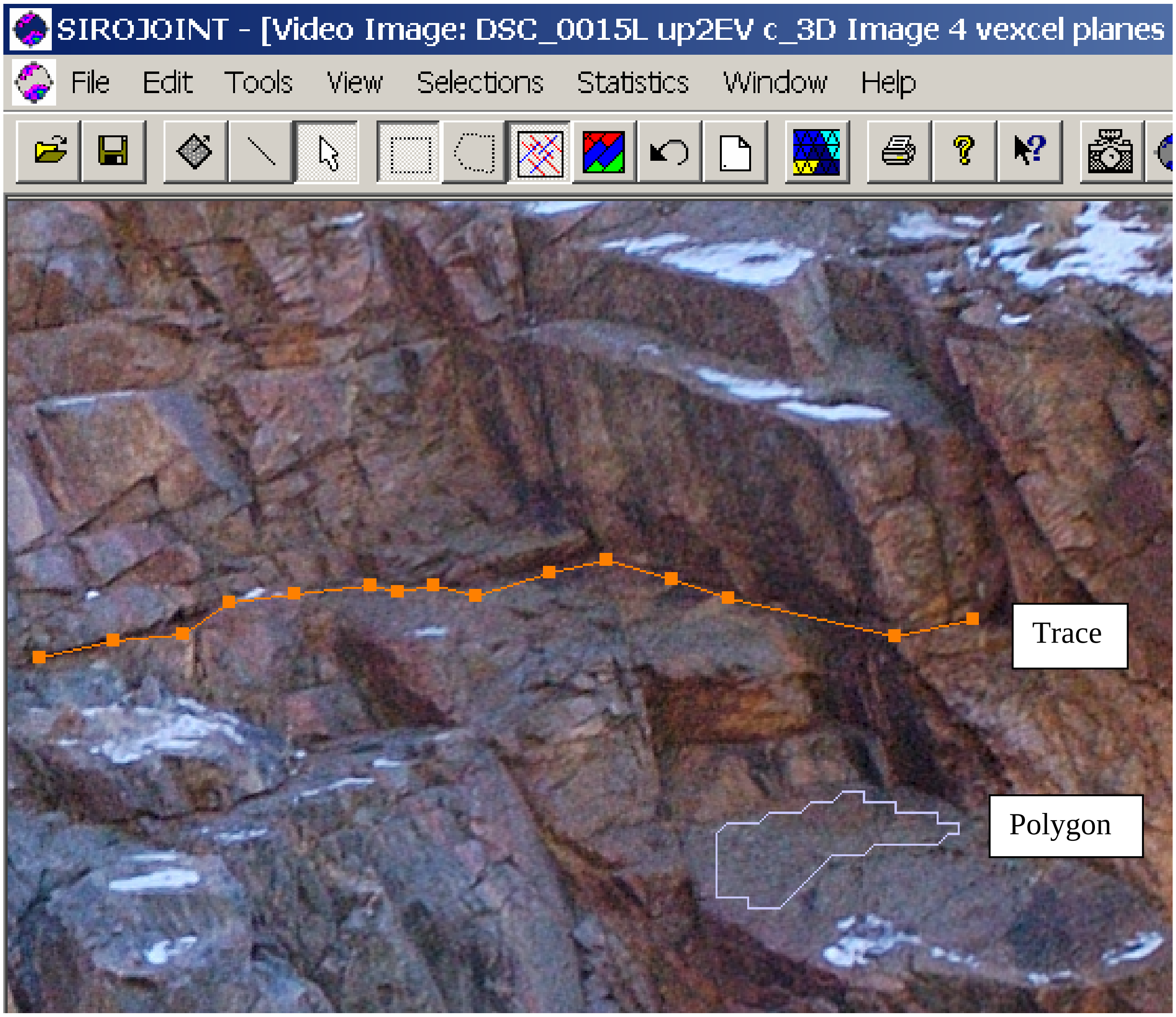
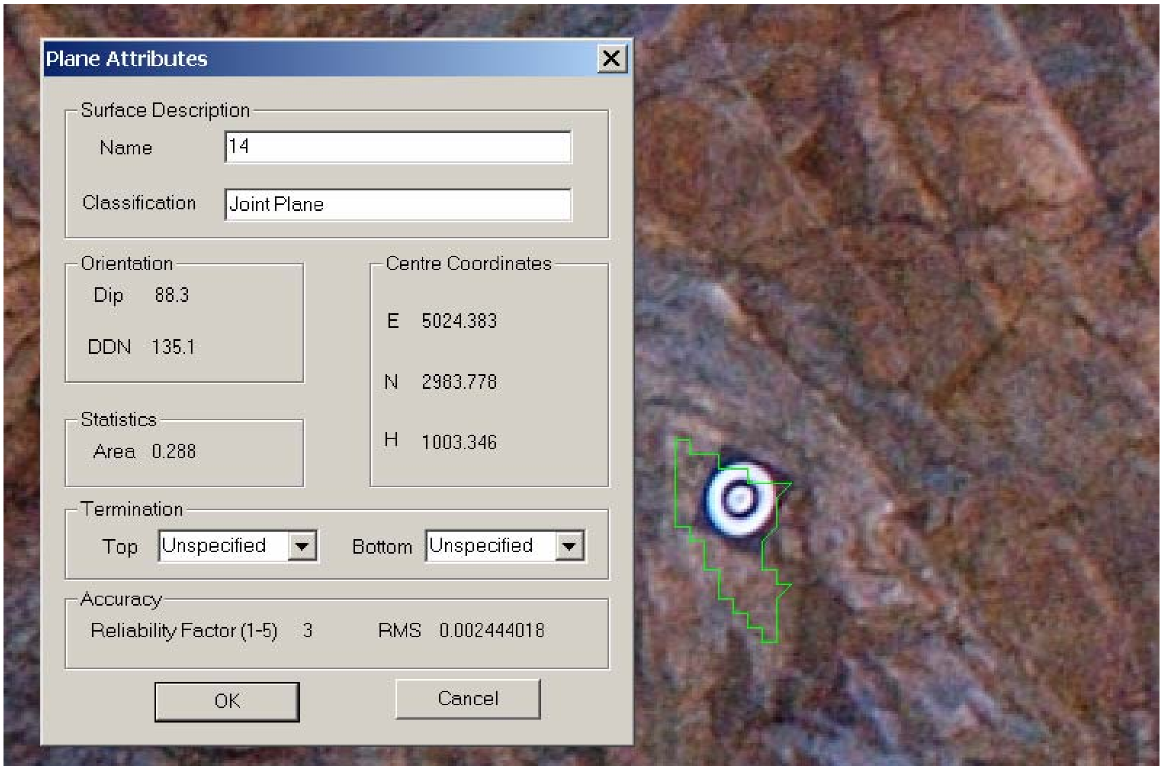


Figure 5.—SiroVision mapping tools: trace line (orange) and plane polygon (gray).

Figure 6.—Polygon drawing objects used to map the orientations of several block faces.



Surface Description
Name 14
Classification Joint Plane

Orientation
Dip 88.3
DDN 135.1

Centre Coordinates
E 5024.383
N 2983.778
H 1003.346

Statistics
Area 0.288

Termination
Top Unspecified
Bottom Unspecified

Accuracy
Reliability Factor (1-5) 3
RMS 0.002444018

Figure 7.—Attributes information window for a plane feature mapped in SiroVision.

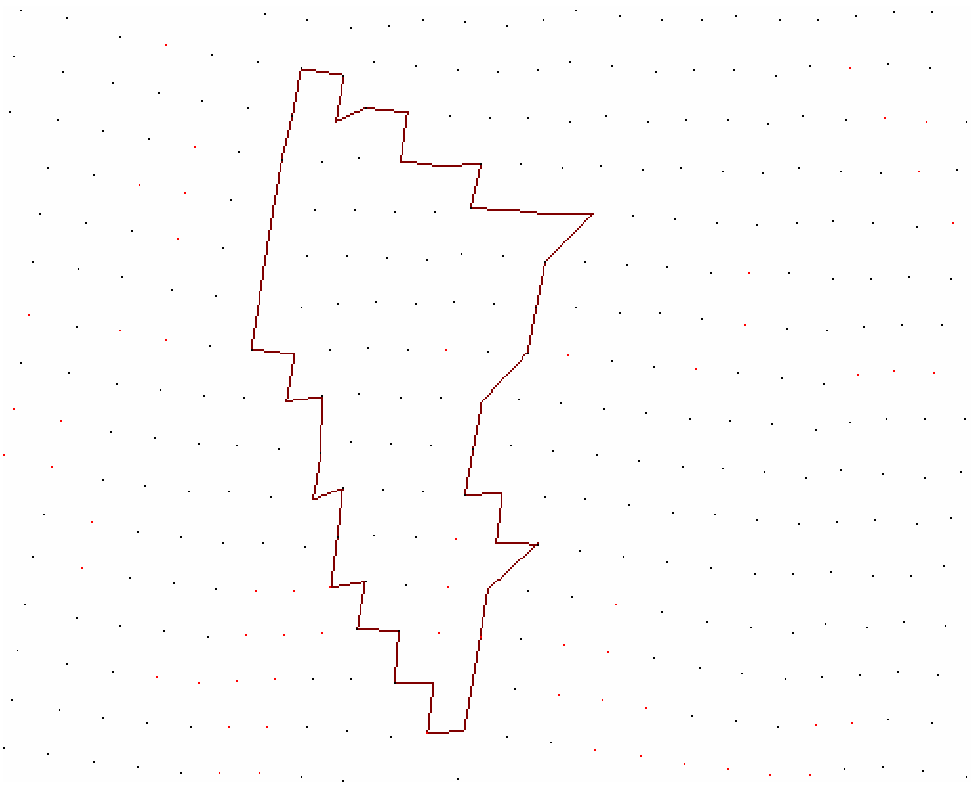


Figure 8.—3D points selected within the polygon used for orientation calculation.

Notice in figure 8 that red and black points are displayed. (When choosing a black background, the black points become white.) The red indicates that the data point may not be good. Black points are probably good. All points inscribed in the polygon are used to define the plane, so it is very important for users to ensure polygon selections encompass valid point data. Otherwise, plane orientations may be in error. Thus, data reliability can be checked several ways:

- Ensure that the ratio of black to red data points in the selected polygon is high.
- Rotate the 3D image screen to observe that the polygon is on a single plane.
- Check the plane information screen for a low RMS and high reliability measures (figure 7).
- When possible, verify a few planes with Brunton readings.
- Common sense - experienced geologists can quickly identify some obvious bad data.

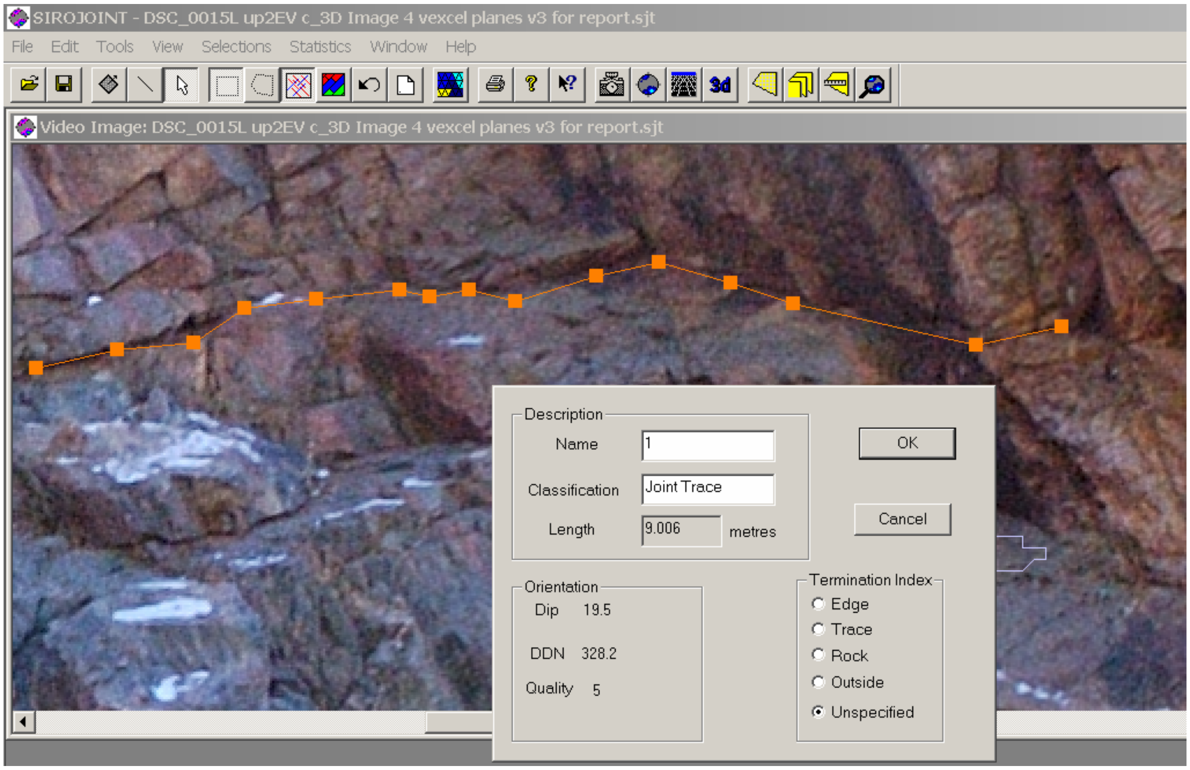
Trace Drawing Feature

When discontinuity faces are not exposed, the plane of the discontinuity can still be determined by selecting a string of points, or trace, along the edge or crack. An example of the trace drawing feature is shown in figure 5. Information about the plane which fits the selected point string is immediately calculated and displayed by SiroJoint software. Figure 9 shows the trace with information such as length, dip, dip direction, and quality. Quality ranges from 0 to 5, with 5 being highest (best) quality. The reliability is based on the straightness of the trace and the numerical quality of the position data.

A low-quality value results when the string of points is nearly a straight line. When the selected points form a straight line, there are an infinite number of planes that could fit these points. To improve this, one of the three coordinates of the points should have as much variance in position as is possible. In figure 9, the quality of the trace is the highest possible because the trace line went around a corner, giving it depth in all three dimensions.

The 3D image screen in SiroJoint can also be used to evaluate trace lines for accurate placement. By requesting the program to show the trace planes, translucent planes appear in the 3D image screen. This model can then be rotated to verify that the calculated plane intersects the joints correctly. The projection of the planes should match the features, as it does in figure 10. Translucent planes can also be shown on the 3D point cloud screen.

To show how a trace can provide bad data when proper procedures are not followed, a new trace is presented in figure 11. The dip of the calculated plane for this trace is 18.4 degrees (very close to the 19.5 degree dip in figure 9), but the dip direction is 0.1 degree, and it has a poor quality rating of 0.3. This low-quality rating tells the user that the points used to draw the trace in figure 11 come close to residing on a straight line and a plane defined using these points is uncertain.



Description

Name: 1

Classification: Joint Trace

Length: 9.006 metres

Orientation

Dip 19.5

DDN 328.2

Quality 5

Termination Index

○ Edge

○ Trace

○ Rock

○ Outside

● Unspecified

Figure 9.—Orientation and quality information of plane derived from trace feature.

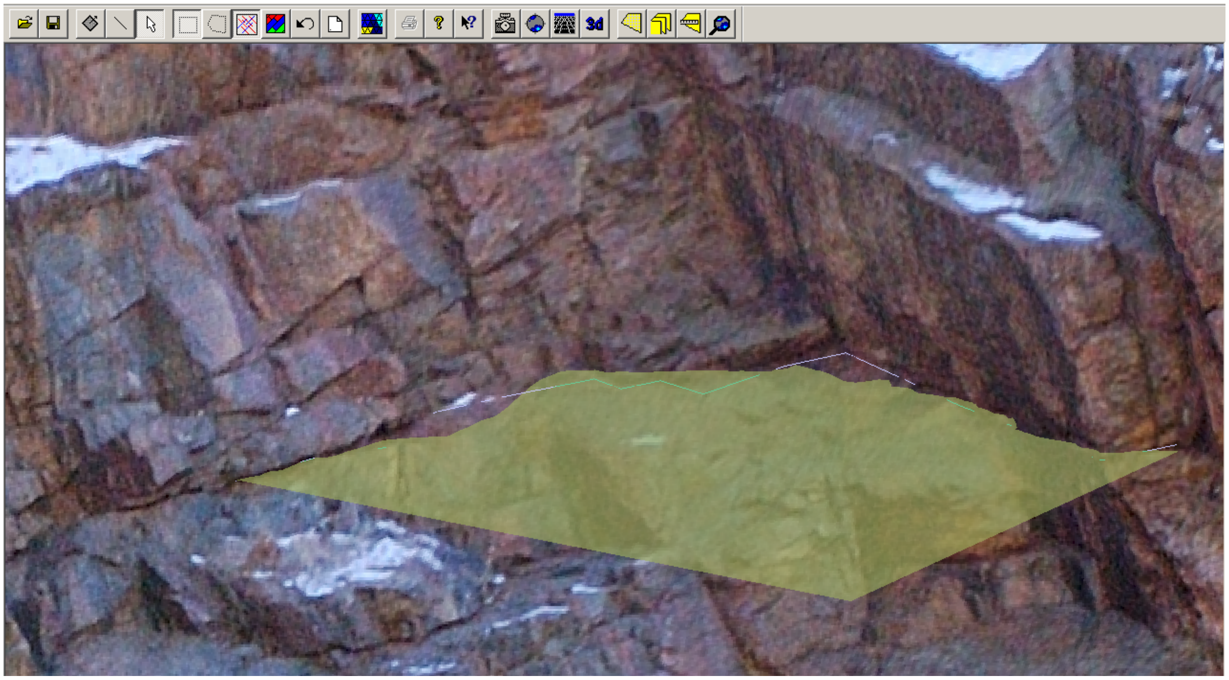
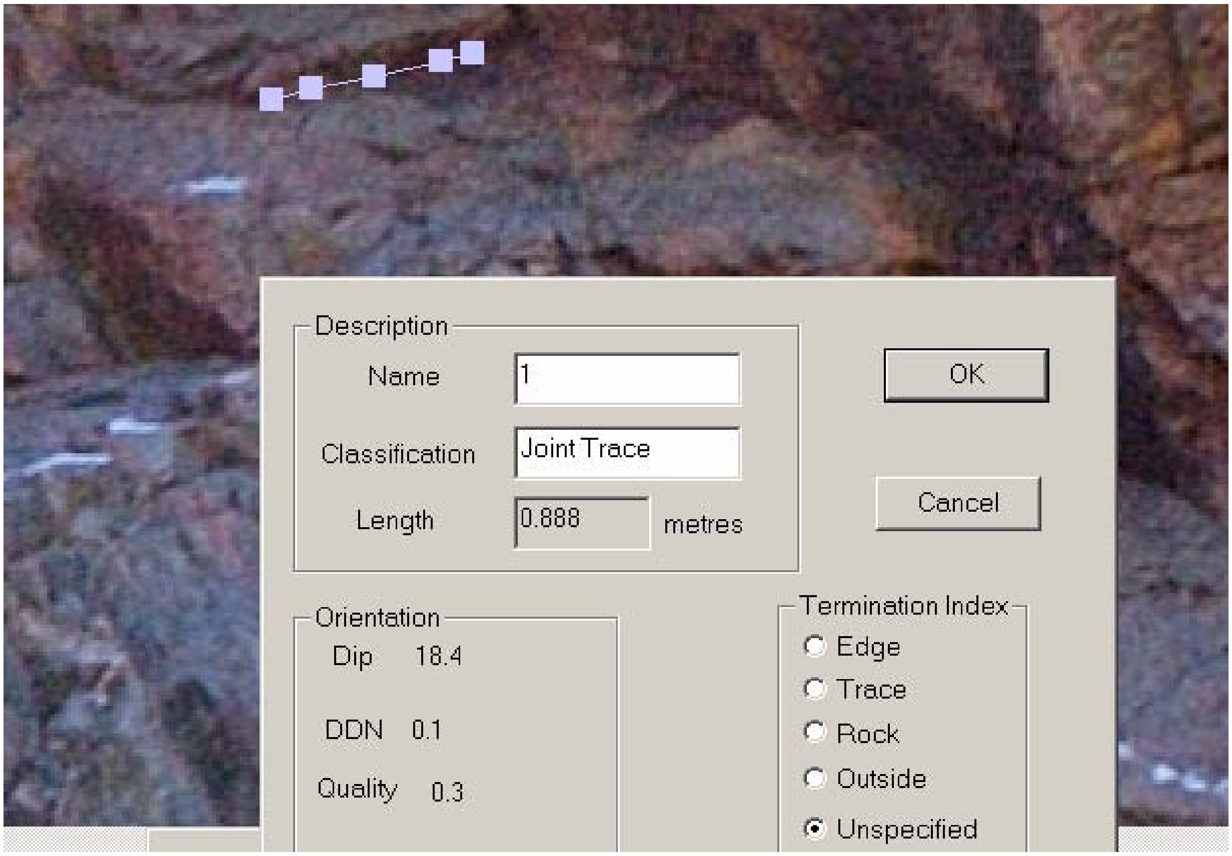


Figure 10.—Projected plane from the trace feature shown in figure 9.



Description

Name: 1

Classification: Joint Trace

Length: 0.888 metres

Orientation

Dip: 18.4

DDN: 0.1

Quality: 0.3

Termination Index

○ Edge

○ Trace

○ Rock

○ Outside

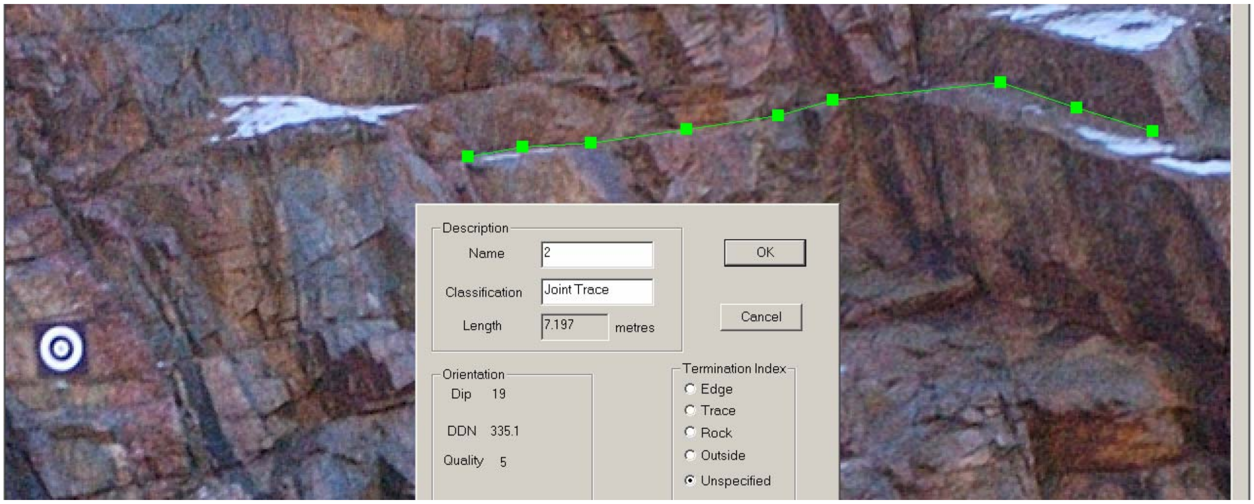
● Unspecified

Figure 11.—A second trace and information for the joint in figures 9 and 10.

Another example is used to illustrate how to identify when a high-quality plane is not properly defining the joints. Figure 12 shows a trace placed to describe a joint. The quality value is 5, so the line is very good in that the trace points are far from making a straight line. However, a second check should be made to verify that the plane is correctly describing the intended joint. In doing so, figure 13 shows that the plane calculated from this trace does not follow all the joints correctly, and a second trace should be used to determine a second plane for the joint on the right side where the single plane no longer follows the feature being mapped. Figure 14 shows the orientation differences in the two planes when the initial trace is reconstructed and a second trace (on the right) is added.

These examples demonstrate the importance of geologists recognizing valid and invalid feature selections. They show:

- How results can be checked
- How users can be fooled if they do not check carefully
- The value of multiple trace selections to quickly identify inconsistencies
- The value of experience as it relates to accuracy improvements



Description
Name: 2
Classification: Joint Trace
Length: 7.197 metres

Orientation
Dip 19
DDN 335.1
Quality 5

Termination Index
○ Edge
○ Trace
○ Rock
○ Outside
● Unspecified

Figure 12.—Trace and information for a likely joint. The quality value of the feature is excellent, and the trace appears to follow the joints quite well.

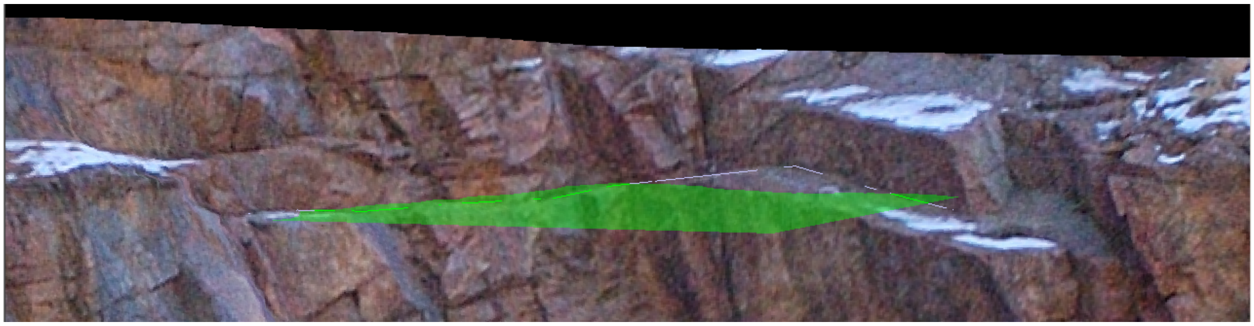


Figure 13.—The calculated and displayed plane for the trace in figure 12. While the plane intersects the left joint, it is noticeably above the right joint. Here, a decision can be made to use two different traces to map two different joints.

Figure 14.—Using two traces (and planes) to improve the mapping of the actual joints.

Software Evaluation Criteria

This research had a distinct focus on geologic mapping. The ability to map the location and orientation of joints, shears, fractures, and bedding planes and produce stereonet plots of these features was given a high priority during the software evaluation. The SiroVision software was the only program geared specifically towards geologic mapping.

Most, if not all, photogrammetry software packages should be able to produce a three-dimensional data set of points, referred to as a point cloud. Also, most programs should be able to use the point cloud to generate a triangulated surface. To be of maximum use, the software program for this research needed to couple the photographic image with the 3D surface and allow direct measurements of geologic features from the coupled model.

Another approach to photogrammetric mapping of rock abutments is to generate the 3D surface or point cloud using photogrammetry and export the points or the surface into a separate 3D CADD system. The third-party CADD system could then be used to create the surface, or manipulate and measure the surface, to determine the orientation of planar features. There was much discussion among researchers regarding the difficulties or added complexities associated with exporting points or surfaces from one program to another for analysis. For experienced CADD operators using high-quality computers, this approach may be acceptable or even preferred. However, for this initial geologic research into the value of photogrammetry in the Reclamation Safety of Dams Program, it was decided that a simpler program that could be used by more people at a lower cost was preferable to more complex systems. To be of value, any system needed to be at least as accurate as Brunton compass readings, which geologists have used for over 100 years.

The research team’s approach was to spend less time searching for the perfect software program, and more time using, learning, and applying the selected software to actual rock outcrops. This allowed faster implementation of a geologic mapping photogrammetry system into Reclamations toolbox, with the possible drawback of having a system that is not as robust for use in other non-geologic applications. This decision was not difficult, since the more advanced systems are typically four times the price and require more training and expertise to operate.

The evaluation criteria included the following considerations:

- Ease of collecting digital images

- Ease of image processing to obtain 3D point cloud data

- Mosaic capabilities (combining a string of images to create a panoramic view)

- Ease of mapping discontinuities using the 3D data
- Built-in data analysis tools (or is additional software required)
- Built-in visualization tools (stereonets, point cloud, and 3D image with discontinuity planes) with capability to rotate 3D data
- Data accuracy (spatial and orientation)
- Data (point cloud, orientations, trace data, plane data) export capabilities to move data to CADD systems
- Minimal training time and cost
- Minimal license cost
- Minimal cost of hardware

The evaluations of these criteria are divided into two sections. The first includes the qualitative nature of the 3D image data collection tools, such as ease of use, processing time, training time, and cost. Since these are subjective, this discussion will be provided only in this section (Software Evaluation Criteria). The second part is the evaluation of the more objective, or quantitative, data obtained by the LIDAR and photogrammetric systems, when available. The details of the methods used to evaluate the data accuracy and the findings and discussion of the accuracies follow in more detailed sections.

Table 1 makes a general comparison of the four 3D data collection systems evaluated. The only system actually used by Reclamation was SiroVision. It was used because of its clear focus on geologic mapping and minimal learning time requirements. Information about Foto-G, ShapeCapture, and RIEGL (or I-Site) is based on several days of working with each vendor. As Reclamation expands its use of photogrammetry into areas other than geologic mapping, these other software programs should be carefully evaluated.

Table 1.—Comparison of 3D data collection systems				
Feature	**SiroVision**	**Foto-G**	**ShapeCapture**	**RIEGL LPM-800HA LIDAR**
Calibration	User manual states that, because of a unique algorithm, calibration is not necessary for most applications but may be performed if required. Provides lens correction parameters.	Requires camera and lens calibration.	Requires camera and lens calibration.	Unknown.
Ease of collecting digital images	No tilt is allowed in camera, so camera must be on a tripod. Only two images can be used to create a 3D image. Two camera control points and one face control point near the image center are required for orientation control.	No tripod is required. Images can be obtained while moving because no camera positions are needed. Requires three ground control points at the image edges. Multiple images can be used to develop 3D image combining near, far, high, and low shots.	No tripod is required. Images can be obtained while moving because no camera positions are needed. Requires three ground control points at the image edges. Multiple images can be used to develop 3D image combining near, far, high, and low shots.	Fast scan. Usually requires data from several positions. Accuracy is inversely proportional to distance between scanner and object. Accuracy improves as distance decreases.
Ease of processing to obtain 3D point cloud data	Program uses tutorial style to direct the user. Very easy to learn. Fast processing.	Unknown at this time, but appears to require more photogrammetry knowledge. With specified targets placed on surface, matching is automatically performed, resulting in full point cloud data.	Unknown at this time, but appears to require more photogrammetry knowledge. A light grid can be projected onto the surface for auto-bundling.	Unknown at this time.
Mosaic capabilities	Can combine image pairs only for visualization purposes (cannot map across mosaic); however, data can be exported to CADD system for joining.	Can join multiple images into a single set; however, the CADD program taking the 3D data must be able to manage the large data file.	Can join multiple images into a single set; however, the CADD program taking the 3D data must be able to manage the large data file.	Can join multiple scans into a single set; however, the CADD program taking the 3D data must be able to manage the large data file.
Ease of mapping discontinuities using tools that geologists are familiar with, such as the ability to trace intersections or measure planes	Very easy. No CADD program is required but 3D data (points, TINS, traces, and polygons) can be exported and managed in a CADD program.	Only observations of these tasks were available. Does not seem as intuitive as SiroVision. A CADD application is required for mapping.	Only observations of these tasks were available with a small degree of hands on. The mapping tools are not intuitive.	Only observations of these tasks were available. Does not seem as intuitive as SiroVision. CADD application is required for mapping.

Table 1.—Comparison of 3D data collection systems (continued)

Feature	**SiroVision**	**Foto-G**	**ShapeCapture**	**RIEGL LPM-800HA LIDAR**
Built in data analysis tools (evaluate requirements for having to use additional software)	The discontinuity analysis tools available are rose diagrams; stereonets; joint area, spacing, and persistence plots	No discontinuities tools are available. Planes are derived in the CADD application.	A plug-in can be made available that provides exportable dip and direction. No other tools available.	Analysis needs to be performed in CADD system. Not automated.
Built-in visualization tools with rotation capabilities of 3D data (point cloud, 3D image, planes of discontinuities)	Available.	Available in the CADD application.	Available in the CADD application.	Available in the CADD application.
Data accuracy	All can probably get micron spatial and subdegree angle accuracies, but the time/cost in getting this may vary by system. The final accuracy should match the task requirement.			+/- 25 mm plus 20 parts per million (ppm) distance error.
Data (point cloud, orientations, trace data, plane data) export capabilities, such as to CADD systems	Available.	Must be exported to CADD.	Must be exported to CADD.	Must be exported to CADD.
Training time and cost	Two days of training was provided at no cost. Vendor supports new development with focus on geologic mapping.	Three days of training expected to cost $2,000, depending on number being trained.	Two days of demonstration provided for a fee. Additional training is required, for a fee.	Unknown.
License cost	$5,000 for first license and $2,500 for second. Free updates and customization.	$20,000 per seat per year + maintenance fee.	$1,500 per seat per year.	Processing software costs about $20,000.
Hardware cost	$7,000 for camera and lenses but could go lower if using lower resolution camera.			$50,000 - $100,000 for scanner.
Web sites	<www.SiroVision.com>	<www.vexcel.com>	<www.shapecapture.com>	<www.riegl.com>

Methods for Quantitatively Evaluating Software

General

Different techniques were used to check the orientation and spatial accuracies of the data obtained from photogrammetry.

Orientation and spatial data were collected from three different sites with specific objectives. The sites are East Canyon Dam, Morrison Test Site, and LaFarge Open Pit Mine. Since Foto-G, ShapeCapture, and LIDAR were demonstrated only at the Morrison Test Site and were demonstrated without targets, no spatial data could be obtained for comparison and only casual observations can be made about these systems and the orientation accuracy findings. Most of the evaluations presented are from SiroVision testing.

The objective for East Canyon was to collect geotechnical data for a foundation stability analysis. This was the first location in which the data would be used for a Reclamation stability analysis. The second location, the Morrison Test Site, was used to observe other photogrammetry software vendors and to begin outlining the procedures that would be used to compare features. The work done at the LaFarge Open Pit Mine was a collaborative effort with the Colorado School of Mines. Lisa Krosley, the principal investigator and Colorado School of Mines student, assisted a mining class in the use of digital photogrammetry to collect geotechnical data for open pit slope stability analysis. The professor of the class, Dr. Ugar Ozbay, chose to use SiroVision software because the software was easy to learn, provided all the necessary analysis and visualization tools, and was offered free of charge for a limited time.

The summary findings of the spatial and orientation accuracy are provided in the section, “Findings and Discussions of Spatial and Orientation Accuracies.” The details for each site (investigation objective, project layout and data acquisition, and results and discussion of the spatial and orientation accuracy data) are covered in the following appendices:

- Appendix A – East Canyon Dam Foundation Stability Study
- Appendix B – Morrison Test Site
- Appendix C – LaFarge Open Pit Mine Slope Stability Study

The results, in addition to showing a range in accuracies that we, as new users, can expect, will show whether the average accuracy improves as users become more familiar with the software and the art of photogrammetry.

There are many sources of error that cause loss of spatial and orientation accuracy. Many are human sources; so the error contribution will always be present and will always vary. However, it is assumed that the total error contribution will decrease as more experience is gained with each system. Of this long list of possible error sources, the largest and most likely contributors are:

- Incorrectly surveyed camera locations (this parameter is not required by Foto-G or ShapeCapture).
- Camera tilt not removed (this parameter is not required by Foto-G or ShapeCapture).
- Camera line of sight to the face of interest is far from perpendicular.
- Left and right camera lines of sight either diverge or the convergence angle is too large.
- Poor camera and lens calibration.
- Incorrect lens and distance-to-face relationship used to get required accuracy.
- Control points are not placed at optimum positions.
- For SiroVision, the single control point is not near the image center.
- For Foto-G and ShapeCapture, the four control points were not placed near the image edge.
- Targets were placed at the very edge of images, where lens distortion is the worst (although lens calibration may correct this).
- Control points were not surveyed correctly.

Method of Measuring Spatial Accuracy

For the three sites used in this report, targets were placed on the rock outcrops (figures 15 and 16) and surveyed using reflectorless total station technology. The surveyed coordinates were typically presented as northing, easting, and elevation in either a world or local coordinate system. The northing, easting, and elevation positions of these targets were also obtained using SiroVision. The SiroVision spatial coordinates were then evaluated for accuracy. Spatial error is defined as the difference in magnitude between the target's surveyed position and the SiroVision position. The surveyed position of the target is presumed to be more accurate; thus, it is the baseline for comparison. That survey data could have errors should be considered as a possibility. For this phase of the research, using the survey as a datum seems justifiable. For each site, the SiroVision errors for the multiple targets were averaged. The average SiroVision errors for each of the three sites and the overall average error are listed in table 2, which appears in a later section.

Figure 15.—Targets placed on rock outcrop at Morrison Test Site for evaluating spatial accuracy.

Figure 16.—Painted targets placed on rock outcrop at LaFarge Mine for evaluating spatial accuracy.

Methods of Measuring Orientation Accuracy

Orientation errors are more difficult to verify because there is rarely a perfectly planar discontinuity on a natural rock face. In other words, the natural roughness or waviness makes this comparison difficult. The orientation results using photogrammetry methods will depend on where a selection boundary is placed on the face or which points of a trace are used. (See figure 5.) It is the 3D points within the selection boundary (see figure 8) or those selected for a trace that are used to calculate the orientation. Likewise, the results of a Brunton orientation will depend on where the Brunton is placed on the feature, as well as the skill of the user.

Given this information, a statistical method is most often used where the photogrammetry orientations are either compared to Brunton measurements or the photogrammetry orientations from the different systems are cross compared. The tightness of the cluster will qualify the accuracy of the orientations. Also, a possibly unique opportunity was available at the East Canyon Dam site to verify the photogrammetry orientation value. A concrete wall constructed to protect a weak shale seam extended diagonally across the left abutment. The orientations of the wall sections were provided in an as-built drawing. These orientations were compared to the orientations found by SiroVision. This provided at least one sound quantitative comparison. At the Morrison Test Site, the orientations of five planes were compared. The orientations were measured using Brunton, Foto-G, LIDAR, and SiroVision.

Findings and Discussion of Spatial and Orientation Accuracies

Spatial Accuracy Findings

Table 2 provides a summary of the average spatial accuracy error using SiroVision for each location. A summarized discussion of the problems that occurred at each setting is also provided in this section. In-depth details, which include the objective, method, findings, and discussion for each location, are found in the following appendices:

- Appendix A – East Canyon
- Appendix B – Morrison Test Site
- Appendix C – LaFarge Open Pit Mine

Table 2.—Individual and average SiroVision spatial error from three sites

Site	Average magnitude of error
East Canyon Dam Abutment	4.57 inches
Morrison Test Site	2.63 inches
LaFarge Open Pit Mine	0.72 inches
Average of All Three Sites	2.64 inches

Spatial Accuracy Discussions

For the three sites used in this report, targets were placed on the rock outcrops and surveyed using reflectorless total station technology. The surveyed coordinates were typically presented as northing, easting, and elevation. The northing, easting, and elevation positions of these targets were also obtained using SiroVision. The SiroVision spatial coordinates were then evaluated for accuracy. Spatial error is defined as the difference in magnitude between the target's surveyed position and the SiroVision position. The surveyed position of the target is presumed to be more accurate; thus, it is the baseline for comparison. That survey data could have errors should be considered as a possibility. For this phase of the research, this is a justifiable assumption. For each site, the SiroVision error for the multiple targets was averaged

East Canyon

The largest spatial error of 4.57 inches occurred at East Canyon Dam. The probable causes for the spatial error are as follows.

The greatest contributor to the large spatial error was probably a lack of good communication with the survey crew. The face control, near the center of the image, was surveyed and physically marked on a photo while in the field. However, it was not possible to accurately relocate where the actual survey shot was on the photo as required for image processing. This was because the pencil lead mark covered an area up to 6 inches relative to the image scale. To prevent this in the future, highly enlarged images will be provided to the survey team and the geologist will work directly with the surveyors, when possible, to help mark the photographs.

Another possible cause in spatial error was an inability to find the camera's precise center. A different tripod system has been developed to remove this large source of error (Appendix E).

The targets used to examine spatial accuracy were placed at the bottom of the abutment wall, as high as one could reach without climbing. For reasons of safety and cost, no climbing could be conducted. Unfortunately, these target positions were also at the photo edge where high lens distortions are known to exist. Despite the likely errors, the targets were placed as an error observation. With this in mind, the poor spatial accuracy of the East Canyon targets could be eliminated. These results are presented to show what can happen when procedures are used that do not follow the photogrammetry software requirements.

Finally, having the left and right cameras closer together may have improved the results. With the large amount of relief with respect to the cameras' line of sight, the perspective changed significantly from one image to the next. The software's image collection tool was used to estimate the necessary space between camera positions, but face relief is not a parameter considered by the software, and the user's knowledge and experience of photogrammetry must be relied upon in this matter. In general, because this was the first real application of the software, experience was lacking. This factor, fortunately, will dissipate with increased use of this tool.

Morrison Test Site

The error at the Morrison Test Site was found to be 2.63 inches. This error could probably have been reduced by using a more powerful telephoto lens or getting closer to the face. Also, the same problem exists as found at East Canyon: obtaining an accurate camera center location.

LaFarge Open Pit Mine

The smallest error of 0.72 inches occurred at LaFarge Open Pit Mine. This small error illustrates how close actual accuracy may approach to the potential accuracy. To be fair, there were only two targets used to evaluate the spatial accuracy. This alone is not statistically conclusive but can still be used in an average. Data accuracy improvements, in comparison with the other sites, may be because:

- There were many students confirming the location of the camera position.

- The control and targets were in the middle of the images, rather than on the edges.

- The locations of the targets were indisputable.

- There was very little perspective change of the features between the left and right images because of the low relief of the wall.

Orientation Accuracy Findings

Table 3 provides a summary of the orientation accuracy findings from SiroVision. Greater details are found in:

- Appendix A – East Canyon
- Appendix B – Morrison Test Site
- Appendix C – LaFarge Open Pit Mine

Table 3.—Orientation error findings from three locations

Location	Orientation error findings					
East Canyon	The difference between the SiroVision dip direction and the as-built specification of a concrete support wall on the left abutment is less than 1/2 degree. In the image area where photogrammetry data are useable (not along edges), Brunton readings could not be collected without a climb team. Foto-G, ShapeCapture, and LIDAR were not used at this site.					
Morrison		Data Source as dip/dip direction in degrees				Range dip/dip direction (deg)
	Plane	RIEGL	Foto-G	SiroVision	Brunton	
	Plane A	73.2/307.7	74/308.3	74.2/317.4	73/310	73 to 74/ 308 to 317
	Plane B	34.3/338.1	34.4/338.7	34.9/335.9	35/337	34 to 35/ 336 to 339
	Plane C	64.5/222.5	63.3/229	64.2/224	64/232	63 to 65/ 223 to 229
	Plane D	69.3/203.6	68.7/204.4	70.3/202.3	65-75/ 195-215	65 to 75/ 195 to 215
	Plane E	84/195	76/198	82.8/12	80-85/ 185-205	76 to 85/ 185 to 205
LaFarge	In evaluating the Brunton and SiroVision orientation clusters, the dip values had ranges of 2 to 14 degrees and the average was 7.6 degrees. The dip direction ranged from 14 to 68 degrees, and the average was 36 degrees. Foto-G, ShapeCapture, and LIDAR were not used at this site.					

Since the Morrison data in table 3 provides the most quantitative evaluation, further examination of these results are shown in table 4. In this table, differences between RIEGL, Foto-G, and SiroVision orientations for the five planes of interest are extracted.

Table 4.—Three-way comparison of the 3D imaging systems for the evaluated five planes

	Angle between normal of the plane (degree)		
Evaluated Planes	**RIEGL vs. Foto-G**	**RIEGL vs. Siro**	**Foto-G vs. Siro**
A	1.0	9.4	8.8
B	0.1	1.7	1.7
C	6.0	1.4	4.6
D	1.0	1.6	2.5
E	8.5	13.5	22.0

Orientation Accuracy Discussion

In summary, the orientations obtained from SiroVision, Foto-G, ShapeCapture, and LIDAR were more accurate than those obtained using a Brunton. Because the photogrammetry data are even quicker to collect than the time allocations required for traditional methods, photogrammetry is a very viable tool. It is doubtful that any task will require dips and dip directions more accurate than 1 degree.

East Canyon

The 0.5-degree difference between the as-built specification orientation and the SiroVision results is quite acceptable. The East Canyon orientations obtained using the SiroVision software are believed to be sound, based on this comparison and by sound geologic judgment of how well the data compare with the observed trends.

Morrison Test Site

The discussion of the Morrison Test Site results is very complex, and it is suggested that Appendix B be read for the full details. In summary, however, comparisons between planes A, C, and E should be eliminated for the following reasons.

The SiroVision data for Plane A was only a portion of the plane mapped by the Foto-G software (by Vexcel). While this joint face is rather planar, it is not perfectly planar. The area mapped by SiroVision could have a significantly different resulting orientation than that mapped by Vexcel. Also, Plane A was at the edge of the SiroVision image pairs, where distortion is likely to exist.

Plane E was too small for SiroVision to accurately map because of the lens and distance-to-face combination used when collecting the images. The camera and scanner positions used by Vexcel and RIEGL, respectively, were much closer than those used by SiroVision. Had it been known that this small joint face would be used for an accuracy comparison, the SiroVision camera would have been placed closer to the outcrop.

Plane C was at a poor angle to the SiroVision camera positions used for this comparison. Again, had it been known that this joint, or joint set, was of particular interest, different camera positions would have been used during image collection.

In comparing the data from the three imaging sources for the remaining planes B and D, the results are very good. Table 4 shows that RIEGL and Foto-G had the greatest agreement in plane orientations for planes B and D. According to table 3, the orientations by all photogrammetry and LIDAR sources are probably better than the Brunton reading. In hindsight, more Brunton readings should have been obtained to observe the Brunton’s accuracy and the planes to be measured should have been selected before the photographic work was performed.

LaFarge Open Pit Mine

There are several factors that could explain the variations in dip direction. For the Brunton measurement, which is probably the least accurate of the two data sources, it is very difficult to get a good dip and dip direction on a small block face; especially when only a portion of the block face is exposed. Also, only one location was used to get the orientations at this site. Variations in SiroVision dip directions probably occur because the data points in the trace had very little change in relief from the camera’s point of view. It is similar to finding the orientation of a surface that is nearly horizontal. The smallest amount of waviness in the horizontal surface will cause the plane poles (a pole is a line normal to a plane) to appear near the center of the stereonet but in any of the four quadrants. The dip will be consistent, but the dip direction will vary dramatically. To correct this problem, one could try to extend the trace line as long as possible. If this doesn't resolve the problem, mapping multiple traces along the same edge or crack and finding the center of the data cluster may be possible.

Conclusions

Digital photogrammetry is found to be a safe, fast method for collecting geotechnical data of steep rock outcrops. The data it provides are abundant and, potentially, can be more accurate than data obtained using traditional methods. If not the primary source for providing discontinuity and spatial data, digital photogrammetry can be used, along with traditional methods, to increase the confidence in the data, especially until more case histories are developed to provide statistical verification of the accuracies of this technique. It is probably not cost effective if only a handful of orientations or spatial locations are required.

The photogrammetric system we now operate is capable of mapping geologic discontinuities and has been implemented at East Canyon Dam. The orientation accuracy is very good, and it is reasonable to believe that the spatial accuracy will improve as the photogrammetry team gains experience and the new camera/survey tripod system is implemented. In comparing the photogrammetry software systems, SiroVision requires more work and has more constraints in gathering images than Foto-G and ShapeCapture, but the data processing appears easier and the software provides analysis tools.

Evaluations will continue as work is completed at project and test sites. Also, collaboration with other groups using photogrammetry for geotechnical data collecting will continue. Networking with partners is a way to find quick solutions to problems.

In addition to examining the quantitative and qualitative capabilities of the photogrammetric software available, many observations were made:

- A special team is needed because experience is tied directly to accuracy and the ability to know if the data are legitimate, or at least to evaluate the uncertainty.

- Geologic mapping skills are important when working with these images.

- Geologists must always stay involved in these mapping projects. The feedback between the geologist and engineer is vital to both sides. They educate each other regarding the data needs and the uncertainties of the data.

- There are other completely feasible but unexplored applications, such as concrete crack mapping, wall deflection deformation, slope stability monitoring, mapping hydraulic bed changes with time, and borrow pit volumes.

- All photogrammetry systems and LIDAR have the potential to produce orientations that would be useful for geotechnical work.

- Through a casual observation of spatial accuracy, Foto-G and LIDAR appear to be more accurate than SiroVision. However, this is only a casual observation, and rigorous testing for all the systems would be required to verify this statement. What may be more important is that these differences may be insignificant for rock mechanics work.

- Data are acquired faster using digital photogrammetric and LIDAR methods than using traditional methods.

- Digital 3D images can be archived for later reference in the event that an important discontinuity is missed or for comparison of changes with time.

- Photogrammetry, a remote method of data collection, is safer than traditional methods.

After reviewing the results from the photogrammetry and LIDAR evaluation conducted at the Morrison Test Site, it was determined that a controlled testing approach needs to be defined to justly compare the different photogrammetry systems. This includes taking all photos at a distance that is likely to be used at a real site (e.g., 50 feet), using the same camera and lens for all systems, and defining the planes of interest for comparing orientations and targets for spatial comparisons before collecting the images. With the technology exactly equal and the art of photogrammetry as equal as possible, most of the differences between the resulting data will be attributable to the science, or the algorithm used by the software.

Another approach could be to place several targets on the face to collect spatial data and define planes to be used for orientation data gathering and then let the users of each software system do what is necessary to obtain an orientation accuracy of +/- 1 degree and spatial accuracy of 1 inch. This method may, however, have several disadvantages. First, a user may get the accuracy by collecting images standing within 5 feet of the slope using a 20 mm lens, but this proximity to the face will not often be possible at most Reclamation sites. Second, many trials using different lens and distance combinations may be needed by each user to finally attain the predetermined accuracies. This could be very time consuming. Finally, if one user can get a spatial accuracy of 0.5 inches with a distance of 30 feet using a 50-mm lens and another achieves an accuracy of 1.0 inch by standing 110 feet from the face using a 100-mm lens, it will be difficult to determine which method was more accurate. Each achieved the minimum spatial accuracy of 1 inch, but getting 0.5 inch by standing closer may still be poorer than getting 1.0 inch by standing farther away.

Recommendations

Based on the findings from this research, several tasks have been identified as requiring further investigation. They include improving the results of the system we already know (SiroVision) and then learning and implementing the Foto-G and ShapeCapture software. Breaking this down further, the research plan would include the chronological tasks of:

- Testing SiroVision using the new camera mount to see if spatial errors decrease.
- Using ShapeCapture in some trial runs.
- Purchasing the Foto-G software, attending the Foto-G training, and practicing with the system.
- If more spatial accuracy verification is required, conducting a controlled test of all three systems.
- Evaluating the potential for accurate crack mapping using several products.
- Further evaluating SiroVision on dam projects where Brunton readings are possible for comparison.

Finally, it is recommended that digital photogrammetry be implemented when significant amounts of geotechnical data are required or when accuracy or safety is an issue. The data can be used alone or with data obtained using traditional methods for cross checking. Very soon, photogrammetry may be considered a necessary tool.

References

Burtch, Robert. April 24, 2003. History of Photogrammetry; web site: <http://www.ferris.edu/faculty/burtchr/sure340/notes/History.pdf>

Krosley, L., P. Shaffner, M. Neeley, 2003. East Canyon Dam Engineering Geology Review Memorandum, Bureau of Reclamation.

Appendix A

East Canyon Dam Photogrammetry Mapping Using SiroJoint

Objective

The objective at this site was to collect geological and geotechnical data for foundation stability analysis of the left abutment. Photogrammetry was used to reduce the cost of determining the orientation of the major joints and bedding planes.

Project Layout and Data Acquisition

The Provo Area Office surveyed the camera and ground control point locations using a reflectorless total station. NAD83 coordinates were eventually established to obtain absolute location. Table D1, Appendix D, provides the survey coordinates. Targets, shown in figure A1, are located at the base of the left abutment. Not all targets are present in this image. Three pairs of images were collected for discontinuity mapping of the downstream left abutment. The camera positions were about 180 feet from the face (on the right abutment). The camera was fitted with a 20-mm lens.

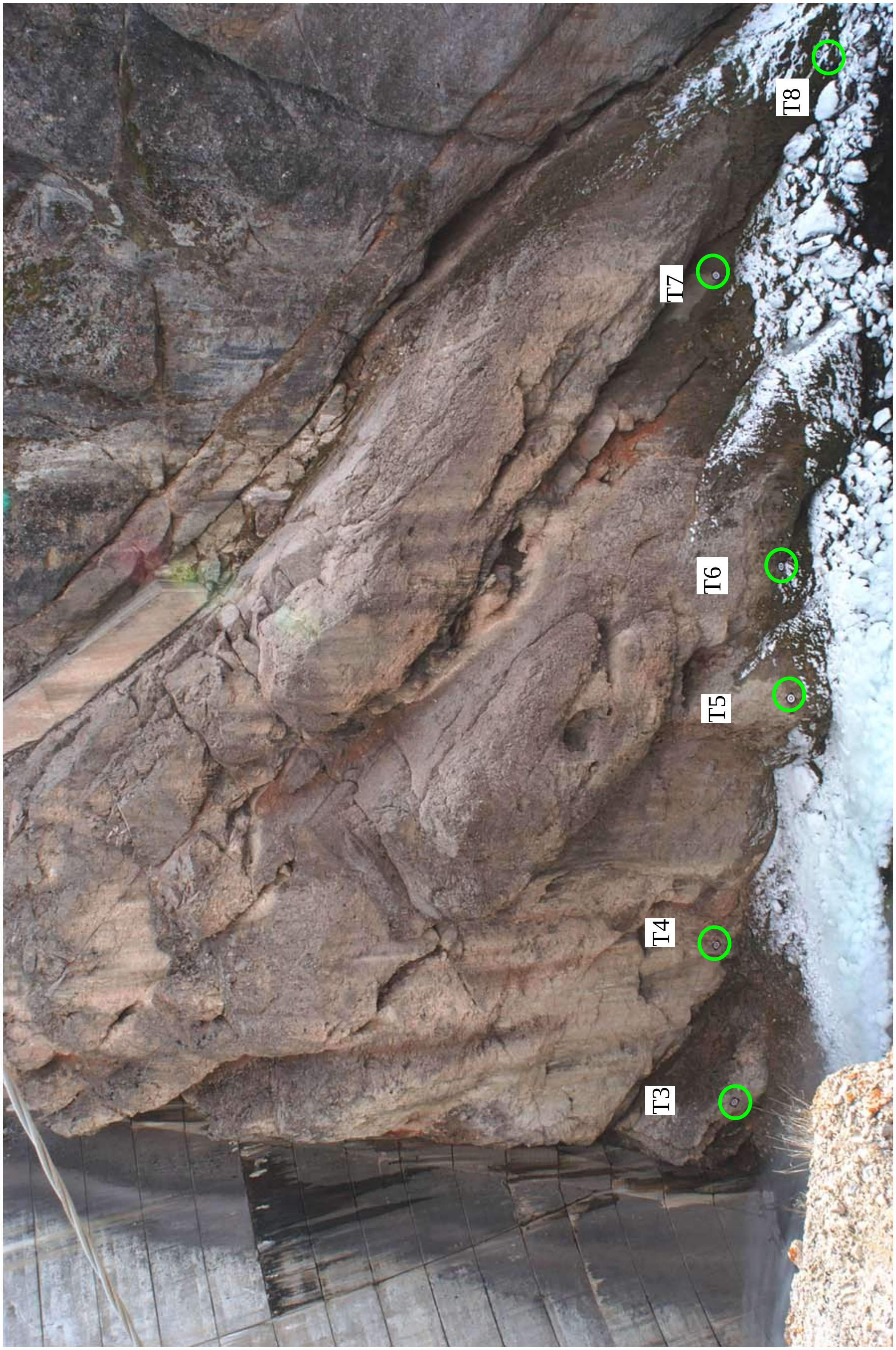


Figure A1.—East Canyon left abutment with targets.

Results and Discussion of Accuracy Evaluation

Spatial Accuracy

Of the 10 targets placed along the bottom of the left abutment, only 8 targets were in positions for the cameras to capture spatial measurements. The survey and SiroVision photogrammetry coordinates for these targets and their differences are shown in table A1. The last column in the table shows the source of data and, for SiroVision, which image set was used to extract the data. Assuming the survey coordinates are correct, the differences between the two data sources are attributed to SiroVision error. The final average SiroVision spatial error is found to be 4.57 inches at this site.

Table A1.—SiroVision spatial error results based on survey data for East Canyon

Survey and SiroVision Coordinates for eight targets				
Northing (ft)	**Easting (ft)**	**Elevation (ft)**	**Targets**	**Data source**
4712.96	459.43	5515.06	T3	Survey
4712.81	459.52	5514.89	T3	SiroVision
0.15	0.09	0.17	= Absolute difference between coordinates	
4711.45	435.58	5515.30	T4	Survey
4711.44	435.67	5515.42	T4	SiroVision
0.01	0.09	0.12	= Absolute difference between coordinates	
4737.29	400.36	5517.53	T5	Survey
4736.73	399.90	5517.67	T5	SiroVision
0.56	0.46	0.14	= Absolute difference between coordinates	
4729.27	334.96	5516.00	T7	Survey
4728.85	335.19	5515.46	T7	SiroVision
0.42	0.23	0.54	= Absolute difference between coordinates	
4742.39	283.66	5509.61	T9	Survey
4741.81	283.20	5509.24	T9	SiroVision
0.58	0.46	0.37	= Absolute difference between coordinates	
4745.28	267.07	5507.37	T10	Survey
4744.65	266.27	5506.97	T10	SiroVision
0.63	0.80	0.40	= Absolute difference between coordinates	
4746.09	251.18	5508.10	T11	Survey
4746.22	251.30	5508.56	T11	SiroVision
0.13	0.12	0.46	= Absolute difference between coordinates	
4756.54	229.21	5505.45	T12	Survey
4755.95	227.84	5505.19	T12	SiroVision
0.59	1.37	0.26	= Absolute difference between coordinates	
				Average error for eight targets using all coordinates = 0.38 ft = 4.57 in

In comparing the spatial error of 0.38 feet to the photogrammetry distance from the face of about 180 feet, the ratio of 475:1 is the probable spatial accuracy for this project. This is considerably less than a potential error of 10,000:1 as found by CSIRO. There are three possible causes for this difference.

First, there was poor communication between the research team and the survey team. The surveyor was provided with a photograph of the downstream left abutment showing which planes and features they were to obtain survey points on. The team shot in and marked the control points and bedding point locations on a photograph as requested; however, when these locations were then transferred to the actual image within SiroVision, the marks covered an area of about 1/2 foot. It was not possible to tell where, exactly, the control point should be placed. A suggestion to improve this source of error is to provide the surveyor with a zoomed-in image of the desired control point. When the surveyor annotates the image with the location of the control point actually shot, a circle drawn about the feature could be used along with the exact point on the photograph.

Next, it was difficult to project a good location of the camera onto the ground surface and to get a good measurement of the camera height. The tripod does not allow the plumb bob to drop unobstructed and gets in the way of the tape for finding the camera center height. Also, the tripod leveling bubbles were not survey quality and may have low accuracy, allowing tilt in the system. A camera mount was designed and produced that would make camera setup faster and improve the accuracy of the camera location coordinates. Details on the mount are provided in Appendix E.

Finally, the targets were placed along the base of the abutment as high as possible without climbing. Unfortunately, being at the bottom of the photo, they lie in an area where lens distortion is the worst. Therefore, the spatial comparison was made in an area where the distortion is greatest. This could mean that the spatial accuracy toward the center of the image is better than what is listed in table A2. This is not possible to verify at East Canyon, mainly because of the lack of control points near the middle of the abutment, but distortion and target placement are important factors to learn for future studies.

Orientation Accuracy

The primary technique used to examine the accuracy of the SiroVision orientation was to compare these data to known orientations of a concrete wall that protects a weak shale bed. The orientations are documented on the as-built drawing. Figure A2, below, shows this wall along the rock face of the downstream left abutment. Figure A3 is an excerpt from Drawing 526-D-2902 that provides the specifications of the protective concrete wall. The highest concrete wall section, from Point A to Point B, could not be matched by the SiroVision software because the face of this section was hidden from the camera. The two usable wall sections (outlined in red) are noted as section BC and section CD. According to Drawing 526-D-2902, the highest section, BC, has a strike of N 43º46' W (dip direction of 46.23º NE) and section CD's strike is N 59º46' W (dip direction of 30.23º NE). The dip directions obtained from SiroVision are 45.80º for section BC and 30.20º for section CD. The differences between the drawing and SiroVision orientations are very small: 0.43º and 0.03º for these two sections. (See table A2.) In this section of the mapped area, the orientations of the concrete obtained using photogrammetry match the true orientations very well. This excellent agreement between known orientation and predicted orientation could be influenced by the fact that the feature is near vertical. The influence of dip magnitude on the photogrammetry systems should be evaluated in further studies.

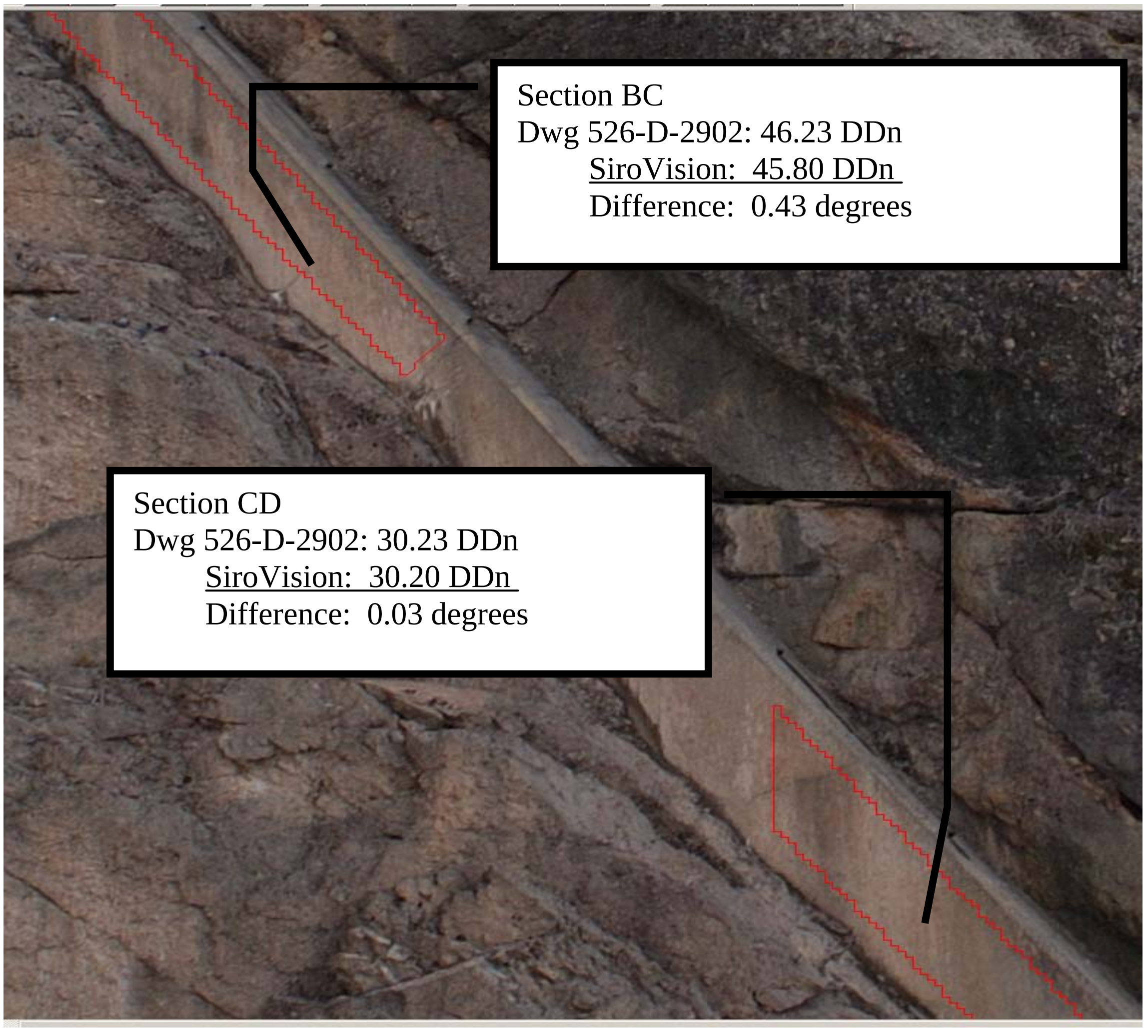


Figure A2.—Protective concrete wall, downstream left abutment, November 2002.

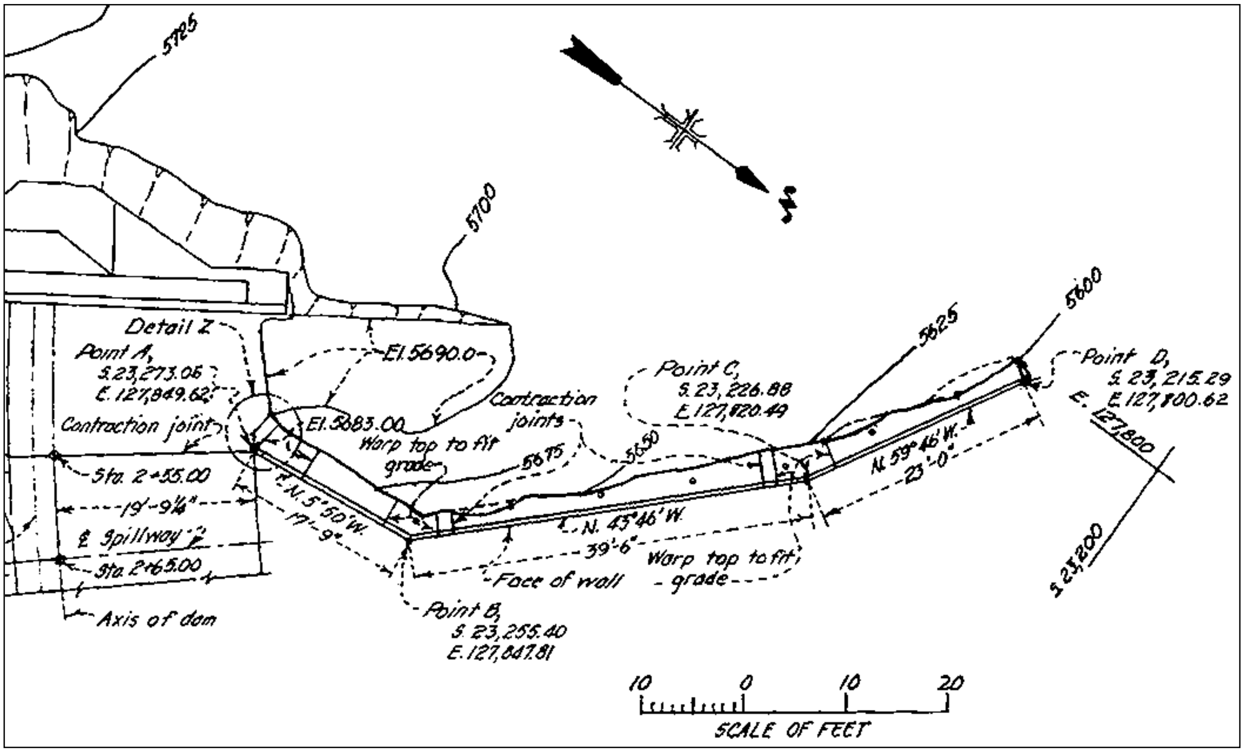
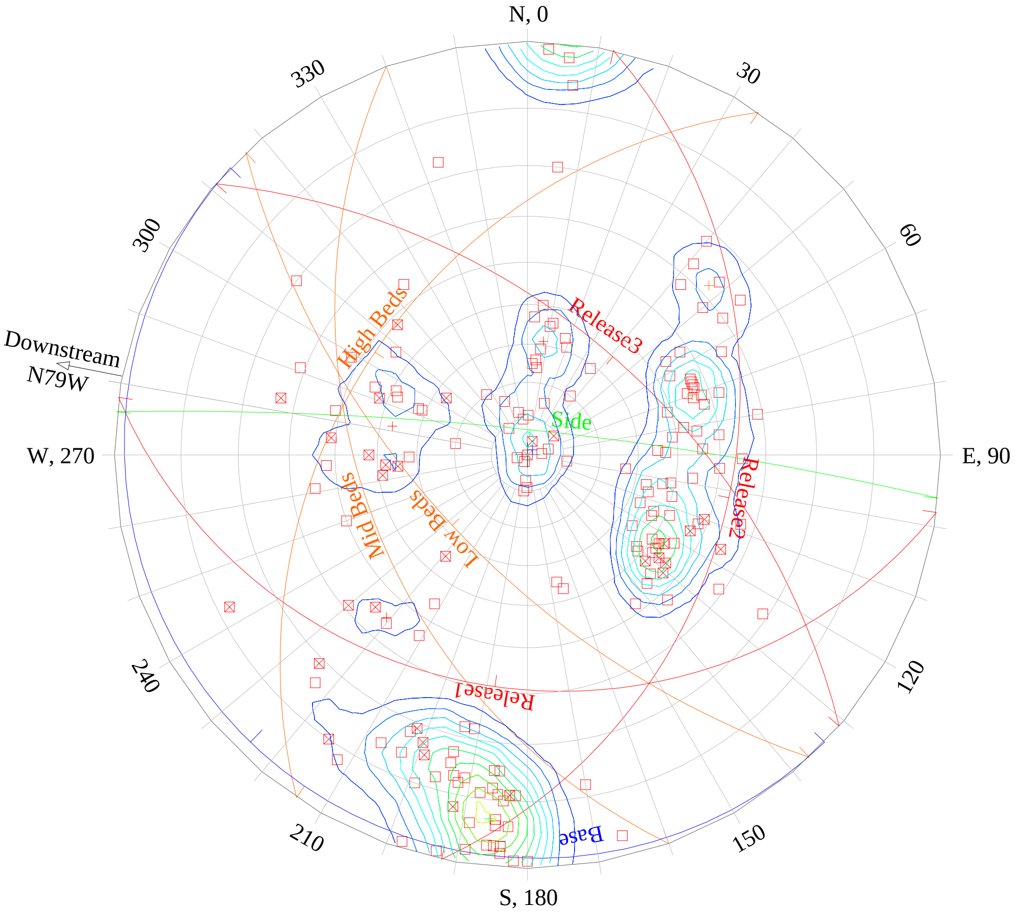


Figure A3.—Concrete support wall specifications for Sections BC and CD from Drawing 526-D-2902.

Table A2.—Comparison of concrete wall dip directions using Drawing 526-D-2990 and SiroVision data

	Orientations of wall sections (degrees)		
	Drawing dip direction	**SiroVision dip direction**	**Dip direction difference**
Section BC	46.23º	45.80º	0.43º
Section CD	30.23º	30.20º	0.03º

The second check to evaluate orientation accuracies is more qualitative. The data provided by SiroVision of the mapped plane and trace features were visually examined for ambiguities. The data should fall within the bounds of the expected orientations that the geologist visualizes at the site. The judgment of the geologist is a very important tool in verifying data accuracies. The SiroVision orientation data was determined to be reasonable. Stereonets were used as further guidance. Figure A4 is an example of SiroVision orientation data for East Canyon’s left abutment (Krosley et al., 2003). Good pole clusters are present and agree with the site structure.



Notes:
-Great circles are annotated according to the joint descriptions in Sections 4.2.2.2 to 4.2.2.5.
-Pole numbers correspond to annotations in Figure C3, Appendix C.
-Complete data found in Table C7 and C8, Appendix C.
-179 Poles

☒ Upstream Poles

☐ Downstream Poles

Joint Sets:

Label	*Average Cluster Dip/Dip Direction*
Release1	31/188
Release2	37/102
Release3	55/41
High Beds	42/304
Mid Beds	46/250
Low Beds	62/227
Side	83/6
Relief	2/224

Figure A4.—Orientation data of the left abutment of East Canyon using SiroVision. The plane poles and pole clusters are in good agreement with the site conditions. This comparison aids in verifying the accuracy of data obtained from photogrammetry.

Conclusions

The work performed at East Canyon presented several benefits.

First, it provided experience in photogrammetry and an outstanding education, both generally and in the specifics of SiroVision. To improve the image matching, image segmentation was used for the first time. Often, this SiroVision technique is not required unless the object has high relief, such as at East Canyon. We also learned that, to ensure the survey data are accurate, surveyed points should be verified while everyone is still in the field. If the survey data are incorrect, the entire model will be incorrect. When everyone is in the field, corrections can be made. It may also be feasible to process the images in the field and map some features that can be verified immediately.

Finally, this work verified that SiroVision software could be used as designed to remotely measure the orientation of discontinuities on the steep abutment of a concrete dam.

Appendix B

Morrison Test Site

Objective

The Morrison test site was chosen as a local test site to examine the ease of use and accuracy of Foto-G, LIDAR, SiroVision, and ShapeCapture. It was initially intended that the vendors merely demonstrate their systems. While some data comparisons were possible, the procedures provided very little control; thus, the results cannot be considered rigorous.

Project Layout and Data Acquisition

Location

The rock outcrop used to evaluate and test the three photogrammetry and LIDAR systems is located just west of Morrison, Colorado, near mile marker 17 on Highway 8.

Site Characteristics

The outcrop was chosen for this task because the face was accessible for target applications and Brunton readings. The parking lot just west of the face provided numerous locations for camera and scanner setups. The outcrops had a strongly planar jointing system resulting in blocks of varying sizes.

Target Setup

Four targets were placed on the face for use as spatial accuracy checks and as ground control points. The ground control points were required by the software. The 1.5-ft by 1.5-ft targets were secured to the face with a single bolt in the center. The bolt holes were drilled using a portable hammer drill. Figure B1 shows the four targets. The blocky structure of the face, along with a closeup of a target, are portrayed in figure B2.

Survey and Control

The Technical Service Center (TSC) performed the survey of camera and ground control points using a reflectorless total station. A local coordinate system was established with the ground position of camera location P3 being set to (5000, 3000, 1000) as easting, northing, and elevation in meters. For a back site, a reflector was set close to true north from camera location P3 and surveyed to obtain the position of (5000.000, 3027.191, 1000.697). With a base point and a “north bearing,” the ground control, various targets, and camera locations were obtained. At a

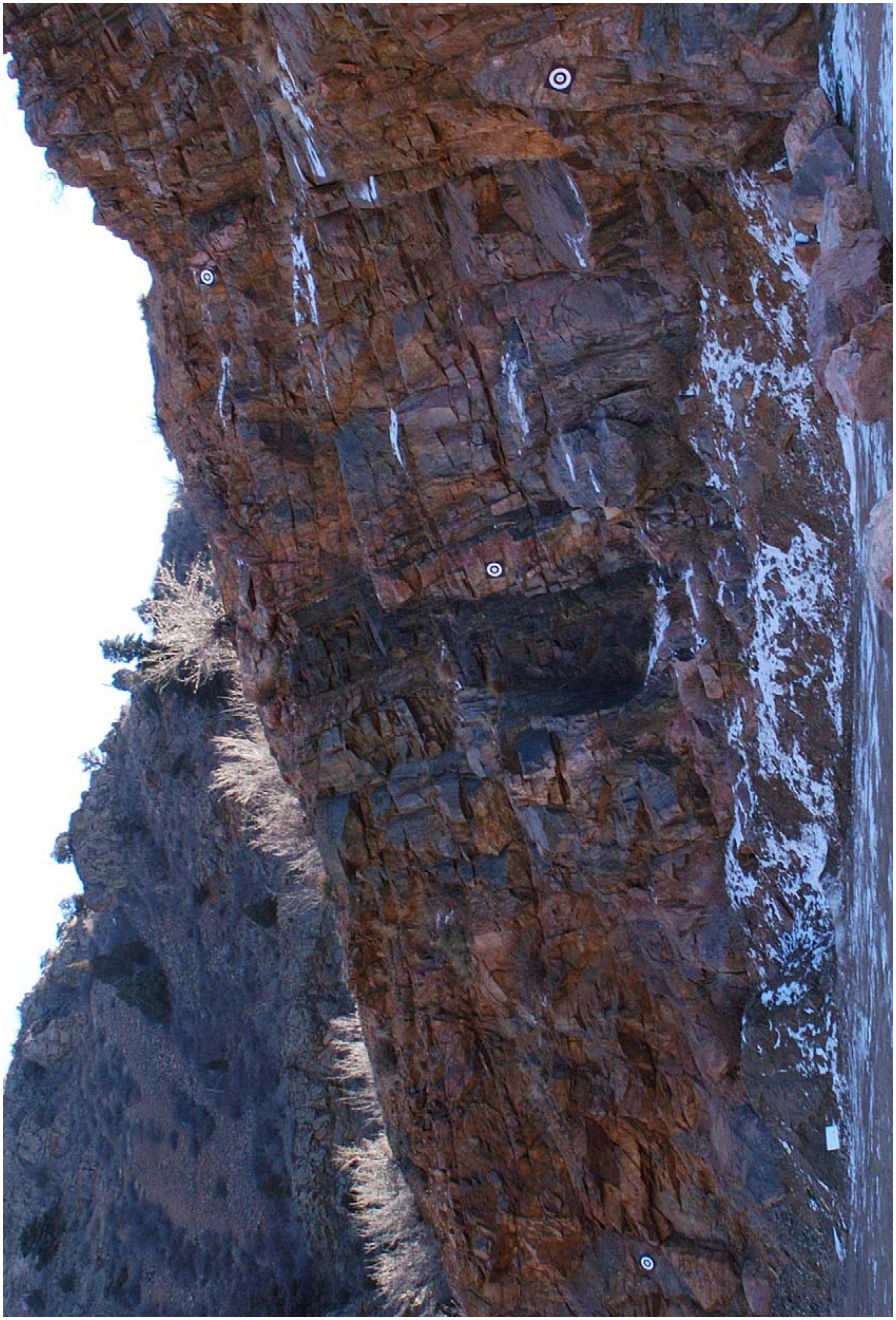


Figure B1.—Morrison Test Site rock outcrop with four targets to evaluate photogrammetry systems. Targets from left to right are T1, T2, T4, and T3.

Figure B2.—Closeup of Target T2 and blocky nature of rock.

later time, the correct true north was obtained using a Brunton set at 12 degrees declination and the original survey points were corrected for the difference between the guessed north bearing and true north. We found that the assumed north was 3 degrees east of north, so the points required a 3-degree counterclockwise rotation about the base. Table D2, Appendix D provides the original survey coordinates, the rotation spread sheet correcting for true north, and the final (rotated) survey coordinates. Targets are marked as T1, T2, etc., and camera positions are P1, P2, etc. After surveying all the required positions, a return to the back site (BS-1) was used to check for survey error. The northing dimension showed the largest error on return at 0.035 m, or 3.50 cm. Taking in the difference for all dimensions, the survey error could be +/- 3.55 cm (1.40 inches).

Data from Digital Camera and SiroVision Software (by Reclamation)

Before Vexcel (using Foto-G software and digital camera) or I-Site (using I-SiTE Studio software and RIEGL scanner) visited the site, images were collected for SiroVision processing. A Nikon D100 with telephoto lenses ranging from 20 mm to 105 mm was used to collect images. Two sets of images were taken with distances between the camera locations and the rock face of 45 meters and 80 meters. Surveyed locations of one target on the face and the two camera positions were used to orient the point cloud data to the local coordinate system. All processing was done by the research group. The locations of the five joint planes used by Vexcel were noted for comparison. SiroVision camera positions were not selected to achieve high accuracy for the planes later chosen by Vexcel because this was not the primary goal of this first step of the evaluation.

Data from RIEGL Laser Scanner and I-SiTE Studio Software (by I-Site)

The scanner used by I-Site was the RIEGL LPM-800 HA. Its accuracy at 100 m is believed to be 17 mm (+/-15 mm plus 20 parts per million [ppm]). Two scans were taken to decrease the shadow effects from the face relief. Surveyed locations of several targets and the two scanner positions were used to orient the point cloud data to the local coordinate system. I-Site processed the scan data using their I-SiTE Studio software and provided the resulting 3D data to the research group. From this data, the orientations from the five planes were extracted by Joe Kottenstette using AutoCAD.

Data from DigitalFoto-G Software (by Vexcel)

When Jason Szabo, from Vexcel, visited the site, the targets were not set up, but most, if not all, bolts were visible. Orientations of resulting 3D data to the local coordinate system were established using the surveyed locations of the four targets. Knowing the locations of the camera positions is not required. Szabo collected and processed the images to produce 3D point cloud data. The camera and lens used by Vexcel are not known. Photos were taken in the parking area in front of the rock face; therefore, the distance between the camera location and rock face was less than 45 meters. At a later time, the software was demonstrated to show how plane orientations could be derived from the 3D point data using AutoCAD as a companion application. The spatial locations of the bolts were not provided by Vexcel, but the orientations from five faces were extracted and provided to the research team. Later, these five planes were located using the LIDAR and SiroVision systems.

Results and Discussion of Accuracy Evaluation

Spatial Accuracy

Since the targets were present only when SiroVision images were being collected, only SiroVision spatial data can be presented. The spatial accuracy examination compares the target coordinates measured using survey and SiroVision software. Table B1 provides the three coordinates of the four targets found by the two methods. It is assumed that the survey data are correct, so any deviation of the SiroVision data from this baseline is considered to be SiroVision spatial error. The average error of the three dimensions for the four targets is 2.63 inches. The z-coordinate of Target T2 had the lowest error, 0.006 meter (0.24 inche). This target was also the face control used by SiroVision for the image pair. The largest error was the x-coordinate for Target T3 at 0.188 meters (7.4 inches). There are many factors that influenced the error, but the largest source in this case is probably incorrectly defined camera position coordinates. To find the northing and easting coordinates of the camera location, a plumb bob is dropped below what is believed to be the center of the camera sensor plate. A short section of rebar is hammered into this position. The problem with this method is that the camera tripod was in the way of the plumb bob drop, so locations were estimated. The estimation of the camera position may add as much as 1 inch of error to the final survey data. The elevation coordinate of the camera sensor plate is the distance, to within ½ centimeter (about ¼ inch), it sits above the ground, as measured using a tape measure. Again, error can also occur getting this measurement because the camera tripod is in the way. To reduce the camera coordinate position error, a camera mount was designed and built that would allow the camera to be placed on a surveyor tripod equipped with a tribrach. The design is shown in Appendix E. The tribrach will significantly improve the accuracy of the camera ground position, and the camera mount is designed to always keep the center of the camera sensor plate directly above the staked ground position. This will reduce the error in finding the height of the camera. In summary, the combination of using a survey tripod, tribrach, tribrach adapter, and camera mount should improve the accuracy and speed of obtaining the camera position locations. This setup has, however, not been tested.

Table B1.—SiroVision and survey spatial data for Morrison Test Site

Morrison Test Site

Location/Target ID	**x-camera's horizontal (m)**	**x-camera's elevation (m)**	**z-camera's depth (m)**	**Data source**
T1	5042.880	3005.959	1002.882	Survey
	5042.843	3006.082	1002.833	Siro3D
	0.037	0.123	0.049	Difference (m)
T2 (control point)	5037.774	2989.879	1006.037	Survey
	5037.808	2989.851	1006.043	Siro3D
	0.034	0.028	0.006	Difference (m)
T3	5024.501	2983.757	1003.513	Survey
	5024.313	2983.897	1003.493	Siro3D
	0.188	0.140	0.020	Difference (m)
T4	5039.375	2982.982	1012.997	Survey
	5039.403	2982.911	1013.076	Siro3D
	0.028	0.071	0.079	Difference (m)
	0.072	0.090	0.038	Average coordinate magnitude error (m)
	2.82	3.56	1.52	Average coordinate magnitude error (inches)
	2.63			Average magnitude error (inches)

Orientations Comparisons using RIEGL, Foto-G, SiroVision Point Cloud Data

The following tables, B2 to B6, and figures B3 to B7 summarize the RIEGL, two photogrammetric (Foto-G and SiroVision), and Brunton orientation results from the Morrison Test Site. Five joint faces were selected for orientation calculations. These planes were somewhat arbitrarily selected by Vexcel because they were not familiar with the previous image areas used for evaluating SiroVision. Some bias was inadvertently inserted because these five planes were chosen based primarily on the point density in the Vexcel results. It is doubtful that Vexcel, or any of the vendors, would choose to examine an area where little data exists. The set of SiroVision images previously obtained that had these planes present were taken at 80 meters from the rock face using a 35-mm lens. This distance and zoom grouping is not ideal for the smaller block sizes analyzed and does not provided enough 3D point density within the small joint faces to be accurate.

The five selected joint faces were named joints A, B, C, D, and E. These faces, excluding face C, which is off the image to the left, are shown in Figure B4. Tables B2 to B6 list the orientation data from the various sources, along with the number of 3D points used to calculate the plane and the root mean square (RMS). The smaller the RMS, the closer the points were to the best-fit plane. With the exceptions of joints D and E, Brunton measurements were obtained by placing the Brunton on the face of interest. Only one Brunton reading was obtained using a position that appeared to be typical. Joints D and E were too high to physically reach, so readings were obtained by line of sight; hence, the large range in dip and dip direction.

Table B2.—Orientation results for plane A at Morrison Test Site

Joint A				
Method	**Dip (degrees)**	**Dip direction (degrees)**	**Number of points**	**Root mean square, RMS**
RIEGL	73.2	307.7	3934	0.0164
Foto-G	74	308.3	356	0.0080
SiroVision	74.2	317.4	59	0.0054
Brunton	73	310	1	NA
SiroVision did not capture the entire joint face that RIEGL and Vexcel used to derive their orientations. A small subset was used (note the low number of points), but this area is also at the image edge where distortion is worst. These are two possible reasons for difference in the SiroVision orientation compared to the other two systems.				

Table B3.—Orientation results for plane B at Morrison Test Site

Joint B				
Method	**Dip (degrees)**	**Dip direction (degrees)**	**Number of points**	**Root mean square, RMS**
RIEGL	34.3	338.1	2470	0.0277
Foto-G	34.4	338.7	364	0.0294
SiroVision	34.9	335.9	~240	0.0021
Brunton	35	337	1	NA

Table B4.—Orientation results for plane C at Morrison Test Site

Joint C				
Method	**Dip (degrees)**	**Dip direction (degrees)**	**Number of points**	**Root mean square, RMS**
RIEGL	64.5	222.5	134	0.0219
Foto-G	63.3	229	106	0.0263
SiroVision	64.2	224	9 (trace)	NA
Brunton	64	232	1	NA
This face was not observable in the SiroVision image. Only the edge could be seen, so a trace line containing nine data points was used to define the orientation of this plane. The RMS is not provided by SiroVision for planes defined by trace data points.				

Table B5.—Orientation results for plane D at Morrison Test Site

Joint D				
Method	**Dip (degrees)**	**Dip direction (degrees)**	**Number of points**	**Root mean square, RMS**
RIEGL	69.3	203.6	836	0.0158
Foto-G	68.7	204.4	5680	0.0093
SiroVision	70.3	202.3	~300	0.0025
Brunton	65 - 75	205 +/- 10	1	NA

Table B6.—Orientation results for plane E at Morrison Test Site

Joint E

Method	**Dip (degrees)**	**Dip direction (degrees)**	**Number of points**	**Root mean square, RMS**
RIEGL	84	195	236	0.0251
Foto-G	76	198	32	0.0145
SiroVision	82.8	12	38	0.0021
Brunton	80 - 85	195 +/- 10	1	NA

The point clouds were selected over a non-planner area. This poor selection created wild results on this plane. The images were re-evaluated, points reselected, and orientations recalculated. The residuals were not available for the new plane fit.

The stereonet in figure B3 summarizes the orientations for each plane and for each system, with a couple of exceptions. The SiroVision orientation for planes A and E was removed based on the following justifications. Plane A was only captured in part and at the extreme edge of the image. Data at the photo edges are influenced by lens distortions, making the results less reliable. The face of plane E was too small for the lens (35 mm) and the distance (80 m) between the camera and outcrop used by SiroVision. Had it been known before the images were obtained that this small plane would be used in the evaluation, the camera positions would have been placed closer or a more powerful telephoto lens (such as 105 mm) would have been used.

Of the data that remain, the pole clusters are quite tight, indicating that any system would provide sufficiently accurate orientations. Notable is that the three large faces (planes A, B, and D) have the tightest clusters. This shows the intricate relationship between the face dimensions of interest and the image capture art and technology—the camera resolution, the lens magnification, the distance and line-of-sight bearing to the objective, and the camera baseline.

For the LIDAR and Foto-G point data, two plane fitting methods were used: least squares estimate and minimum bias estimate. The estimation methods did not result in significant differences in the residuals (average distance between each point and the plane) in most cases. The residuals, or root mean square (RMS), are provided in tables B2 to B6. The residuals were within a few 1/100 of a meter between the RIEGL laser data and the Foto-G data for planes B and C. The RIEGL laser data are slightly better for planes B and C. However, the residuals for planes A, D, and E from the Foto-G data were smaller than for the RIEGL data. Residuals for the SiroVision data are provided internally during the mapping process, when the plane orientations are displayed or can be exported as a text file.

One must be very cautious when interpreting the RMS values. As an example, SiroVision has the lowest residual of the three methods when comparing the plane E results, but the SiroVision orientation is very likely incorrect. The residual shows the scatter of the points about the best fit plane. This is the precision of the data to the assumed plane, but in the case of SiroVision plane E, the assumed plane orientation is not accurate. The residual of these same SiroVision points to any of the more accurate planes derived by the other methods would have indeed been very high. Another factor that must be considered for the residual to be meaningful is the number of data points used to derive the best-fit plane. The more data points, the more confidence one can place in the validity of the value.

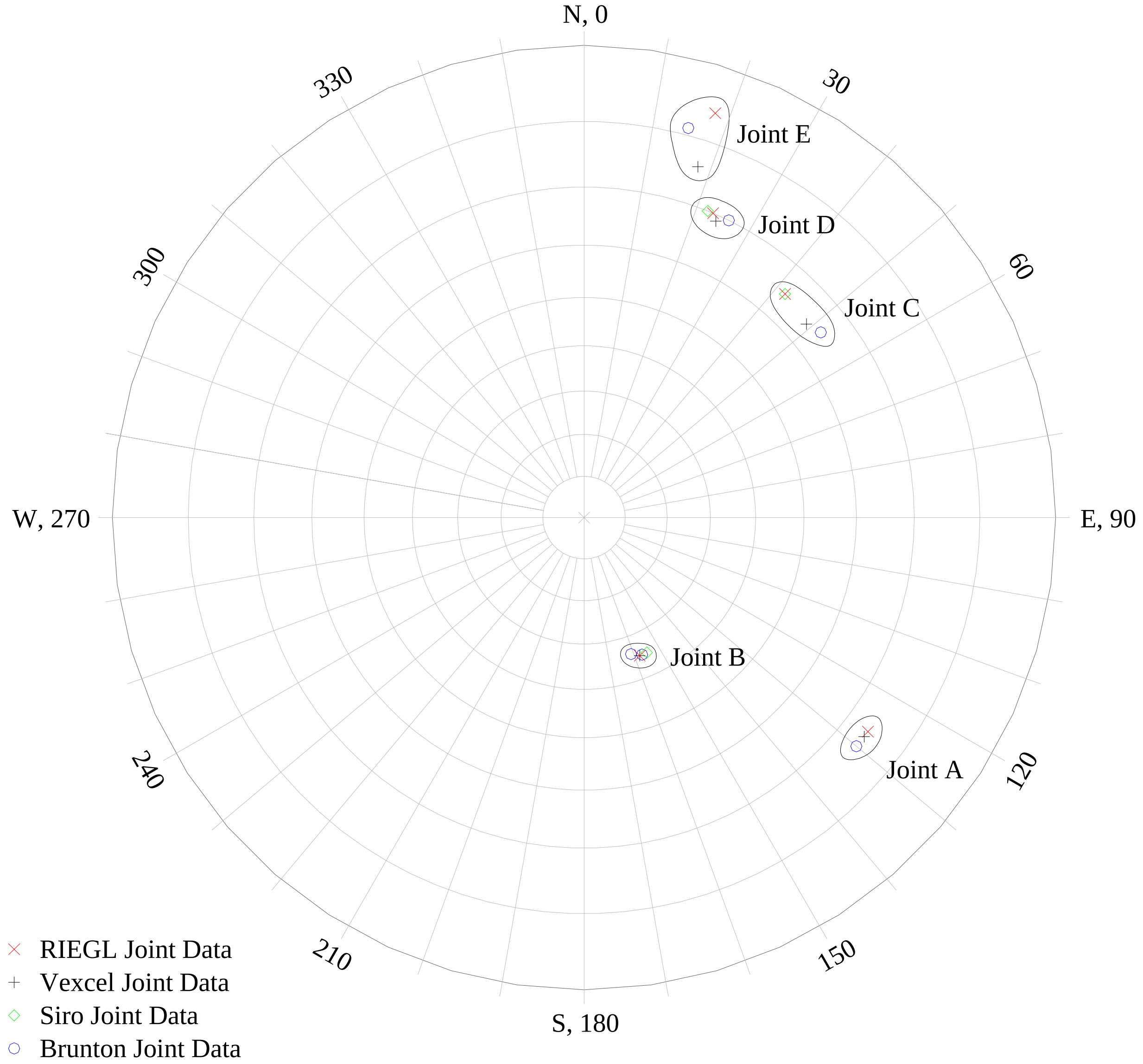


Figure B3.—Stereonet showing normal poles for planes A to E of REIGL, Vexcel, SiroVision results.

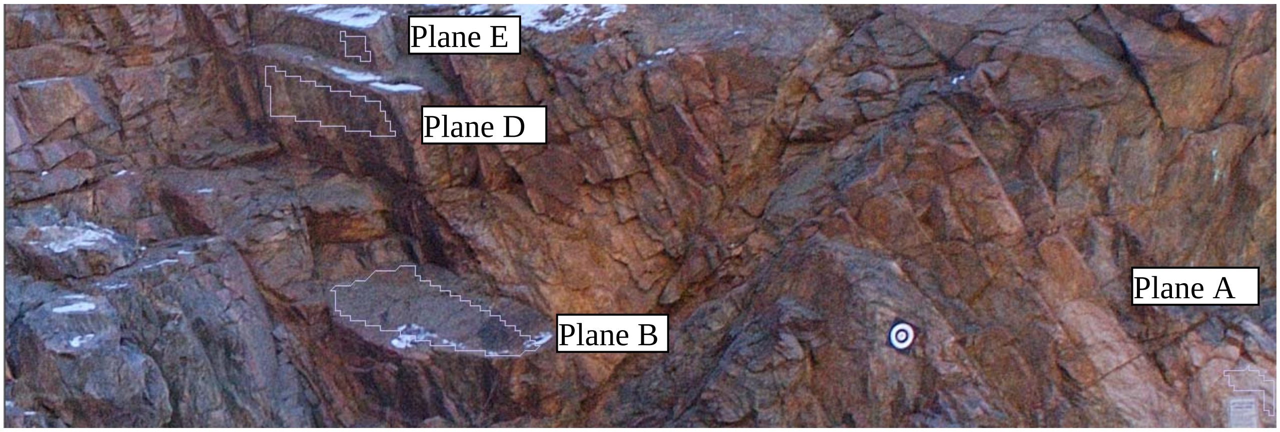


Figure B4.—Example of SiroVision Mapping Boundaries for Planes A, B, D, and E.

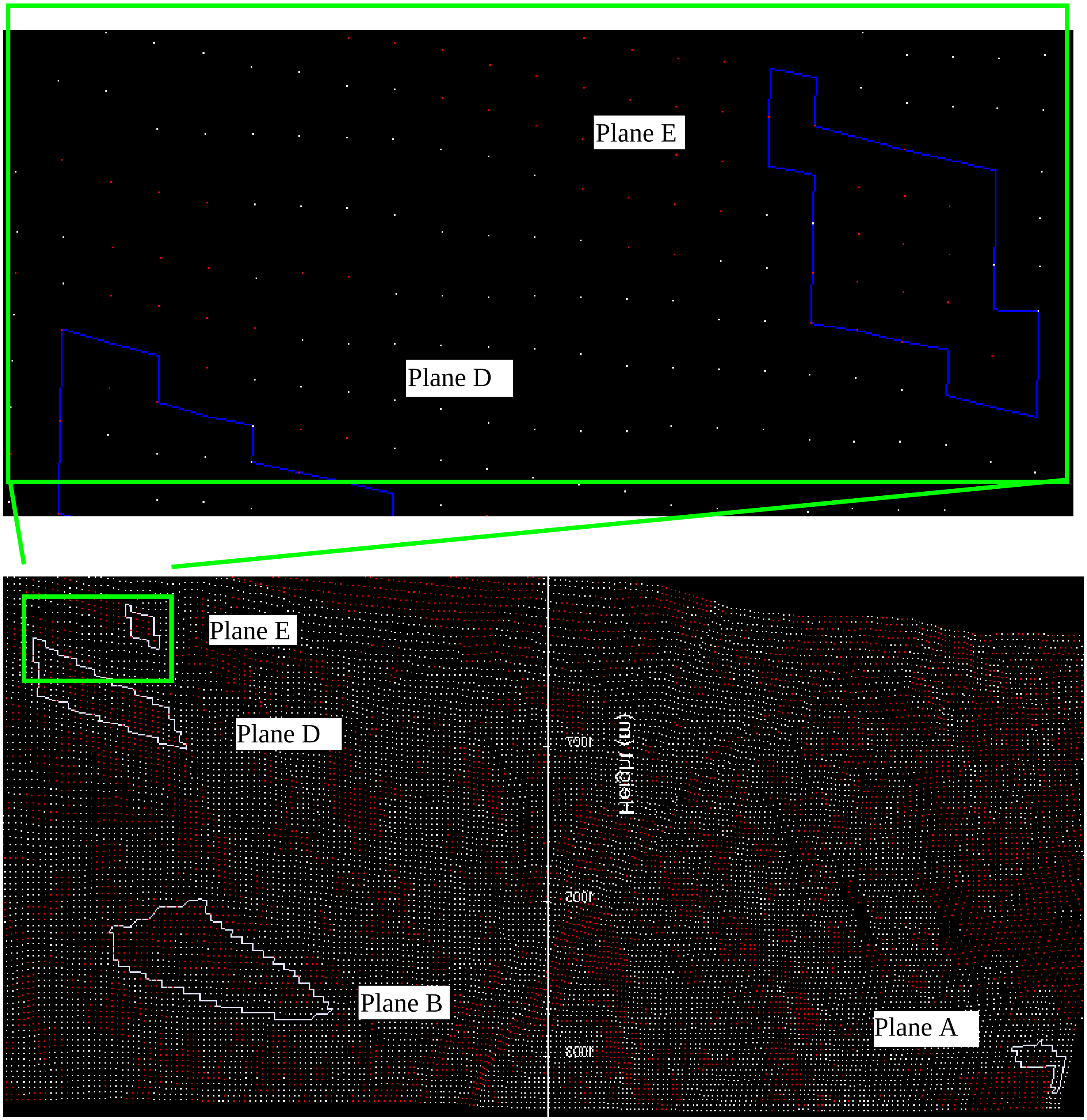


Figure B5.—SiroVision point cloud data of large outcrop area at Morrison Test Site (bottom) and enlargement of insert (top).

What this orientation comparison shows is that each 3D-imaging technique has the potential of providing very accurate orientation data. The trick is how to recognize bad data. The methods of recognizing bad data will depend on the program. In general, however, one should first question whether enough points are available on the plane for the RMS to be valid. If there are not enough points in the plane of interest, the cameras should either be placed closer to the feature or a higher power lens should be used.

In SiroVision, a 3D image of the point cloud data is available that differentiates between the good and the questionable points. A closeup of the 3D point cloud and plane E is shown in figure B5. Potentially bad points are shown as red. Good points are white on a black background. Notice how plane E, for which SiroVision did not provide an accurate orientation, has no good data points within the plane. On this basis alone, the orientation must be questioned. To get good data for this rather small face, the distance between the cameras and the object of interest should be decreased or a higher power lens should be used. It may be feasible to process the images while in the field and verify that the point cloud density is high enough to map the smaller faces of interest.

To make this a more rigorous test of comparable accuracies between the 3D data collection systems, more control should have been placed on the systems and the data collection method. The following suggestions are made in the event a second test is considered:

- Predetermine the faces and traces to be analyzed before collecting any field data.

- Keep the cameras at a constant distance from the outcrop and use the same camera and telephoto factor for all photogrammetry applications.

- Keep track of field data collection and data processing times and keep them separate.

The plots of the test site joint data were evaluated, and the following important visual observations are provided. Figure B6 shows the point clouds from Foto-G, RIEGL, and SiroVision and the boundaries and relative positions for all five planes. Figures B7 through B11 show each plane individually. The top drawing in each figure shows the view looking perpendicular to the plane. The bottom drawing portrays the edge view that would be seen looking along the strike of the plane.

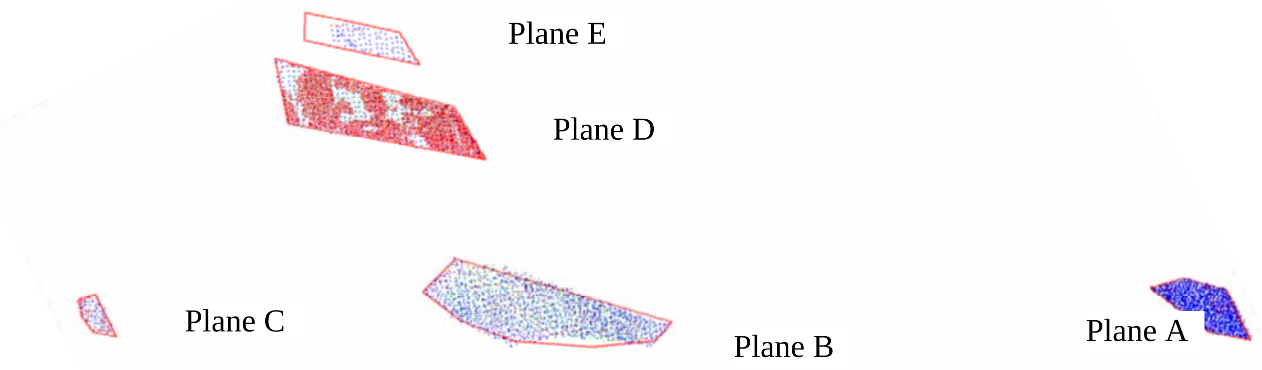


Figure B6.—Relative positions of the five planes evaluated with SiroVision, Foto-G, and LIDAR.

A - Joint Visual Observations (Figure B7)

The large, green and red reference circles shown in figure B7 are each 2 meters in diameter. The circles are perpendicular to each other so that when one is shown on edge, the other shows as a perfect circle. The data is in a band about 0.8 meter wide.

The RIEGL (in blue) data points are the densest; however, they have the most scatter.

The Foto-G data (in red) is sparse and not well distributed in the true size view. However, this set does have dense patches of points at the extremes of the area and, therefore, will provide strong orientation results as long as the points are on the surface. The edge view shows that the Foto-G points are all contained inside the RIEGL point cloud, except for one point.

The SiroVision (in green) data is well distributed over the plane; however, the density is the lowest of the three sets. The edge view shows a scatter similar to that of the RIEGL data and that the SiroVision data is shifted to one side. This data is suspect because it is shifted in location from the other two sets. The dip and dip direction do compare well to the other sets, so a translation or a mild stretch in the SiroVision data must exist.

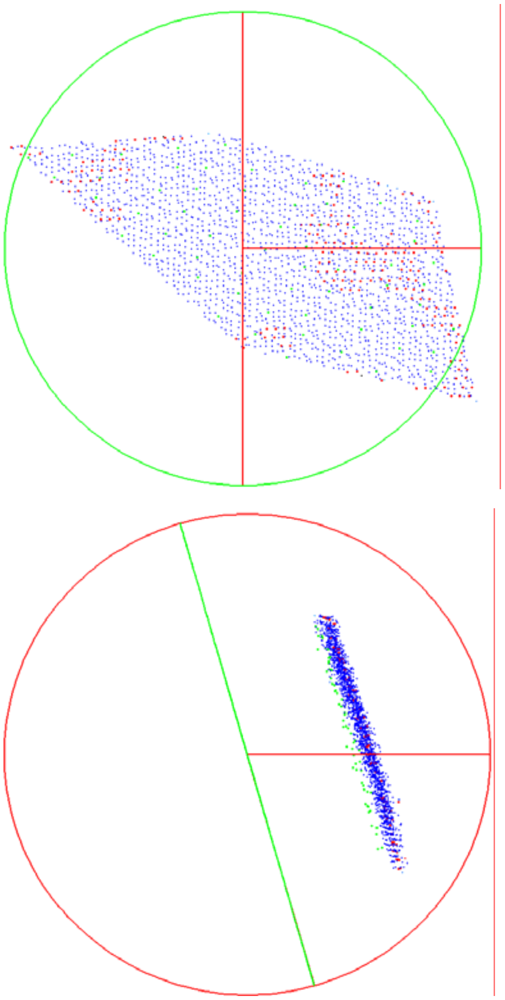


Figure B7.—SiroVision (green), Foto-G (red), and RIEGL (blue) points for plane A, looking normal (top) to the plane and on edge (bottom).

B-Joint Visual Observations (Figure B8)

The three sets of data are very close. The RIEGL data is the densest and covers the largest area. The SiroVision data is the second densest. The RIEGL and Foto-G data give dips and dip directions that are closer to each other than to the sets given by the SiroVision data.

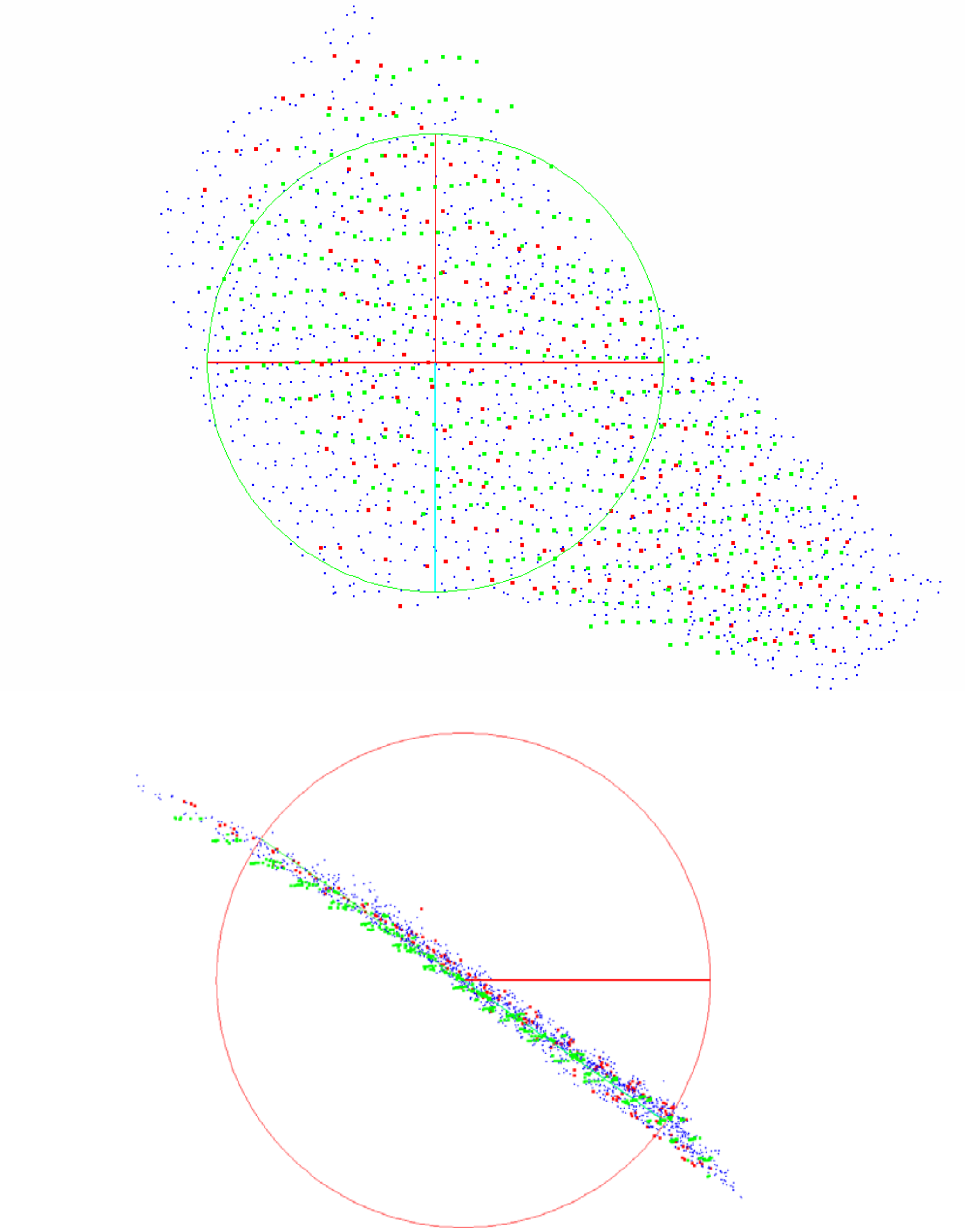


Figure B8.—SiroVision (green), Foto-G (red), and LIDAR (blue) points for plane B, looking normal (top) to the plane and on edge (bottom).

C-Joint Visual Observations (Figure B9)

This joint is the smallest of the set. The pattern covers about 1/8 of the 2-meter reference circle. The narrow width is slightly larger than the E-joint at 1/3 meter. The scatter is about the same for both sets (RIEGL and Foto-G). Point cloud data was not available from the SiroVision model on this joint because the face was almost parallel to the line of sight of the SiroVision cameras. These data are the weakest of the five joints. The data can be improved in this location by taking more photos or selecting more tie points near this feature or both. Adding additional tie point is a processing feature in the Foto-G and ShapeCapture products. It does not require more field work, just more processing time.

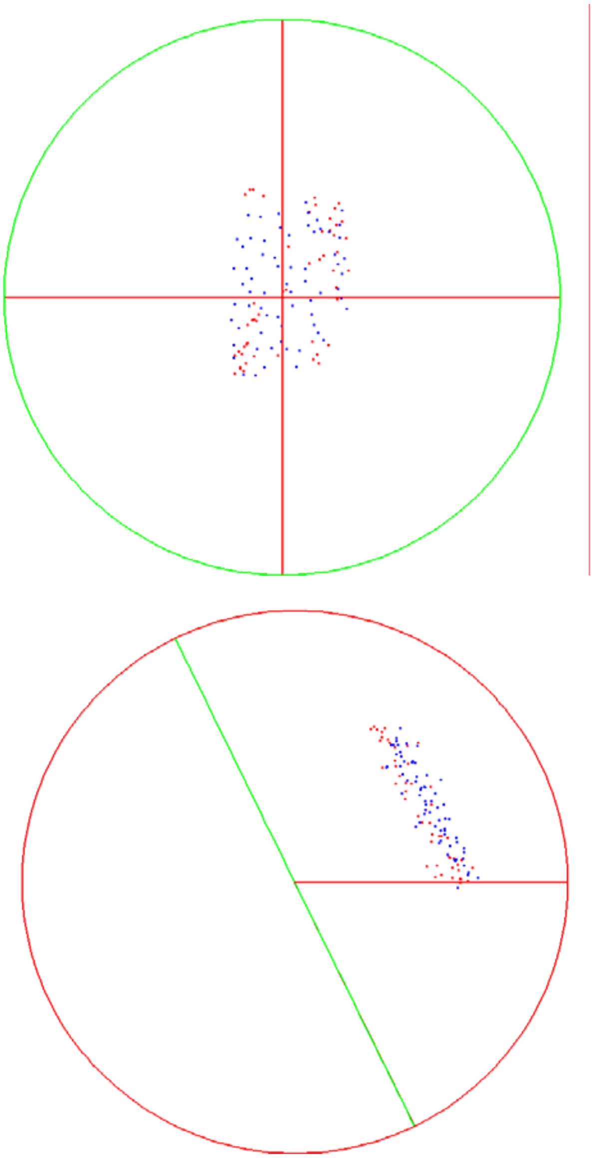


Figure B9.—Foto-G (red) and RIEGL (blue) points for plane C, looking normal (top) to the plane and on edge (bottom).

D-Joint Visual Observations (Figure B10)

The edge view of this data shows a clear shift in location for all three sets. The densest point set is from the Foto-G data (in red). The top image (normal to the points) shows that some areas are not covered by the Foto-G data. These blank areas result from the images not being defined well enough to get convergence from multiple sets of photos. The shift in location can result in significant differences in volume calculation; however, the joint orientation data are not as adversely affected.

These data cover an area about 3.5 meters by 1 meter. The edge view shows the point cloud pattern to be very tight on the Foto-G data. The RIEGL data also have a tight pattern. The SiroVision pattern is also tight but is the most varied of the three and has a lower point density.

The lower point density can affect the accuracy of the orientation results of the SiroVision joint program.

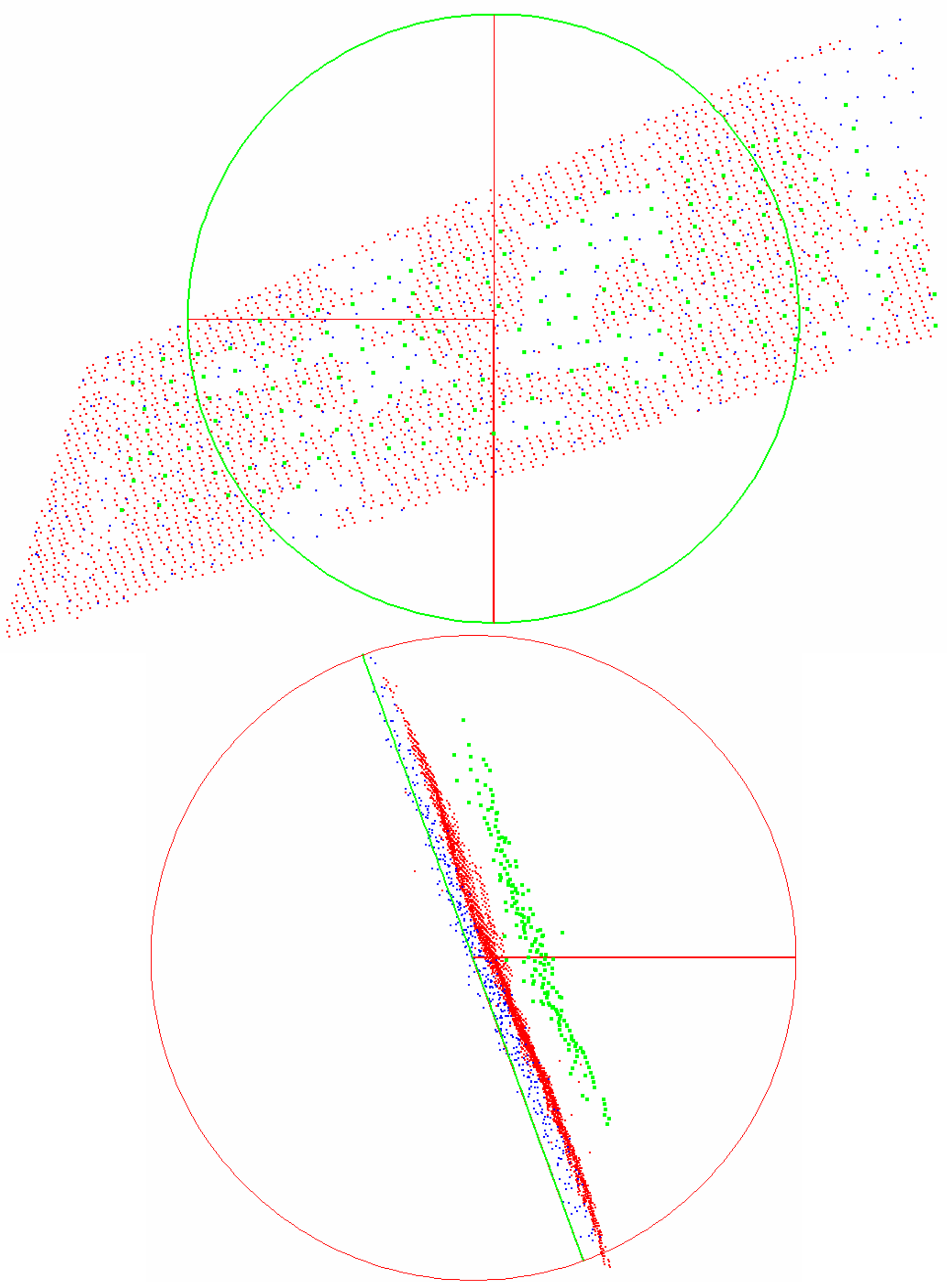


Figure B10.—SiroVision (green), Foto-G (red), and LIDAR (blue) points for plane D, looking normal (top) to the plane and on edge (bottom).

E- Joint Visual Observations (Figure B11)

The reference circle is 2 meters. These data are in a narrow band about 1/3 meter wide.

The RIEGL (in blue) data is the densest; however, it has the most scatter.

The Foto-G data is sparse and not well distributed when looking normal to the point set. However, this set does have points at the extremes of the area and, therefore, will provide strong orientation results as long as the points are on the surface.

The SiroVision data are well distributed over the plane and in a tighter pattern than the RIEGL data; however, the data are suspect because the points are shifted in location from the other two sets and the dip and dip direction do not compare well to either of the other sets. Also, the joint is near the perimeter of the SiroVision joint stereo model (an unreliable location for that system). This could be overcome by ensuring that important features are not located near image boundaries when obtaining field data.

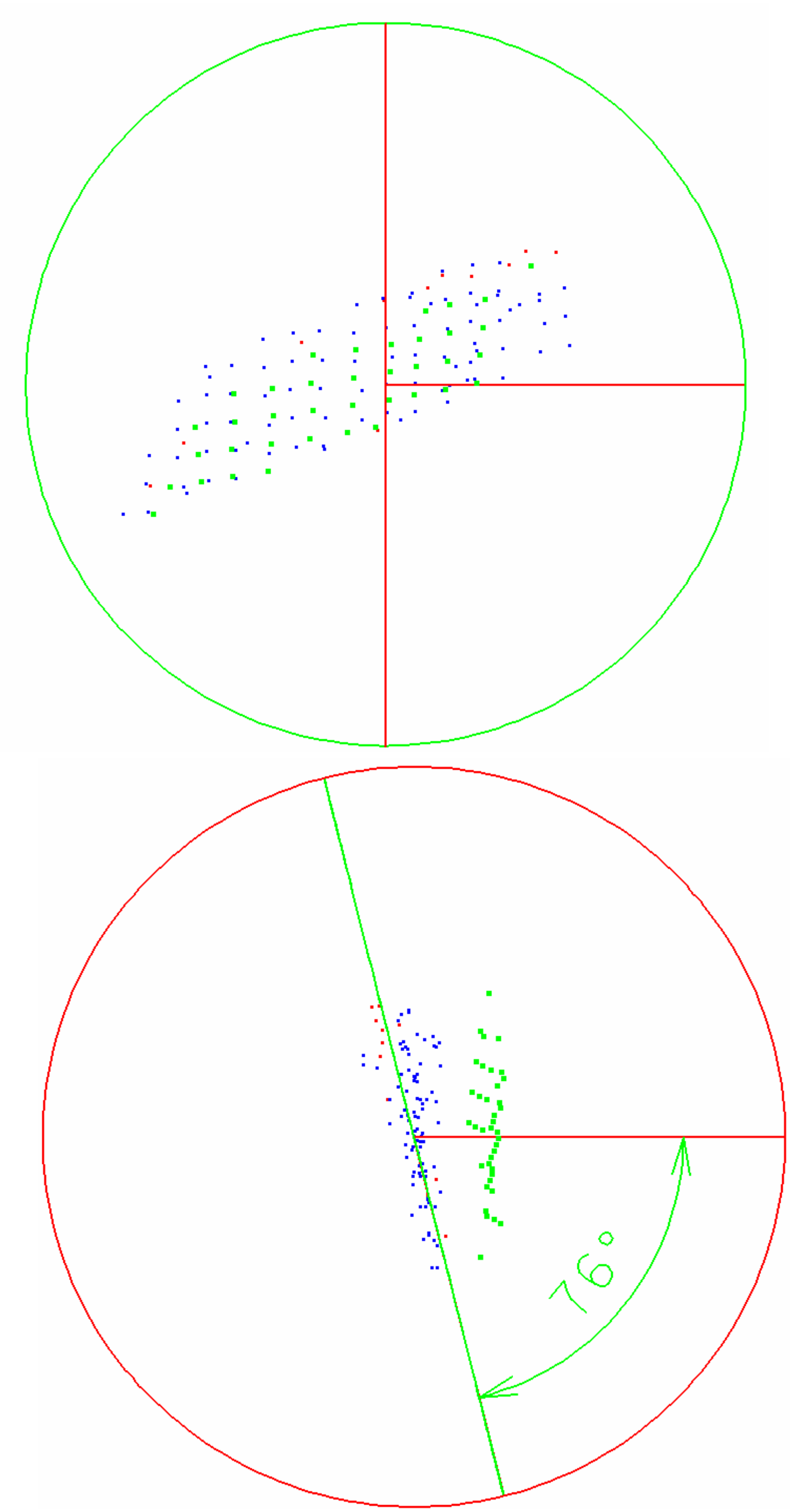


Figure B11.—SiroVision (green), Foto-G (red), and RIEGL (blue) points for plane E, looking normal (top) to the plane and on edge to the Foto-G and LIDAR data (bottom).

Appendix C

Lafarge Open Pit Mine Photogrammetry Mapping Using SiroJoint

Objective

LaFarge Mine, in Golden, Colorado, allowed access of their property to a group of Colorado School of Mines students to learn how digital photogrammetry may be used for open pit design.

Project Layout and Data Acquisition

The TSC photogrammetry research group collaborated with Dr. Ugar Ozbay from the Colorado School of Mines during the discovery and evaluation phases. Dr. Ozbay is the professor of the Open Pit Slope Design course (Spring 2003) in the Mining Engineering Department under the Engineering Division. SiroVision was the tool of choice of Dr. Ugar Ozbay because of its reasonable cost (free academic evaluation) and ease of use. Surveying of camera location, control points, and targets was conducted by two of the students, using a reflectorless total station. A local coordinate system using meters and aligned to true north was established. Because of rock fall hazards, Brunton measurements were supplied by the LaFarge Mine personnel. Students were not allowed within 50 feet of the face. The Brunton and survey target locations were compared to the SiroVision results to evaluate orientation and spatial accuracy. Figure C1 shows the face of interest with the two spray-painted targets (one used as control). The target numbers were about 10 inches high, for scale. The face, in general, is highly fractured.

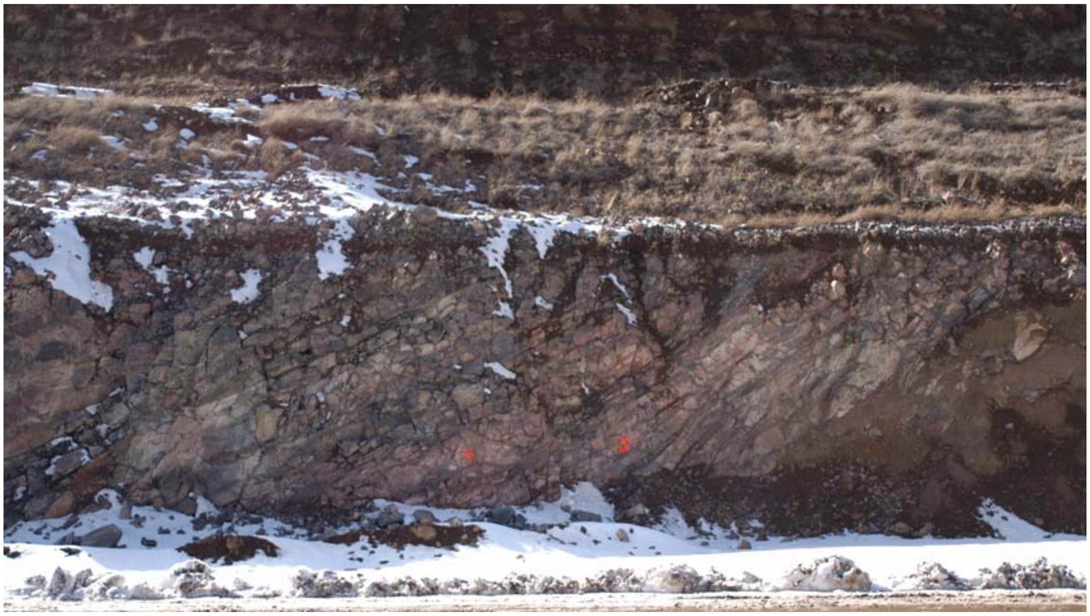


Figure C1.—Highly fractured LaFarge open pit excavation face with steeply dipping slope.

Results and Discussion of Accuracy Evaluation

Spatial Accuracy Results

The two targets, painted onto the face, were used to examine differences in survey and SiroVision spatial accuracy. Target 4, T4, was also used as the face control. Survey data are assumed to be the more accurate; thus, they are the baseline for comparison. The possibility that survey data are in error should also be considered. Table C1 shows the survey and SiroVision spatial results and the differences between the two data sources for each target. First, the magnitude difference in length between the data sources for each coordinate is found (T4 and T5 difference). Then, the average coordinate magnitude error is calculated, in meters, and also converted to inches. These three coordinates (x, y, z) are averaged to find the SiroVision error for the LaFarge site, 0.72 inche.

Table C1.—Survey and SiroVision coordinates of the two targets on the excavated slope face at LaFarge Mine

Target ID	x coordinate (camera's horizontal) (meter)	y coordinate (camera's elevation) (meter)	z coordinate (camera's depth) (meter)	Data source
T4 control point	1491.636	1536.591	31.458	Survey (m)
	1491.671	1536.570	31.455	Siro3D (m)
	0.035	0.021	0.003	T4 Difference (m)
T5	1491.097	1541.239	31.852	Survey (m)
	1491.102	1541.214	31.872	Siro3D (m)
	0.005	0.025	0.020	T5 Difference (m)
	0.020	0.023	0.012	Average coordinate magnitude error (m)
	0.79	0.92	0.46	Average coordinate magnitude error (inches)
	0.72			Average magnitude error (inches)

Spatial Accuracy Discussion

Of the three sites that SiroVision used (East Canyon, Morrison, LaFarge), this site showed a significant improvement in spatial accuracy. In obtaining the camera locations, there were many students that verified the camera positions. Errors in this variable have the greatest effect on spatial accuracy.

Orientation Accuracy Findings

A total of eight orientations of Brunton and SiroVision results were compared, as listed in table C2. The first set of column data are the LaFarge Brunton results, and the second and third columns of data were provided by two Colorado School of Mines students. Figure C2 highlights the locations of the eight white traces mapped onto the excavated face using SiroVision. The variations in dip for each orientation are not as spread out as the dip directions. The stereonet in figure C3 shows the three data sources as clusters 1 through 8 for each of the planes. Most noticeable is the spread in dip direction.

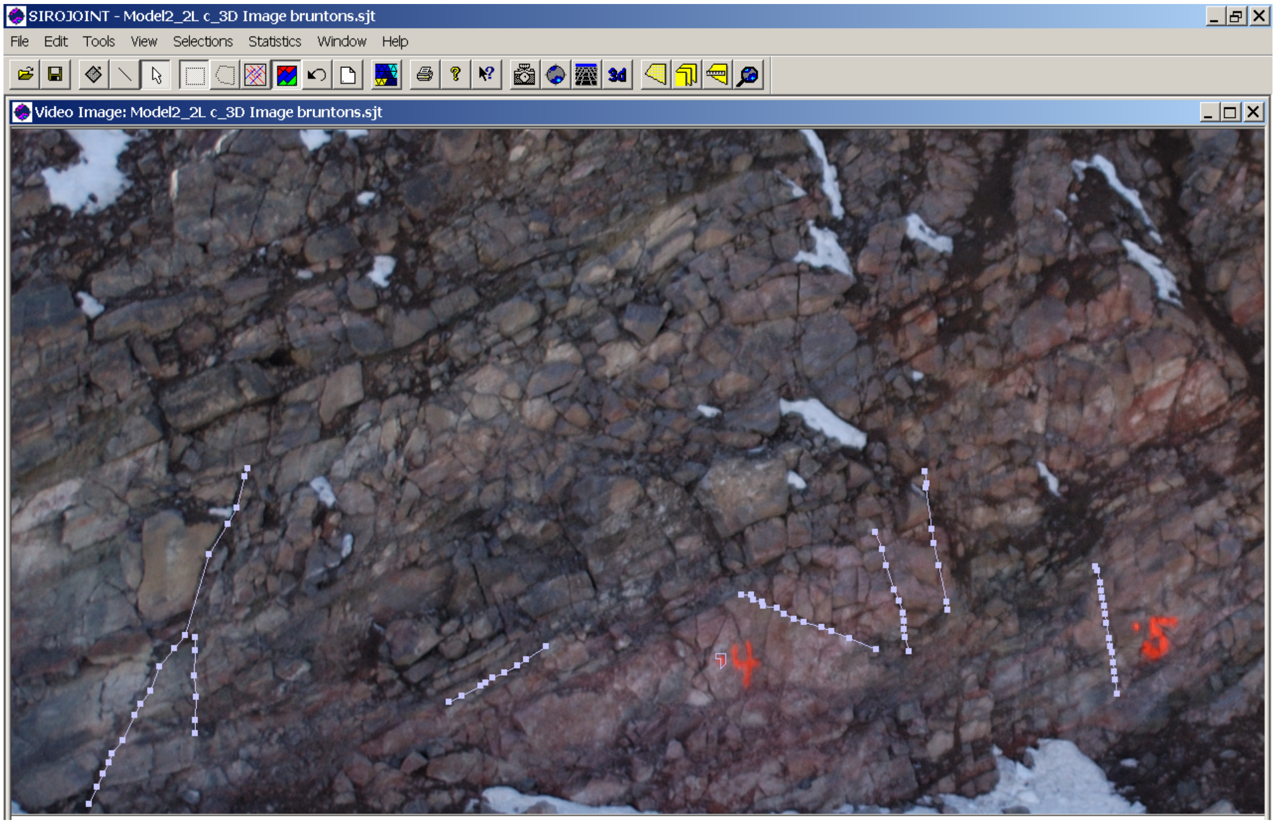


Figure C2.—Screen capture of SiroVision trace lines used to obtain joint orientations.

Table C2.—SiroVision and Brunton orientation findings for LaFarge Open Pit Mine

	LaFarge Brunton data		Student #1 SiroVision Data		Student #2 SiroVision Data		Range Difference	
Orienta-tion No.	**Dip (degree)**	**Dip Direction (degree)**	**Dip (degree)**	**Dip direction (degree)**	**Dip (degree)**	**Dip direction (degree)**	**Dip (degree)**	**Dip direction(degree)**
1	62	197	61	161	66	176	5	36
2	89	182	87	10	88	355	2	15
3	37	156	46	125	31	193	15	68
4	70	263	75	258	73	249	5	14
5	22	339	36	45	34	32	14	66
6	78	7	71	35	72	353	7	42
7	86	6	79	16	77	20	9	14
8	78	354	79	27	81	10	3	33
					Average:		7.5	36

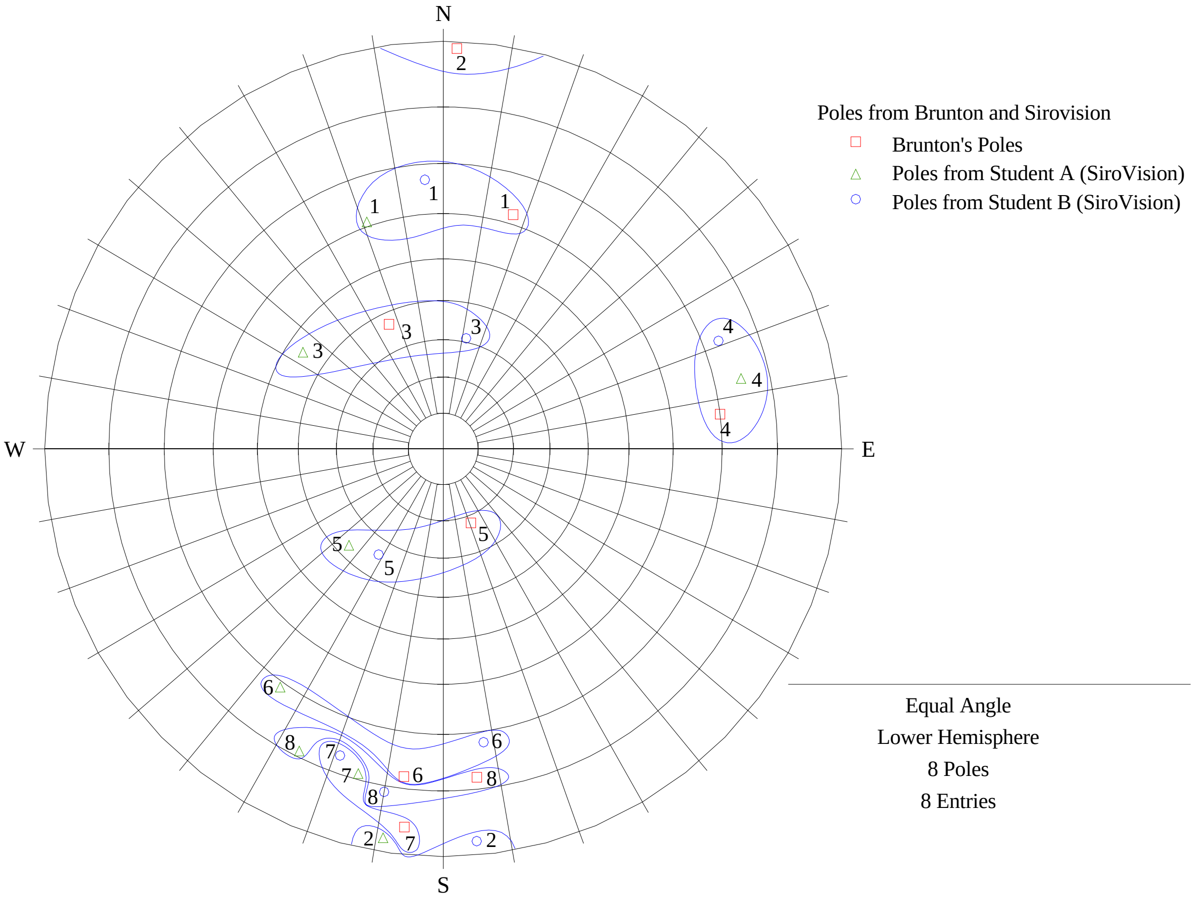


Figure C3.—LaFarge orientations of eight discontinuities using equal angle stereonet of plane oles.

Orientation Accuracy Discussion

There are several factors that could explain the variations in dip direction. For the Brunton measurement, which is probably the least accurate of the two data sources, it is very difficult to get a good dip and dip direction on a small block face, especially when only a portion of the block face is exposed. Also, only one location was used to get the orientations at this site. An average of Brunton readings can be made, but this is not often performed when speed and costs are issues. Variations in SiroVision dip directions probably occur because the points selected to define the trace line reside close to a straight line. That is, the points do not provide enough distance change in all three dimensions, and an infinite number of planes could decrease the line. This problem is similar to finding the orientation of a surface that is nearly horizontal. The smallest amount of waviness in the horizontal surface will send the poles of subsections of this surface around the entire azimuth. The dip will be consistent, but the dip direction will vary dramatically. To correct this problem, one could try to extend the trace line as far as possible. If this does not resolve the problem, mapping multiple traces along the same edge or crack and finding the center of the data cluster may be possible.

Appendix D

Survey Data for Morrison Test Site and East Canyon

Table D1
Survey Data for Left Upstream and Downstream Abutment, East Canyon Dam, Utah

Surveyed: November 11, 2002
Survey Data Provided by Provo, Utah, Office (Recorded by Duane Taylor, Checked by Dave Harris)
Refer to Photo 17, Appendix B for Locations on Image

Camera Locations, ft				Camera Locations, m			Camera Ht.
Northing	Easting	Elev.	Point ID	Northing	Easting	Elev.	m/ft
3494910.97	1612739.55	5720.70	us-1 (L)	1065248.86	491563.01	1743.67	1.485/4.872
3494922.59	1612709.91	5720.64	us-2 (r)	1065252.41	491553.98	1743.65	1.472/4.829
3494693.87	1612485.01	5715.75	dam1 (L)	1065182.69	491485.43	1742.16	1.470/4.823
3494712.75	1612494.34	5715.76	dam2 (R)	1065188.45	491488.27	1742.16	1.470/4.823
3494857.61	1612434.71	5618.84	ds photo2 (L)	1065232.60	491470.10	1712.62	1.420/4.659
3494863.99	1612413.39	5617.99	ds photo1 (m)	1065234.54	491463.60	1712.36	1.575/5.167
3494870.79	1612395.10	5616.10	ds photo3 (R)	1065236.62	491458.03	1711.79	1.445/4.741

Survey Point Locations, ft				Survey Point Locations, m		
Northing	Easting	Elev.	Point ID	Northing	Easting	Elev.
			Targets			
3494656.72	1612458.31	5715.12	T1	1065171.37	491477.29	1741.97
3494692.94	1612484.22	5715.05	T2	1065182.41	491485.19	1741.95
3494713.49	1612459.09	5515.92	T3	1065188.67	491477.53	1681.25
3494711.45	1612435.58	5515.30	T4	1065188.05	491470.36	1681.06
3494737.29	1612400.36	5517.53	T5	1065195.93	491459.63	1681.74
			T6 missed			
3494729.27	1612334.96	5516.00	T7	1065193.48	491439.70	1681.28
			T8 missed			
3494742.39	1612283.66	5509.61	T9	1065197.48	491424.06	1679.33
3494745.28	1612267.07	5507.37	T10	1065198.36	491419.00	1678.65
3494746.09	1612251.18	5508.10	T11	1065198.61	491414.16	1678.87
3494756.54	1612229.21	5505.45	T12	1065201.79	491407.46	1678.06
3494649.07	1612471.86	5714.20	T13	1065169.04	491481.42	1741.69

Table D2.—Rotation Spread Sheet for Morrison Test Site Survey Data Collected by Rich Markiewicz

An Excel spreadsheet was used to correct the point locations. It rotates the points as needed about a predetermined base point. It was used because an assumed north was used while collecting the survey data. Later, the true north was found to be 3 degrees counterclockwise of the assumed north.

1. Enter the Easting (x) and Northing (y) coordinate set around which the surveyed points will be rotated:

Location ID	Easting	Northing	
P-3	5000	3000	= rotation point (survey base point)

2. Enter the rotation value that the points are to move around the base survey location (as degrees; positive for cw, negative for ccw) (radians will be calculated by Excel):

Rotation (degrees)	Rotation (radians)
-3	-0.05236

3. Enter the Easting (x) and Northing (y) coordinates to be rotated (red values in second and third column below):

	Pre-rotated Coordinates				Resulting Rotated Coordinates		
Location ID	Easting	Northing	elev	Location ID	Easting	Northing	elev
LB-1	5031.749	3051.007	1005.746	LB-1	5029.036	3052.599	1005.746
C-1	5036.611	2983.368	1009.767	C-1	5037.431	2985.307	1009.767
C-2	5038.520	2988.316	1008.620	C-2	5000.000	3000.000	1008.620
C-3	5035.393	2983.453	1007.578	C-3	5036.210	2985.328	1007.578
C-4	5031.811	2981.519	1007.517	C-4	5032.735	2983.209	1007.517
C-5	5031.177	2982.524	1004.301	C-5	5032.049	2984.180	1004.301
C-6	5032.412	2983.580	1004.022	C-6	5033.227	2985.299	1004.022
C-5A	5032.235	2983.483	1003.563	C-5A	5033.055	2985.193	1003.563
C-5B	5032.238	2983.368	1003.562	C-5B	5033.064	2985.078	1003.562
C-5C	5032.189	2983.392	1003.445	C-5C	5033.014	2985.099	1003.445
C-5D	5032.192	2983.619	1003.463	C-5D	5033.005	2985.326	1003.463
C-4A	5033.135	2980.813	1007.519	C-4A	5034.094	2982.573	1007.519
C-4B	5032.778	2980.984	1007.459	C-4B	5033.728	2982.726	1007.459
C-4C	5033.046	2980.835	1007.452	C-4C	5034.004	2982.591	1007.452
C-4D	5033.125	2980.893	1007.677	C-4D	5034.080	2982.653	1007.677
C-3A	5035.419	2983.519	1007.677	C-3A	5036.233	2985.395	1007.677
C-3B	5035.339	2983.413	1007.673	C-3B	5036.159	2985.285	1007.673
C-3C	5035.367	2983.400	1007.524	C-3C	5036.187	2985.274	1007.524
C-1A	5036.530	2983.236	1009.744	C-1A	5037.357	2985.171	1009.744
C-1B	5036.571	2983.297	1009.747	C-1B	5037.395	2985.234	1009.747
C-1C	5036.501	2983.199	1009.742	C-1C	5037.330	2985.132	1009.742
C-1D	5036.518	2983.192	1009.790	C-1D	5037.348	2985.126	1009.790
C-1E	5036.555	2983.241	1009.793	C-1E	5037.382	2985.177	1009.793
C-2A	5038.626	2988.427	1008.663	C-2A	5039.179	2990.464	1008.663
C-2B	5038.537	2988.342	1008.653	C-2B	5039.094	2990.375	1008.653
C-2C	5038.536	2988.339	1008.577	C-2C	5039.093	2990.372	1008.577
C-2D	5038.646	2988.452	1008.590	C-2D	5039.197	2990.490	1008.590
C-2E	5038.573	2988.374	1008.582	C-2E	5039.129	2990.409	1008.582

Table D2 (Continued)
Rotation Spread Sheet for Morrison Test Site
Survey Data Collected by Rich Markiewicz

	Pre-rotated Coordinates				Resulting Rotated Coordinates		
Location ID	Easting	Northing	elev	Location ID	Easting	Northing	elev
L-1A	5040.401	2987.873	1010.997	L-1A	5040.980	2990.004	1010.997
L-1B	5040.400	2987.806	1010.993	L-1B	5040.983	2989.937	1010.993
L-1C	5040.318	2987.747	1010.980	L-1C	5040.904	2989.874	1010.980
L-1D	5040.211	2987.484	1011.012	L-1D	5040.811	2989.606	1011.012
L-1E	5040.146	2987.215	1011.040	L-1E	5040.760	2989.334	1011.040
L-1F	5040.078	2987.027	1011.053	L-1F	5040.702	2989.142	1011.053
L-1G	5040.028	2986.871	1011.067	L-1G	5040.660	2988.984	1011.067
L-1H	5039.911	2986.704	1011.084	L-1H	5040.552	2988.811	1011.084
LID-INST	5011.881	2988.640	999.704	LID-INST	5012.459	2989.277	999.704
P1	4998.255	2993.029	999.986	P1	4998.622	2992.947	999.986
P2	4999.387	2996.944	1000.042	P2	4999.548	2996.916	1000.042
P3	5000.000	3000.000	1000.000	P3	5000.000	3000.000	1000.000
P4	5011.811	3016.429	999.688	P4	5010.935	3017.025	999.688
P5	5015.347	3018.004	999.512	P5	5014.384	3018.783	999.512
P6	4986.101	3048.949	1014.924	P6	4983.558	3048.154	1014.924
P7	4982.113	3042.314	1012.898	P7	4979.923	3041.320	1012.898
P8	4979.191	3041.093	1012.931	P8	4977.069	3039.948	1012.931
P9	4989.183	3045.477	1013.236	P9	4986.818	3044.849	1013.236
T1	5043.133	3003.707	1002.882	T1	5042.880	3005.959	1002.882
T2	5037.193	2987.916	1006.037	T2	5037.774	2989.879	1006.037
T3	5023.617	2982.497	1003.513	T3	5024.501	2983.757	1003.513
T4	5038.430	2980.945	1012.997	T4	5039.375	2982.982	1012.997
BS-1	5000.000	3027.191	1000.697	BS-1	4998.577	3027.154	1000.697
BS-1 return	5000.000	3027.226	1000.691	BS-1 return	4998.575	3027.189	1000.691

Appendix E

Nikon D100 Camera Mount for Use with SiroVision Photogrammetry Software

To achieve the best possible 3D data from photogrammetry software, the information provided to the software must be accurate. Aside from possible survey data errors of the camera positions and face control point, determining the location of the camera's sensor plate for surveying can be difficult using a standard camera tripod for several reasons.

First, the accuracy of the camera tripod horizontal bubble level is often unknown. The level is required to remove any camera tilt. A significant error source in the final 3D product is caused by tilt of the camera. Camera tilt is the deviation from horizontal of the camera. When a resulting image has tilt, the calculated orientation between the camera and face control point will be inaccurate.

Second, a typical camera tripod interferes with locating the camera sensor plate's position. If these tripods are used, the camera mount center point shifts as the camera pans along the horizon.

Finally, as the camera is moved up and down, the center position of the sensor plate also changes.

For these reasons, a camera mount was built that would accommodate a professional survey tripod and maintain a constant location of the sensor plate as the camera's elevation and pan views were changed. Using a survey tripod allows the user to quickly and accurately locate the ground position of the camera using an optical tribrach with high-precision bubble levels.

The as-built design of the camera mount built for a 2002 Nikon D100 is provided as figure E1 in this appendix. While the design provides a significant enhancement in locating and maintaining a constant sensor position, the degree of improvement is not known at this time. This mount was not used while collecting the data for this report. And because the position of the sensor plate within the camera is the manufacturer's proprietary information, the planes of the sensor's center had to be estimated.

In using this design, an optical tribrach is attached to the survey tripod. Next, the camera mount is screwed onto a tribrach adapter. The tribrach adapter used for this setup has a low friction rotation capability. This last assembly is then attached to the tribrach. A typical camera mount threaded screw is used to fix the camera to the mount. Figure E2 shows these parts in final assembly. Once the camera mount's vial level is calibrated, the mount and vial level can be used to level (remove the tilt of) the camera's sensor plate.

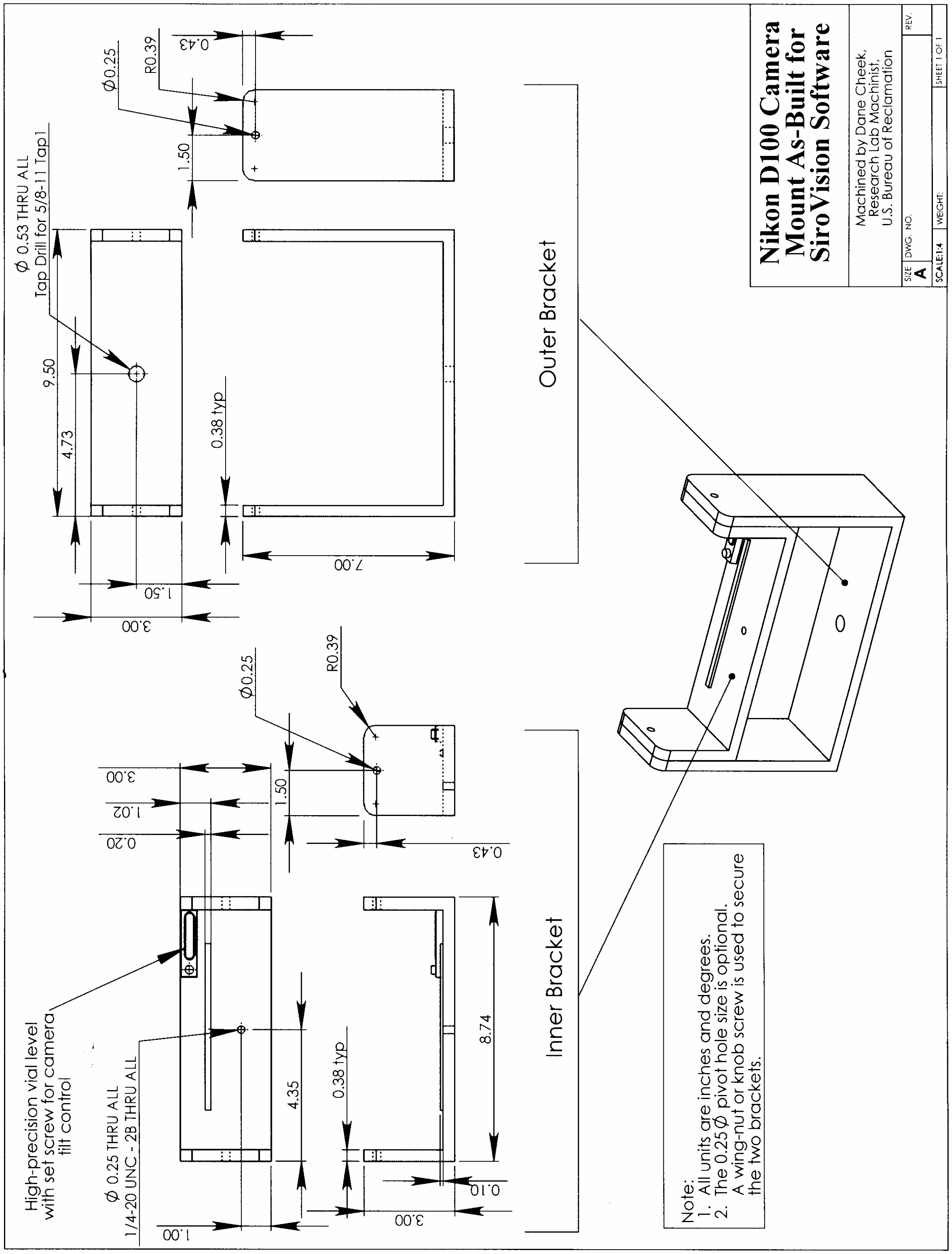


Figure E1.—Nikon D100 camera mount as-built for SiroVision software.

Figure E2.—Complete camera assembly.