TopoDOT™ Tech Notes

Certainty 3D

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To: General Release

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Re: Structural Wall Monitoring (#1017) rev: A

Introduction

TopoDOT™ offers several tools designed specifically for structural monitoring, specifically vertical objects such as buildings or retaining walls. Recognizing that an effective wall monitoring program requires a field to finish process consistent with the program objectives, this document breaks down the monitoring operation into individual process components along with relevant information on data characteristics. Suggested best practices are offered for each process component that will support overall program objectives and requirements.

The process components and related data characteristics addressed in this document are:

- Planning the Wall Monitoring Operation
- Relevant Data Characteristics
- Best Practices for Field Data Acquisition
- Field Data Evaluation
- Application of TopoDOT™ Tools
- Report Generation

This document describes and offers best practices for the entire process from field data acquisition to final report generation.

Planning the Wall Monitoring Operation

There are several aspects of wall "movement" monitoring that should be carefully considered and well-defined prior to commencing operations. Specifically they are:

- Establishment of reference control
- Definition of “movement”
- Minimum distance requirements for movement detection
- Definition of reference features
- LiDAR data characteristics
- Optimizing the acquisition process

These aspects are discussed further below.

Definition of Wall Movement

Wall movement must typically be described in at least two orthogonal or independent directions from some reference. In a simple example, movement of a rigid flat wall can be “practically” described by two orthogonal movements: 1) a “Z” motion orthogonal to some reference plane and 2) a “Y” vertical motion in a direction parallel to the reference plane. Note that this is a “practical” description. Given the high spatial resolution of point clouds any rotation about the X axis (tipping) would be detected as a Z axis motion and interpreted accordingly. Rotations about the Z axis are atypical of wall movement and could be detected thru the identification of two reference points and there Y axis displacement.

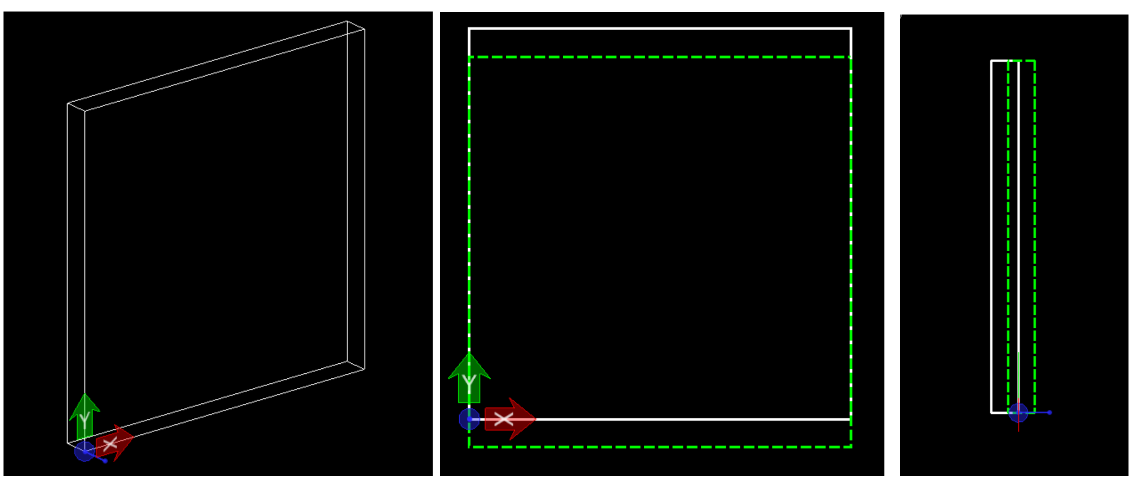


Figure 1: Basic Definition of Wall Panel Movement

Structures such as “retaining” walls are typically much longer and constructed along non-linear paths. Thus the reference must change also such that the “Z” axis and corresponding motion is a least nominally orthogonal to the wall path. Retaining walls are typically comprised of multiple rigid panels attached to rebar from behind. Thus wall movement is often localized within a few panels.

In such cases, a practical reference for Z axis movement is to either extract an essentially 2D reference line along the wall edge, either bottom or top, and define the Z measurement axis as orthogonal to the line 2D reference line. Typically, when available, the design alignment serves an excellent reference since the wall "should" have been built to follow that line. Moreover the alignment line contains the stationing information that would typically match up with some distinctive wall feature such as vertical panel joints.

Minimum Movement Detection Requirement

A realistic impact assessment of any movement in the Y or Z directions within the context of the project requirements is required. What effect will 0.01 (3mm) foot of retaining wall settlement mean to the project versus, 0.05 foot (15mm), 0.1 foot (30mm), etc? Keep in mind that wall monitoring operation is comprised of multiple processes, equipment, etc. each contributing some uncertainty. It is therefore helpful to establish realistic expectations of some minimum required level of measurement resolution and accuracy requirements prior to starting the project.

Definition of Reference Features

LiDAR systems produce point clouds and in many cases calibrated reference images mapped to the point cloud data. In order to detect and measure movement it is necessary to identify features within the LiDAR system data—either point clouds and/or calibrated images—that can be identified within some level of accuracy consistent with the aforementioned requirements for movement.

There are typically two classes of references to be extracted from the LiDAR data, cooperative targets and identifiable features. Cooperative targets are typically in the form of reflectors which can be mounted to the wall and any modern LiDAR scanner can locate and identify. These targets can typically be found very accurately and automatically. However such targets must be mounted and can be rather costly. It can also be very impractical to expect they remain affixed to the wall over time.

Figure 2: Typical LiDAR reference targets

Identifiable features such as joints, corners, edges, etc. within the wall structure can serve as references for monitoring wall movement particularly in the Y direction. However in this case, it is necessary to assess how reliably such features can be extracted and to what level of automation. LiDAR data characteristics should support the identification of such features.

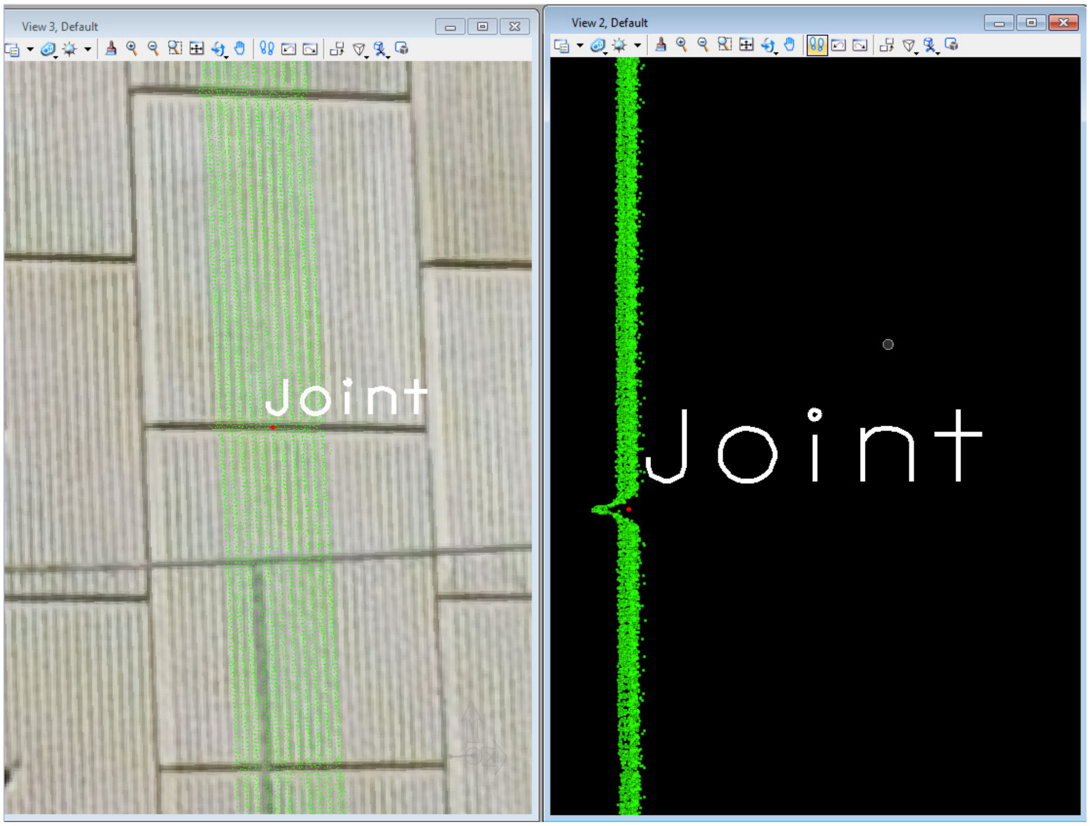


Figure 3: Joint feature clearly identified in point cloud

As for movement along the Z axis, typically comparisons of the point cloud to a virtual or another point cloud can be used to identify and measure movement. Note that in this case also, there is typically a need to process the data to extract consistent identifiable features representative of the wall surface. If the wall is relatively flat this is not difficult. However in many cases the surfaces are not flat such as the wall with deep ridges shown below. In this case, rather sophisticated processing is required to extract features representing the same wall surface consistently.

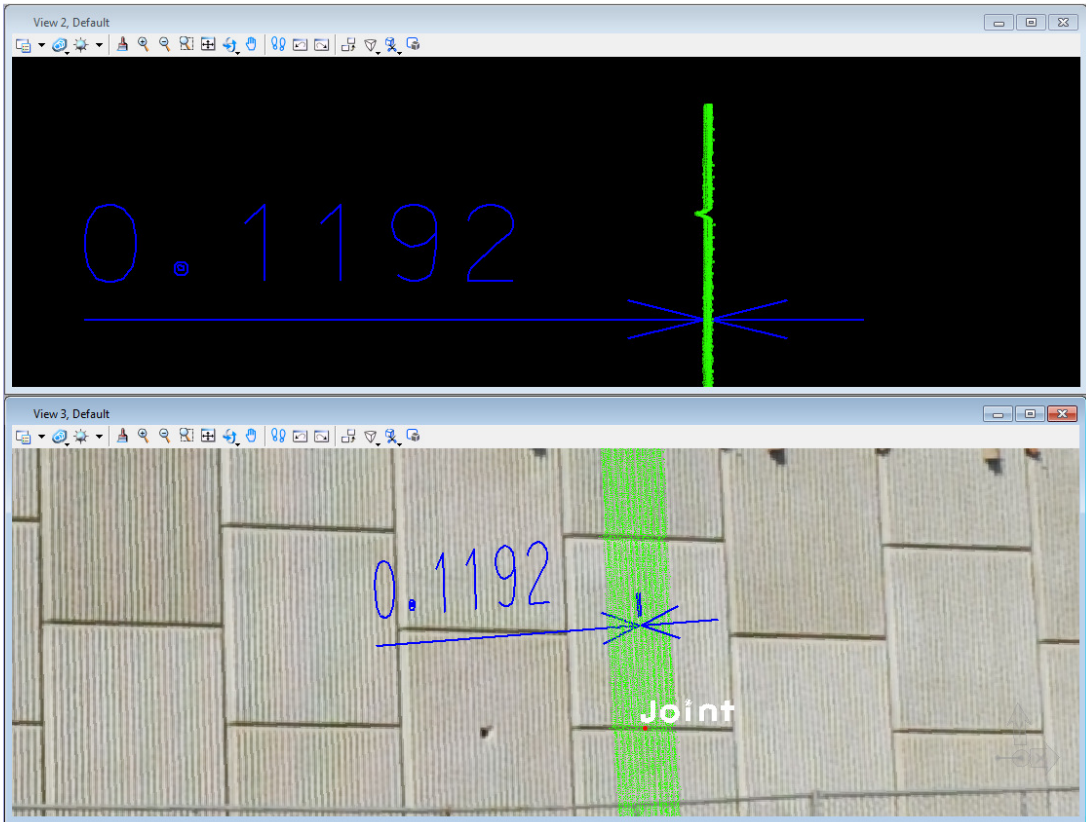


Figure 4: Deep ridges in wall result in “thicker” point cloud

LiDAR System Data Characteristics

There are three primary LiDAR system and data characteristics relevant to wall monitoring performance. These are:

- Reference Target Acquisition Accuracy
- Systematic Error
- Random Error

Reference targets are typically cooperative and as such are constructed of reflective material of known shape and size... Such targets are typically placed over a survey control monument, thereby serving as the lineage back to a traditional survey. Other targets, such as flat adhesive reflectors, are traditionally surveyed thereby establishing their respective location in the project coordinate system. Thus the accuracy with which these targets are identified and located is critical to the overall wall monitoring error budget.

Typically each LiDAR system will offer proprietary targets and internal hardware/firmware systems for locating a target. The location accuracy for each target can vary with range, angle, and just general scanner performance.

Despite these many factors, assessment of the scanner target detection performance can be rather easily quantified. Simply setup targets in a “typical” configuration around a wall—or simulated wall—and scan the same targets from several scan positions keeping the targets in a “scanner” referenced coordinate system, i.e. targets are located relative to each scanner position. By performing a least squares fit of the same target locations from several scan positions, the accuracy and repeatability of a scanner’s target location performance can be quantified and added to the error budget.

Corresponding tiepoints: 7
Standard deviation [US-ft]: 0.0073
Avg. radial deviation [US-ft]: 0.0024
Avg. theta deviation [US-ft]: 0.0007
Avg. phi deviation [US-ft]: 0.0015

Name	Link	Ref...	F...	R...	S	P...	A...	R...	X	Y	Z	R	θ	φ	Δ X	Δ Y	Δ Z
tp001		1	t...	R...	0	2...	4...	2...	0.584	-19.390	0.207	1	8	2.	0.000	0.000	0.000
tp002	PRCS_002	0	t...	R...	0	1...	3...	2...	-144.7...	-24.154	-0.929	1	9	1.	-0.001	0.003	0.005
tp003	212	0	t...	R...	0	6...	3...	1...	-42.952	-5.362	1.868	4	8	1.	0.002	-0.010	-0.004
tp004	PRCS_003	0	t...	R...	0	9...	4...	2...	-42.811	-5.761	-0.477	4	9	1.	0.002	-0.004	0.002
tp005	516	0	t...	R...	0	2...	4...	2...	-55.032	-5.217	-0.207	5	9	1.	-0.009	-0.002	-0.008
tp006		0	t...	R...	0	5...	3...	2...	-65.866	105.932	18.027	1	8	1.	0.000	0.000	0.000
tp007	168862	0	t...	R...	0	2...	3...	2...	172.210	122.908	12.263	2	8	3.	0.013	-0.008	-0.001
tp008	514	0	t...	R...	0	1...	3...	2...	237.457	20.358	-2.932	2	9	4.	0.001	0.015	0.004
tp009	PRCS_004	0	t...	R...	0	1...	3...	2...	127.913	4.742	-2.228	1	9	2.	0.002	-0.001	-0.003

Figure 5: Report summarizing reference target alignment

Having established the uncertainty associated with the scanner locating the targets, Follow up with the same targets placed at survey control reference points. A root sum square of the uncertainty in your original control and scanner target location will describe the expected scanner performance in this area.

Best Practices for Data Acquisition

Scanner position, scanning parameters and control target layout for a retaining wall project are of critical importance in optimizing field efficiency and data quality. LiDAR system data, such as point clouds, calibrated images and reference target locations must be traceable back to the survey control network. LiDAR system data must be acquired in such a way that features can be identified and measurements can be extracted within tolerances meeting project requirements.

Control Target Layout

The reference targets should be linked to an established survey control network in some way. For example, several of the scanner reference targets in the image below are set up on a fixed height rod over a survey control point while others are identified by reflector stickers whose locations are surveyed. Thus identification of the cylindrical reference target can be tied directly to the survey point nail below the rod.

Figure 6: Reference targets along roadside

Positioning of the reference targets along the wall is also critical to optimizing the quality of the data. Keeping in mind that these reference targets tend to “tie down” the data at those points, it is good practice to layout targets in a geometry surrounding the wall but at some distance away in order to minimize the effects of uncertainty in control and reference target location. These images show target locations at opposite ends of the wall, behind the scanners some distance away and at the top of the wall on the upper road surface.

Figure 7: Reference target placed over survey location on top of wall

The image below shows a wall monitoring project with vectors from the scanner positions to target locations. Note the layout of the targets provides a stable geometry for accurately aligning adjacent point clouds and calibrated image data.

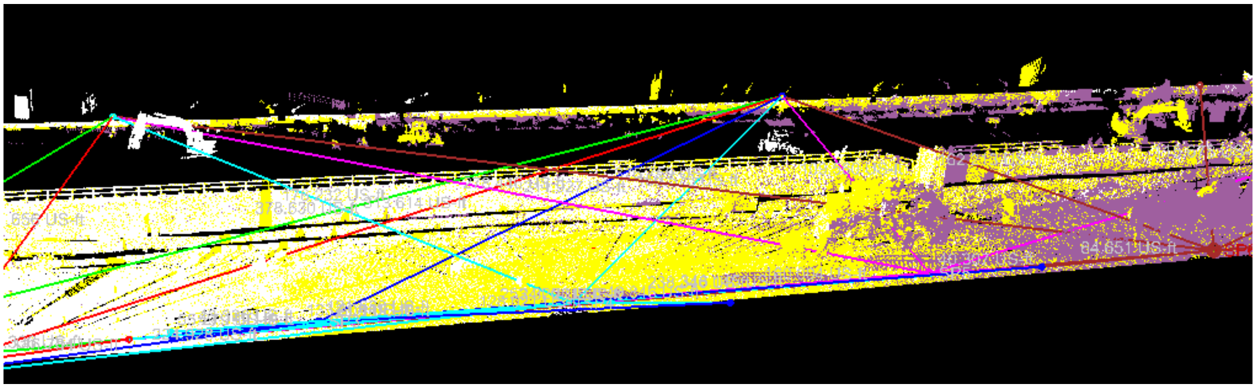


Figure 8: Scanner-to-target vectors

<u>Scanner Position</u>

The positioning of the scanner relative to the wall can influence the quality of the data. Distance and incident beam angle to the wall are the primary parameters influencing data characteristics.

Scanner distance from the wall will influence the spatial density of the point cloud across the wall. The further away the scanner, the larger the distance between neighboring measurements for the same angular step size. Typically every modern scanner will scan with small enough angular steps to achieve a point cloud spatial density sufficient to meet project requirements. The trade-off being scan time and amount of data.

More attention should be paid to avoiding too oblique and incident beam angle from the scanner to the wall. This is especially the case when attempting to identify relatively small features such as panel joints within the point cloud data. Point cloud measurements taken at say 10-20 degrees off parallel to the wall tend to not penetrate into the joint deeply thereby making it more difficult to identify the joints reliably. Such anomalies are easily avoided by optimizing the scanner position setups.

Below is a simple layout plan showing a reasonable geometry. Note that scanner positions were selected such that there is data across the wall taken at incident angles exceeding about 45 degrees.

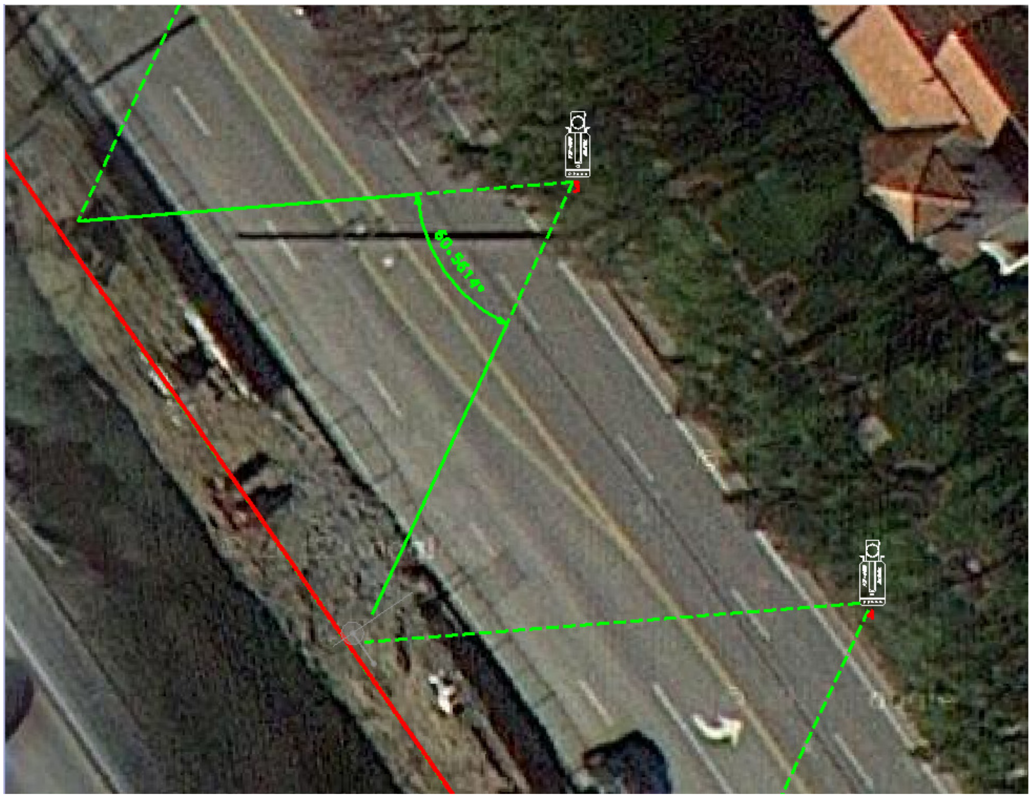


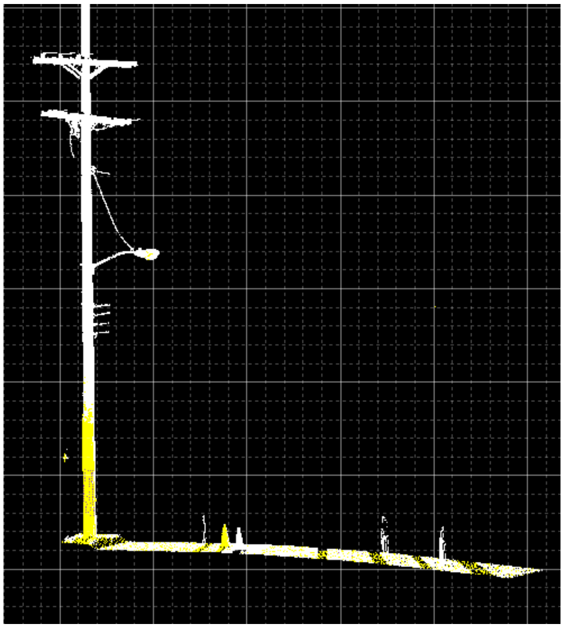
Figure 9: Scanner location relative to wall

Note that it is strongly recommended that each scan be taken for a full 360 degrees at each position. Typically this is necessary to locate reference targets to the side or behind the scanner. Also this extra data can prove quite useful in downstream analysis. In evaluating the wall data inside of TopoDOT™ it is easy to limit point cloud data on the wall to just that data taken at about incident angles of 45 degrees or more for each scan position.

Point Cloud Data Systematic and Random Uncertainty

Most modern scanners designed for civil applications are sufficiently accurate for structural monitoring. So in this section, the topic of uncertainty will be mentioned briefly along with methods for determining the point cloud data characteristics with respect to these two uncertainties.

Systematic uncertainty manifests itself as fundamentally a data "shift". This shift could result from variances in wall reflectivity, background noise from sunlight (seen mostly in phased-type scanners), environmental parameters, etc. Random uncertainty manifests itself as noise or "fuzziness" in the point cloud data. Each of these uncertainty components is easily assessed.



The sheer volume and redundancy of LiDAR data facilitates the estimation of systematic measurement uncertainty. For example, point clouds from different scan positions aligned over the wall “and” surrounding objects can be compared to identify and measure any systematic error. One can easily use TopoDOT™ to cut cross sections across overlapping point cloud areas and measure misalignment between them. Any data shifts will typically become evident as the overlapping points were taken from different distances, different angles, different sunlight conditions, etc…

Figure 10: Road cross section with overlapping data

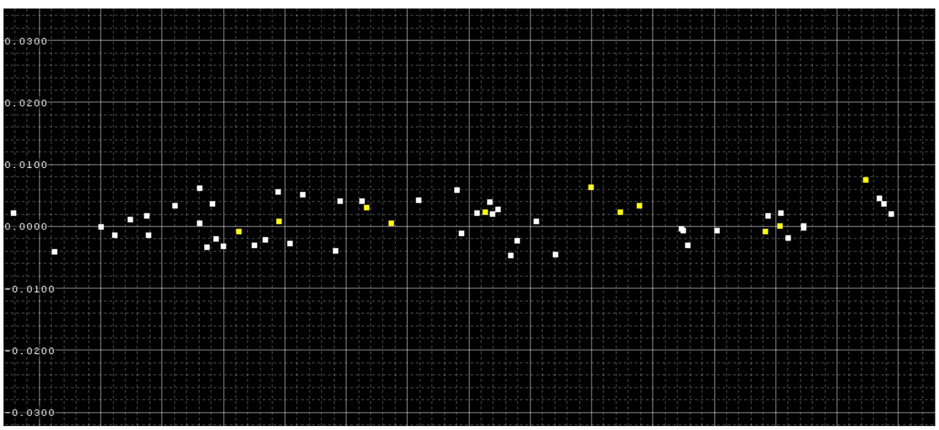


Figure 11: Road cross section reveals tight alignment

Random uncertainty can be easily quantified by analyzing a data sample over a relatively flat surface. For example, a scan of the flat wall will yield hundreds or thousands of points across it. Analysis of those points compared to a virtual plan fit to the data provides a very reasonable assessment of the random uncertainty associated with each point. For example, in the following image a plane is fit to points on a relatively flat surface. The standard deviation is about 0.01 feet (3mm). Given that there is also texture on the concrete surface, this result well exceeds performance requirements for typical wall monitoring projects.

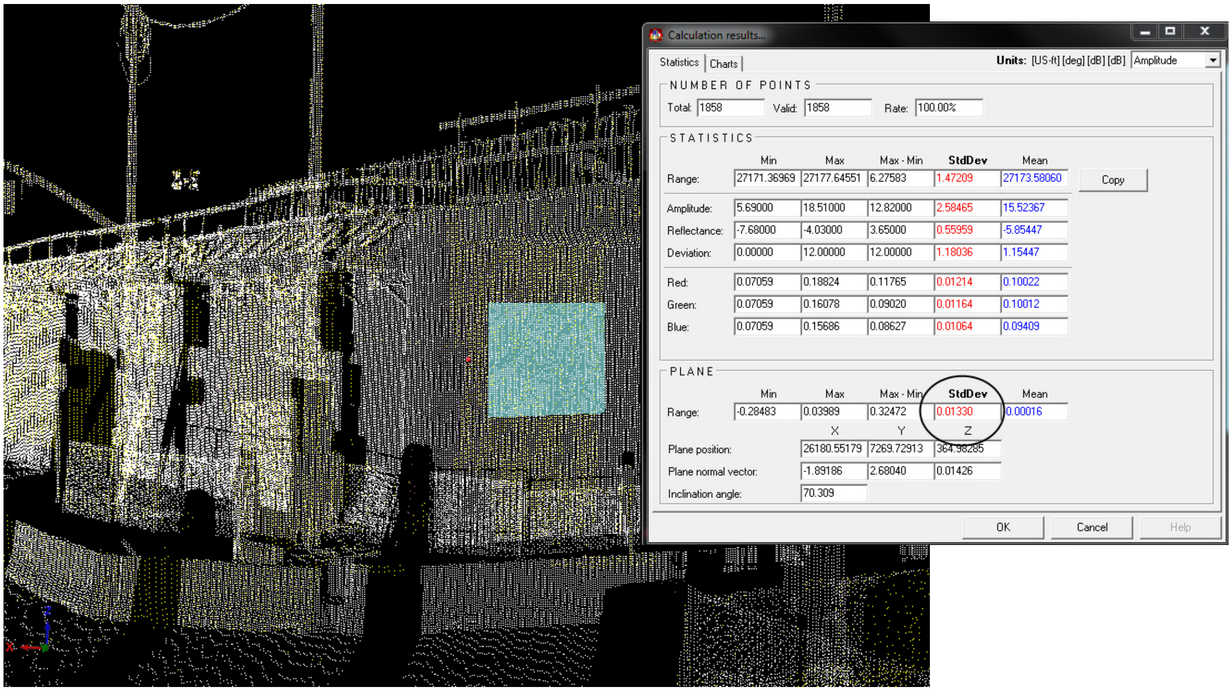


Figure 12: Standard deviation of data about plane describes random noise

As mentioned previously, many scanners operating performance are well within the systematic and random uncertainty tolerances required for structural monitoring. However it should be noted that phase-type scanners will typically exhibit higher levels of uncertainty than pulsed-time-of-flight scanners when exposed to background sunlight. Scanners used in extreme weather conditions may exhibit such uncertainty. Finally, a scanner could just have an internal malfunction. These simple tests can assure that the scanner will perform within tolerances required to meet the wall monitoring project requirements.

Scanner Settings

Selection of the appropriate scanner settings will optimize the data for identification of wall features critical to movement analysis. As stated earlier, the features of interest are some representation of each panel surface and accurate identification of the "horizontal" panel joints. Thus the primary objective for scanner settings is to achieve a point cloud spatial density sufficiently dense to capture the necessary feature information.

Density is a function of vertical/horizontal angular step size for the beam and the distance of the scanner to the wall surface. While more data is typically better, more data also increases file size and scanning time. The spacing between points on the wall is just given by angle step size (radians) x distance to wall. Without going into detail here, reasonable settings for a scanner say 40-50 feet from the wall might be about 0.06 x 0.06 degrees. If the panel joint is not clearly defined at those settings, one can set the horizontal step size at 0.06 degrees and the vertical step at say 0.03 degrees. This will increase the vertical density only thereby better identifying the horizontal panel joint without increasing the scan time or file size too much.

Field Data Evaluation

This section discusses the basic approach to evaluating field data for a single wall acquisition. Wall movement is not measured in this exercise. This should serve as a basic procedure for:

- Establish lineage of LiDAR data to control survey
- Assess reference target to control survey alignment
- Review target configuration geometry
- Quick review of data to confirm proper alignment

The following evaluation uses data from a Riegl VZ series scanner and RiScan Pro as the acquisition software application. Similar techniques are recommended for other scanners and their respective acquisition applications. It is assumed that the reader has some familiarity with either RiScan Pro or similar acquisition applications.

Establish Lineage of LiDAR Data to Control Survey

The RiScan Pro table below shows the global survey coordinates (GLCS) imported into the wall monitoring project for the specific acquisition day. This should be done prior to the acquisition process to reference targets can be matched to these points on site. Note these points are typically in state plane coordinates and imported as Easting Northing Elevation.

Name	Ref...	ReflType	Size	X	Y	Z	Height
201	1	RIEGL Flat 5cm	0.00	6424661.031	1843470.737	330.793	0.000
202	1	RIEGL Flat 5cm	0.00	6424602.455	1843552.110	334.621	0.000
211	1	RIEGL Flat 5cm	0.00	6423659.752	1844879.895	367.433	0.000
212	1	RIEGL Flat 5cm	0.00	6423750.046	1844752.907	364.683	0.000
511	1	RIEGL 10CM CYL	0.00	6423666.175	1844676.619	374.404	0.000
512	1	RIEGL 10CM CYL	0.00	6423434.855	1845016.342	376.241	0.000
513	1	RIEGL 10CM CYL	0.00	6423446.457	1845177.085	367.826	0.000
514	1	RIEGL 10CM CYL	0.00	6423586.083	1844981.856	363.146	0.000
515	1	RIEGL 10CM CYL	0.00	6423667.851	1844870.172	360.138	0.000
516	1	RIEGL 10CM CYL	0.00	6423755.957	1844742.453	357.347	0.000
168862	1	RIEGL 10CM CYL	0.00	6423531.075	1844873.497	375.526	0.000
169227	1	RIEGL 10CM CYL	0.00	6423321.878	1845174.107	377.126	0.000

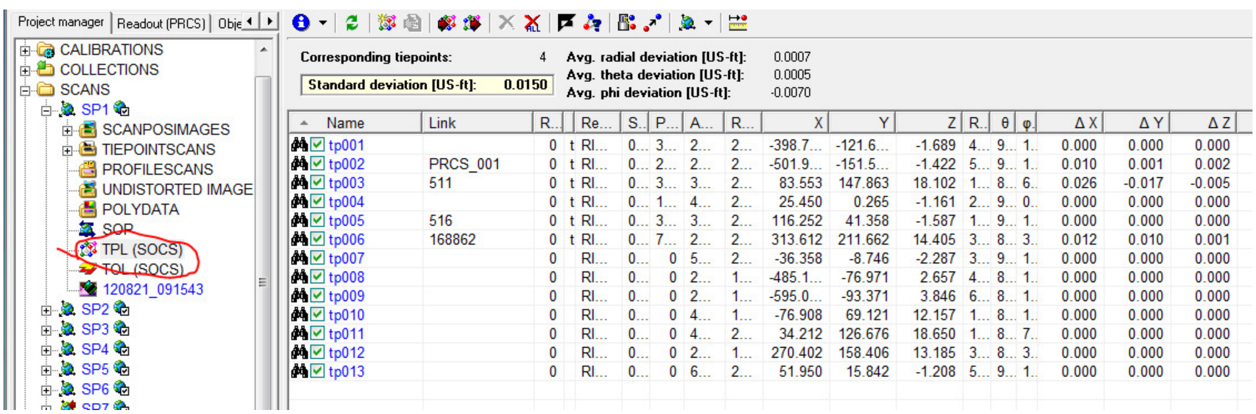
Figure 13: Reference control survey points

The following Project coordinate table (PRCS) shows these GLCS coordinates translated such that they are now single precision numbers. Note that height offsets have been inserted for those reference targets mounted to fixed height rods. No height offsets indicate the use of flat sticker targets or similar.

Name	Link	Ref...	ReflType	Size	X	Y	Z	Height	σ X	σ Y	σ Z
201	201	0	RIEGL F...	0.00	27036.031	6203.737	330.793	0.000	n.v.	n.v.	n.v.
202	202	0	RIEGL F...	0.00	26977.455	6285.110	334.621	0.000	n.v.	n.v.	n.v.
211	211	0	RIEGL F...	0.00	26034.752	7612.895	367.433	0.000	n.v.	n.v.	n.v.
212	212	2	RIEGL F...	0.00	26125.046	7485.907	364.683	0.000	0.002	0.003	0.002
511	511	6	RIEGL 1...	0.00	26041.175	7409.619	374.404	8.154	0.010	0.008	0.006
512	512	2	RIEGL 1...	0.00	25809.855	7749.342	376.241	8.154	0.005	0.002	0.001
513	513	1	RIEGL 1...	0.00	25821.457	7910.085	367.826	4.940	0.000	NAN	NAN
514	514	5	RIEGL 1...	0.00	25961.083	7714.856	363.146	4.940	0.004	0.007	0.006
515	515	0	RIEGL 1...	0.00	26042.851	7603.172	360.138	4.940	n.v.	n.v.	n.v.
516	516	5	RIEGL 1...	0.00	26130.957	7475.453	357.347	4.940	0.009	0.004	0.006
168862	168862	7	RIEGL 1...	0.00	25906.075	7606.497	375.526	8.154	0.010	0.011	0.006
169227	169227	3	RIEGL 1...	0.00	25696.878	7907.107	377.126	8.154	0.005	0.006	0.007
PRCS_001		2	RIEGL F...	0.00	26514.216	6953.548	349.252	0.000	0.004	0.009	0.002
PRCS_002		3	RIEGL F...	0.00	26192.610	7407.619	358.697	0.000	0.003	0.005	0.004
PRCS_003		4	RIEGL F...	0.00	26125.248	7486.264	362.329	0.000	0.002	0.005	0.002
PRCS_004		2	RIEGL F...	0.00	26029.896	7628.243	365.471	0.000	0.000	0.002	0.003

Figure 14: Translated control survey points with fixed height rod offsets

The next step is to open up the Tie Point List (TPL) for each scan position. Each TPL shows the corresponding link to the control survey point, an overall standard deviation of the fit as well as the residual error in the X, Y and Z (Easting, Northing, Elevation) directions. These tables should be quickly examined after each scan on-site as a first assessment of an acceptable lineage between the control and reference target points.



Name	Link	R...		Re...	S..	P...	A...	R...	X	Y	Z	R..	θ	φ.	Δ X	Δ Y	Δ Z
tp001		0	t	RI...	0...	3...	2...	2...	-398.7...	-121.6...	-1.689	4...	9...	1..	0.000	0.000	0.000
tp002	PRCS_001	0	t	RI...	0...	2...	2...	2...	-501.9...	-151.5...	-1.422	5...	9...	1..	0.010	0.001	0.002
tp003	511	0	t	RI...	0...	3...	3...	2...	83.553	147.863	18.102	1...	8...	6..	0.026	-0.017	-0.005
tp004		0	t	RI...	0...	1...	4...	2...	25.450	0.265	-1.161	2...	9...	0..	0.000	0.000	0.000
tp005	516	0	t	RI...	0...	3...	3...	2...	116.252	41.358	-1.587	1...	9...	1..	0.000	0.000	0.000
tp006	168862	0	t	RI...	0...	7...	2...	2...	313.612	211.662	14.405	3...	8...	3..	0.012	0.010	0.001
tp007		0		RI...	0...	0	5...	2...	-36.358	-8.746	-2.287	3...	9...	1..	0.000	0.000	0.000
tp008		0		RI...	0...	0	2...	1...	-485.1...	-76.971	2.657	4...	8...	1..	0.000	0.000	0.000
tp009		0		RI...	0...	0	2...	1...	-595.0...	-93.371	3.846	6...	8...	1..	0.000	0.000	0.000
tp010		0		RI...	0...	0	4...	1...	-76.908	69.121	12.157	1...	8...	1..	0.000	0.000	0.000
tp011		0		RI...	0...	0	4...	2...	34.212	126.676	18.650	1...	8...	7..	0.000	0.000	0.000
tp012		0		RI...	0...	0	2...	1...	270.402	158.406	13.185	3...	8...	3..	0.000	0.000	0.000
tp013		0		RI...	0...	0	6...	2...	51.950	15.842	-1.208	5...	9...	1..	0.000	0.000	0.000

Figure 15: Tie point list showing link to survey control with residual error

Review of the Target Configuration Geometry

Modern LiDAR scanners will locate reference targets very accurately. Thus they should should be placed in such a way that the geometry effectively ties down the point cloud data very tightly over the wall. For example, when scanning a wall from across a roadway, the targets should "not" simply be placed along a line down the road as the baseline effecting the tilt of the data at the wall would be very short. It is better to either place some targets on the wall itself or surround the wall with targets behind it as shown below.

In this example, the reference targets indicated by numbers over the calibrated image are located along the road and on the upper road behind the wall.

Figure 16: Reference targets mapped to calibrated image

A quick examination of target vectors emanating from the scanner positions (SP1 – 7) in RiScan Pro is shown below. Note how targets tie down the scanner orientation tightly behind the wall. Such geometry will result in very tightly aligned point clouds.

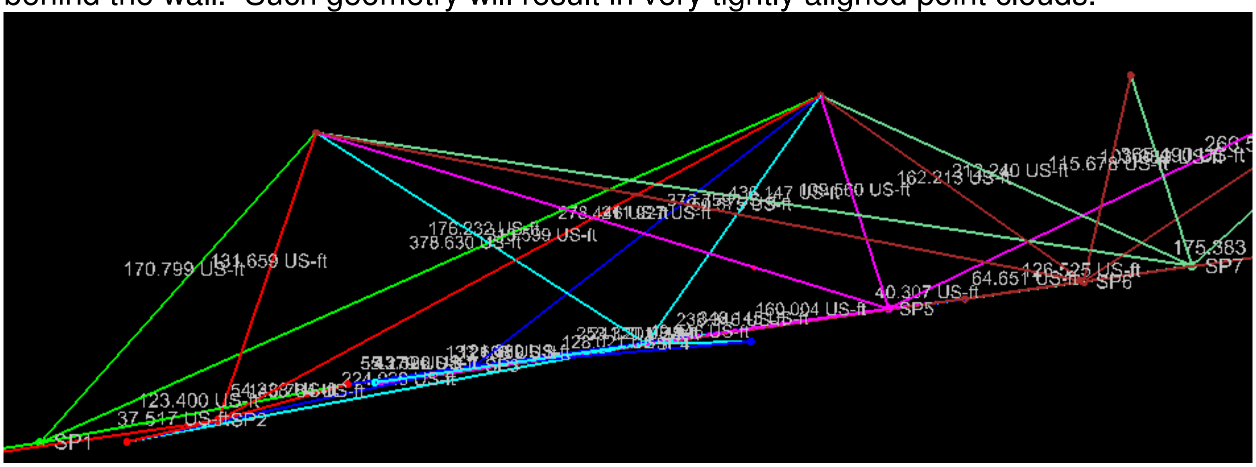


Figure 17: Scan-to-Target vectors

Data Review to Confirm Alignment

As a last step in review of the acquired data, overlapping point cloud areas are checked for alignment. In RiScan Pro, this is easily accomplished by setting each point cloud to a specific color and then inspecting cross sections of overlapping data check alignment.

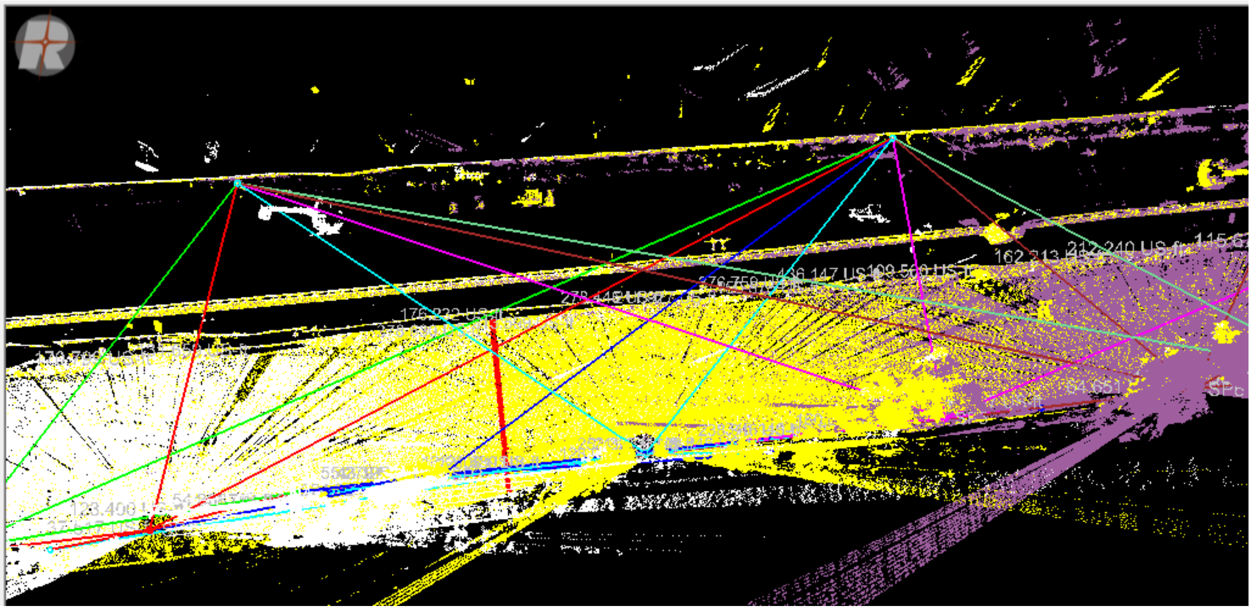


Figure 18: Adjacent point clouds overlapping common areas

In this example, three scans colored as white, yellow and violet are viewed from above. Data has been selected at an overlapping area of the white and yellow point cloud sections. Examining the data below from a view parallel to the road surface there is no discernible misalignment between the yellow and white points. Similar inspections can be made comparing two point clouds against poles, building faces, along power lines or the wall itself. If these static objects are all tightly aligned, then there is great confidence in data quality and its utility in detecting and measuring wall movement.

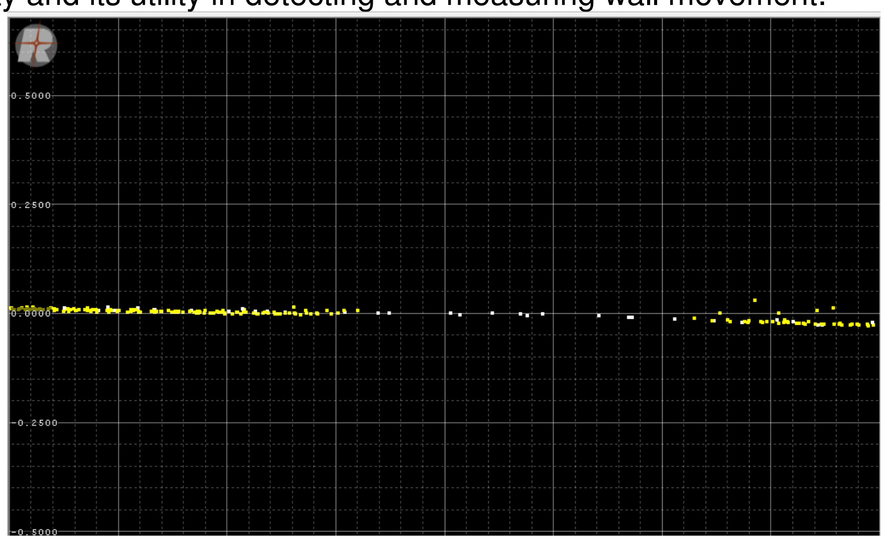


Figure 19: Cross-sections of overlapping point clouds reveal alignment

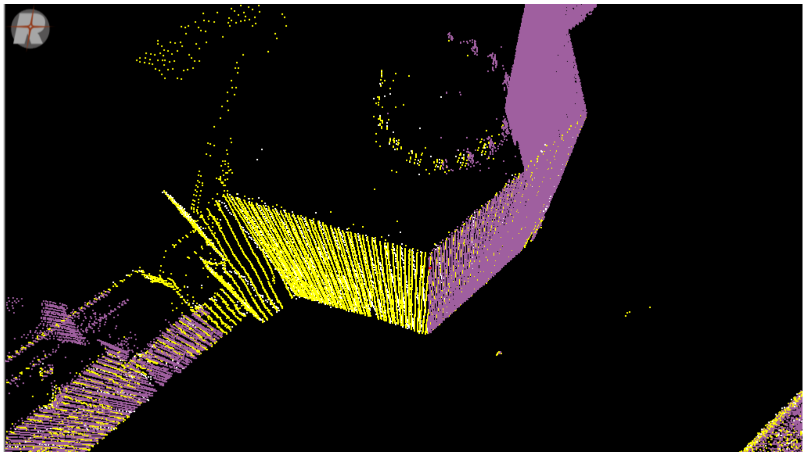


Figure 20: Adjacent point clouds overlap at common surfaces

Application of TopoDOT™ Tools

Having assessed data quality, TopoDOT™ wall monitoring tools may be applied to two or more LiDAR data sets taken at different times. The following is a basic outline of the application of TopoDOT™ wall monitoring tools. This discussion assumes the user has prior TopoDOT™ training. (For training contact Certainty 3D at www.certainty3d.com)

There typically will be two or more scan projects acquired some time apart. Application of TopoDOT™ wall monitoring tools can be outlined in the following steps.

Step 1: Import first project(s) into TopoDOT™

a. Crop out all points not on wall
b. Create another point cloud wall file containing only points on wall

Step 2: QA/QC procedure

a. Control point to data comparison
b. Verify scan-to-scan alignment
c. Assure well-defined joints in data

Step 3: Load Wall Station File (CSV) to identify panel locations

Step 4: Wall Monitoring Tool –Extraction

a. Process panels to monitor motion in local "Z" direction—orthogonal to wall
b. Review motion at each panel as described by extracted features
c. Review motion data at each panel as described in extracted spreadsheets

Step 5: Wall Monitoring Tool—Settlement

a. Process panels to monitor motion in local "Y" direction—vertical to wall (see figure 1b)
b. Review motion as indicated by extracted features.
c. Review motion data as described in extracted spreadsheets

Step 6: Verification of results

In the following, we review each step in more detail and present a corresponding example. Note that this document is not intended as a full tutorial and some prior knowledge of TopoDOT™ is assumed.

Step 1: Import first project (baseline) into TopoDOT™

Having performed the typical TopoDOT™ workflow to create scanner icons for links to point cloud data, select scanner icons and load point cloud data. In order to prepare for initial evaluation of data, select "Individual Scans" in view settings.

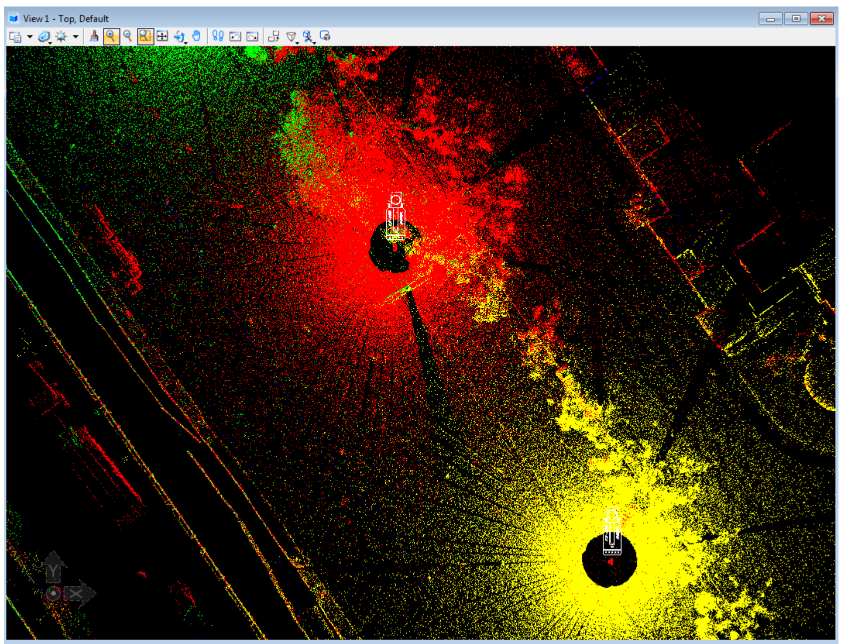


Figure 21: Load scan data and set view to "Individual Scans"

If available, import calibrated images from LiDAR project data file.

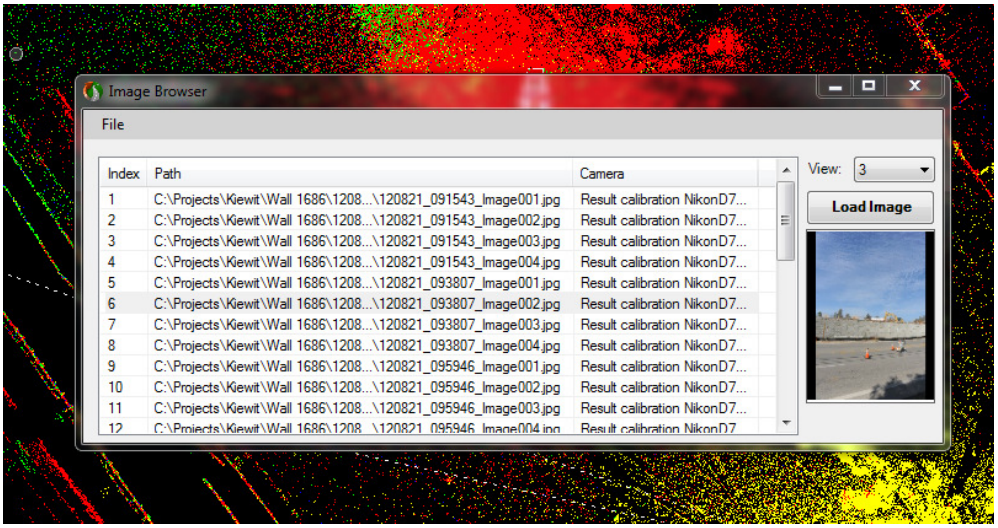
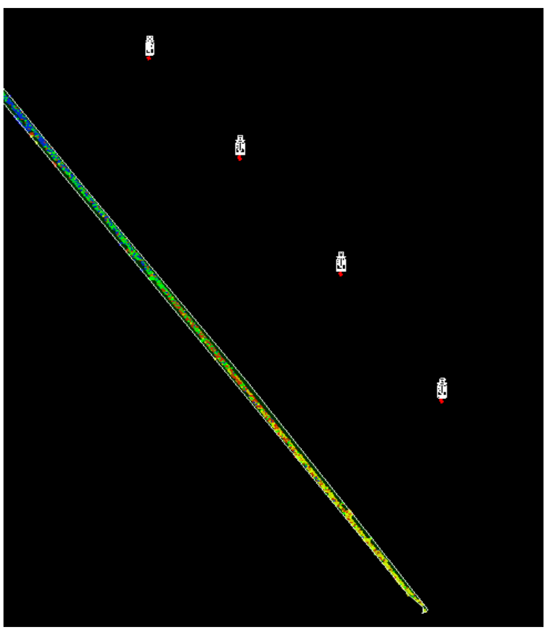


Figure 22: Load calibrated images



Crop out all points not directly on the wall and export this as separate file. Once the quality verifications in Step 2 are complete, this new file will be all that is needed for the wall monitoring operation. This step will greatly increase operational efficiency when loading data from two or more projects.

Figure 23: Crop data for increased efficiency

<u>Step 2 QA/QC</u>

<u>Step 2a: Control Point to Data Comparison</u>

Survey control points imported into TopoDOT™ can be compared to the point cloud data. TopoDOT offers several tools useful for general analysis and measurement of point cloud data deviations from control.

Step 2b: Verify Scan-to-Scan Alignment

It is obvious that scanner orientation will directly manifest itself as a “tilt” in the wall data. Therefore it is imperative that a few simple but effective procedures be executed within TopoDOT™ to assure proper relative orientation of the data.

First note it is highly recommended to acquire a full 360 degree scan of data at each scanner location. While only data on the wall will be used in monitoring, the overlapping data on common surfaces such as buildings, roads, telephone poles, etc. yields an enormous amount of redundancy by which the relative orientation of the point cloud data between scan positions can be confirmed. The following procedure is suggested.

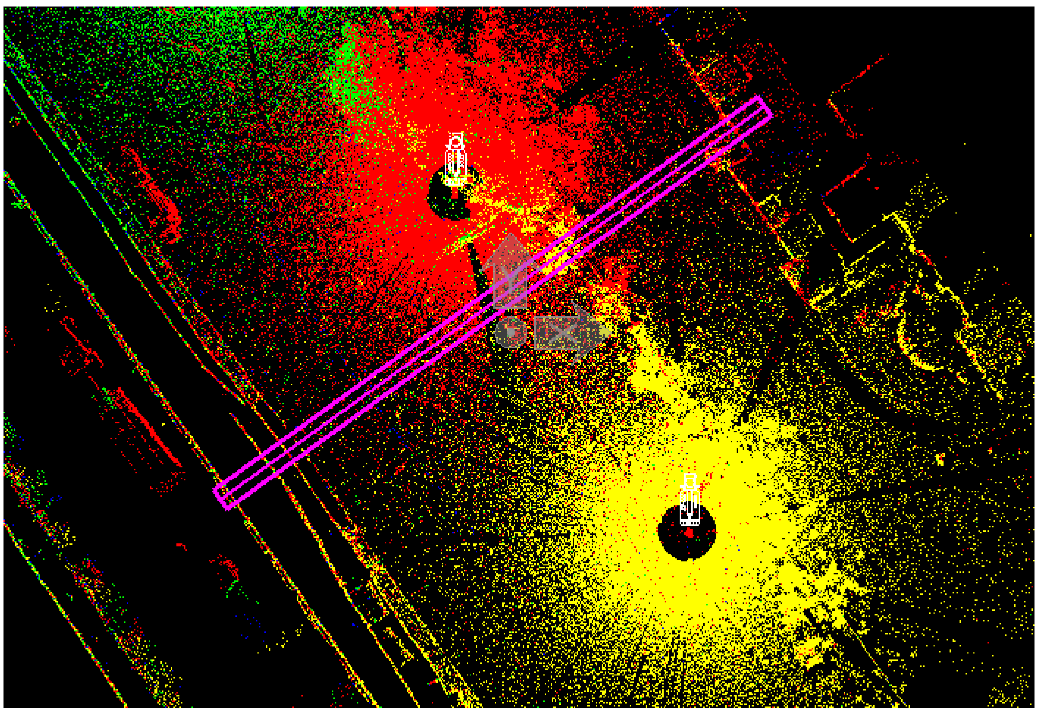


Figure 23: Cross section extraction of overlapping point cloud data

Employ the TopoDOT™ cross-section tool to select a window of data from the top view which encompasses data from adjacent scan positions (yellow and red above). The XY plane will be established as the centerline of the top view. The cropped data will be contained in the outside boundaries of the rectangle. View 2 will provide a cross-section view of the XY plane directly down the Z axis as shown below.

Figure 24: Orthogonal view of point cloud data cross section

Close examination of specific areas gives excellent indication of the relative data alignment as shown below. Here we note that there is no discernible misalignment in the red and yellow data. In fact the data peak-to-peak "thickness" along the road surface is just over 0.01 ft. The red and yellow data is clearly well aligned within that range across all areas of the scan.

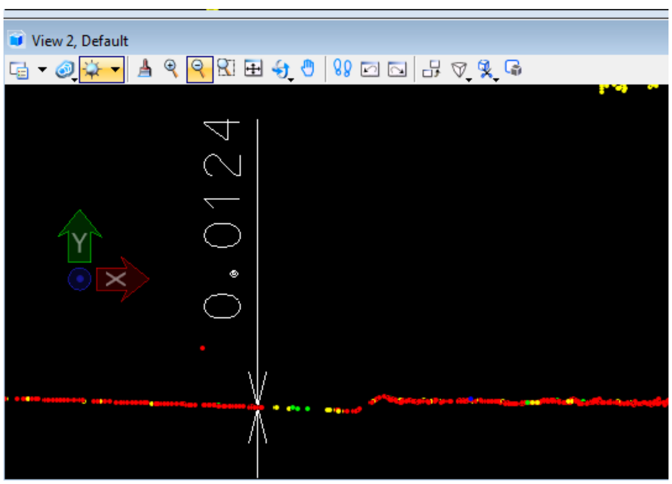


Figure 25: Comparison of overlapping data provides measurable indication of alignment

This simple test should be repeated several times in orthogonal directions such that the relative orientation of each scan is confirmed.

<u>Step 2c: Assure well-defined joints in data</u>

Employ the same TopoDOT™ cross-section tool to determine if joints are sufficiently densely sampled for accurate and repeatable identification. In the following image, the cross section of the data is shown in View 2. A survey point has been place in the XY plane at the center of the joint for reference. This example shows a well-defined joint within the point cloud. For reference, a corresponding calibrated image is loaded in View 3 showing the same survey point against the image. This test also demonstrates excellent camera calibration and alignment.

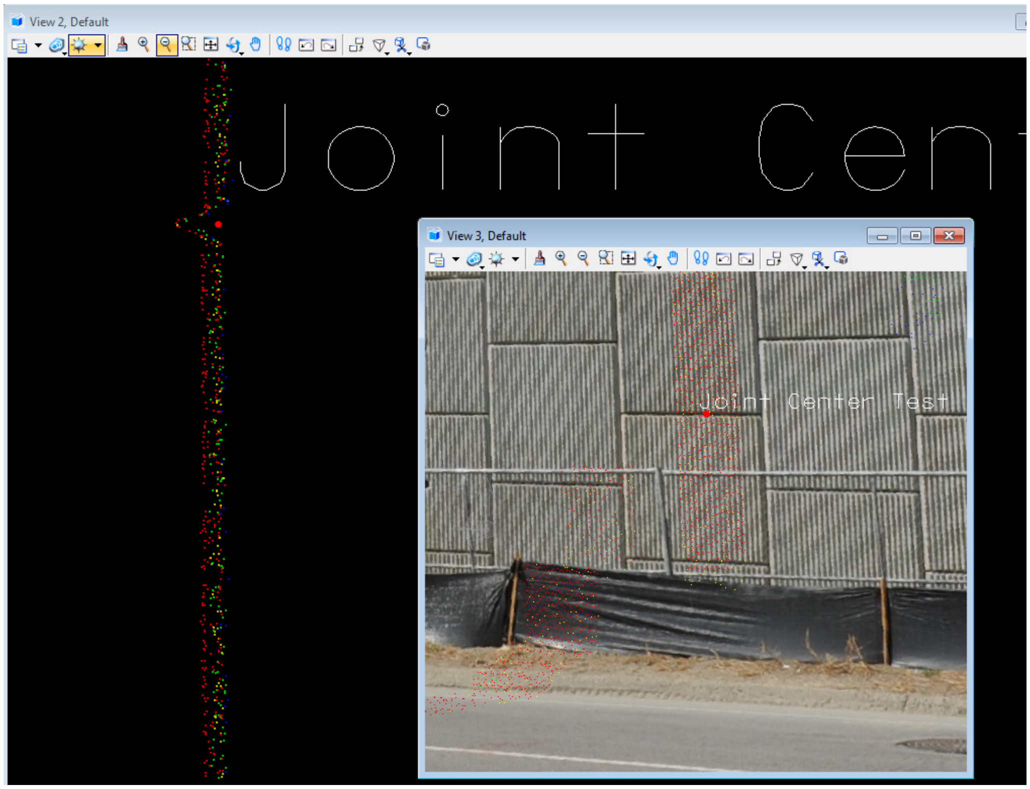


Figure 26: Vertical cross-section shows clearly defined joint

One should note that the data validation tests outlined in Steps 2a thru 2c are intuitive and quickly executed. They are also very comprehensive. An advantage of LiDAR scanning over traditional survey is the sheer amount of redundant data. It is very improbable that any misalignment with control reference targets or relative scanner orientation would manifest itself as some type of misalignment of the point cloud data over common surfaces in the same position relative to the scans. Upon successful results one can proceed to the following steps with a very high level of confidence that this data is well-prepared for effective application of TopoDOT's automated wall monitoring tools.

<u>Step 3: Load Wall Alignment (Station) File</u>

This simple step is necessary as the TopoDOT™ wall monitoring tool suite requires a reference alignment for automation. Such a file can be constructed from the data, but it is typically best to employ the original design alignment. The format for this .csv file is shown below.

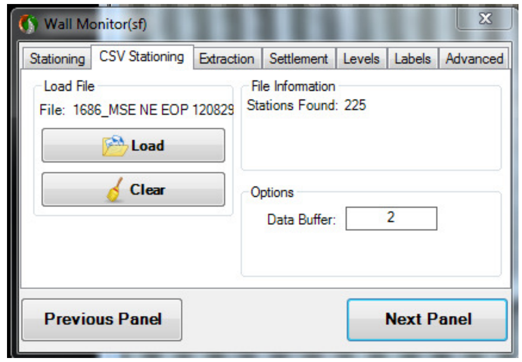
1686_MSE NE EOP 120829.csv

	A	B	C	D	E	F	G
1		10+00.00		1844582	6423780		
2	1		4.72				
3		10+04.72		1844586	6423777		
4	2		4.92				
5		10+09.64		1844590	6423774		
6	3		4.92				
7		10+14.56		1844594	6423772		
8	4		4.92				
9		10+19.48		1844598	6423769		
10	5		5.76				
11		10+25.24		1844603	6423766		
12	6		4.72				
13		10+29.96		1844607	6423763		
14	7		4.92				
15		10+34.88		1844611	6423760		
16	8		4.92				
17		10+39.80		1844615	6423757		
18	9		4.92				
19		10+44.72		1844619	6423755		
20	10		4.92				
21		10+49.64		1844623	6423752		

1686_MSE NE EOP 120829

Figure 26: Wall alignment file

Each column of wall panels has an index, station location and EN location. This file is quickly imported into TopoDOT™ in the wall monitoring tool. Employing the alignment file as a reference, the wall data can be queried relative to a specific station.



Step 4: Wall Monitoring Tool –Extraction

Step 4a: Process panels to monitor motion in local "Z" direction

At this point the data has been prepared for the application of TopoDOT™ automatic wall monitoring tools. In this example, two point cloud data sets taken about a week apart will be compared. The first data set is brown and shown below. Keep in mind that the images used corresponded to the later data set, so the brown point cloud data does not reach the higher level of the image as that part of the wall was not yet built.

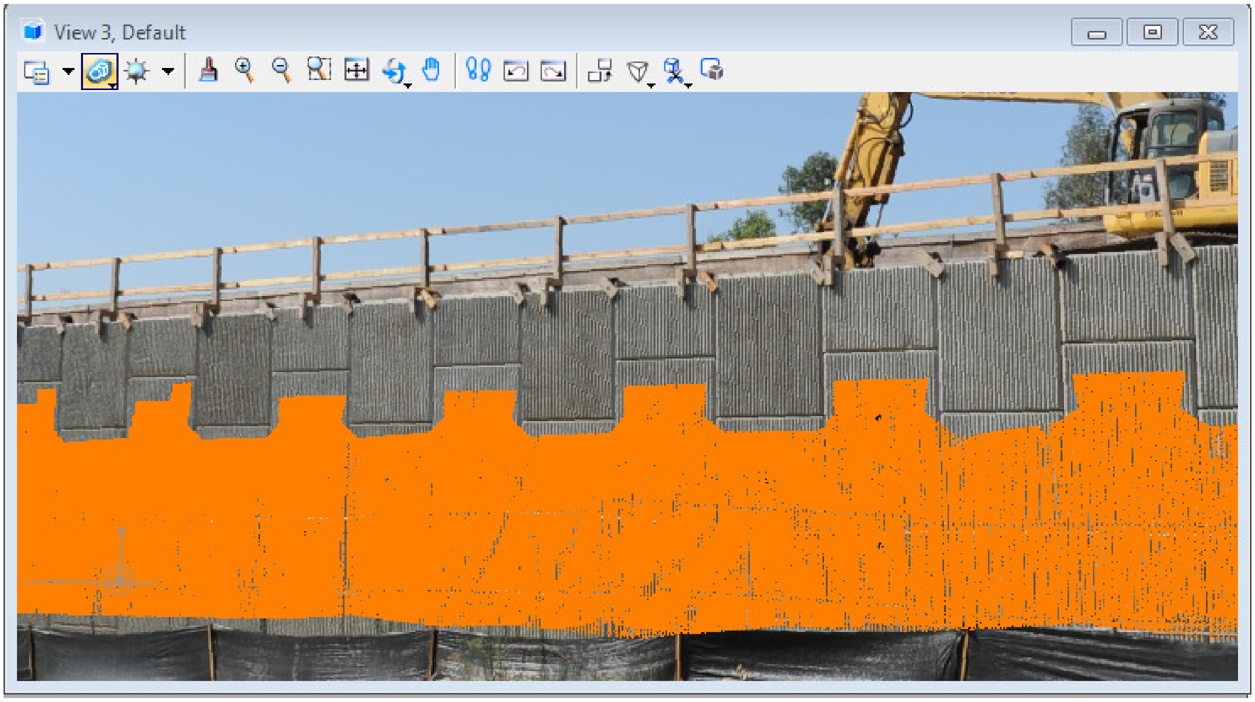


Figure 27: Baseline data projected onto calibrated image acquired at subsequent data acquisition

The second data set is shown in blue. With both data sets turned on, we see that both data sets overlaid over the calibrated image corresponding to the blue data. Note that part of the data preparation process mentioned in Step 1b also requires that extraneous data from wooden braces at the top and obstructions at the bottom of the wall be removed.

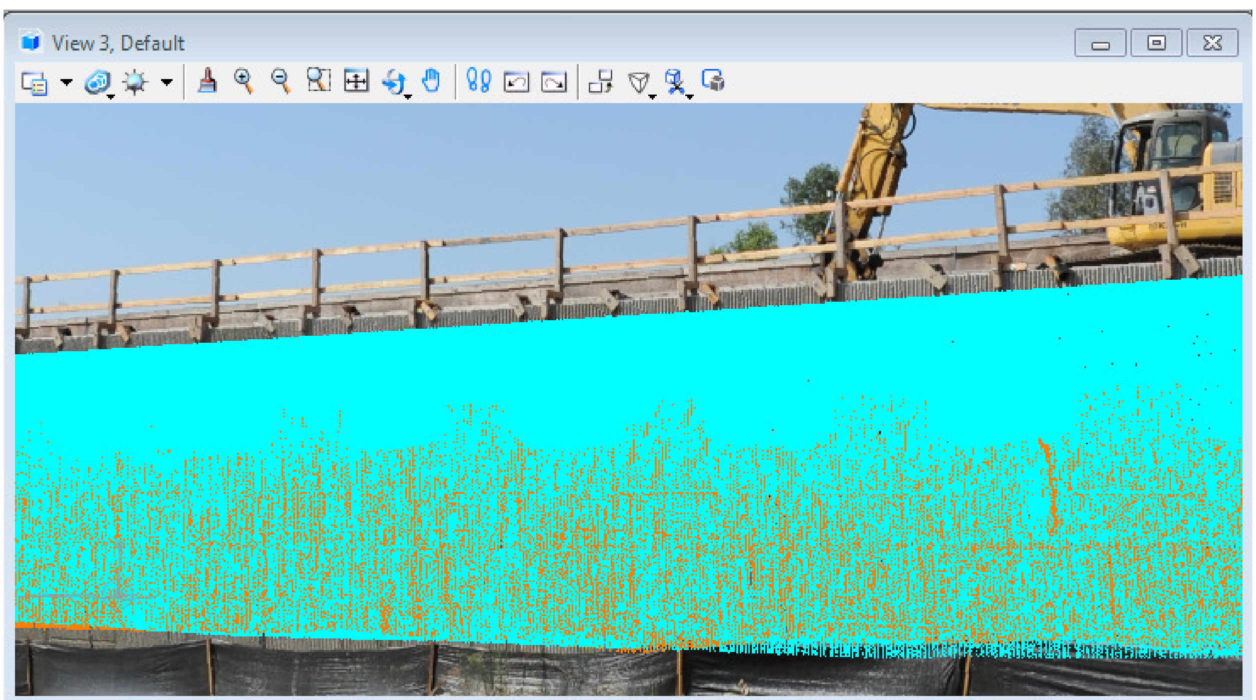


Figure 28: Baseline and Subsequent point cloud data projected onto calibrated image

The next step is to simply select "process all panels" to run the extraction tool. In this example, it will take less than 3 minutes to measure the Z axis motion (orthogonal to the wall surface) from the brown data set to the blue.

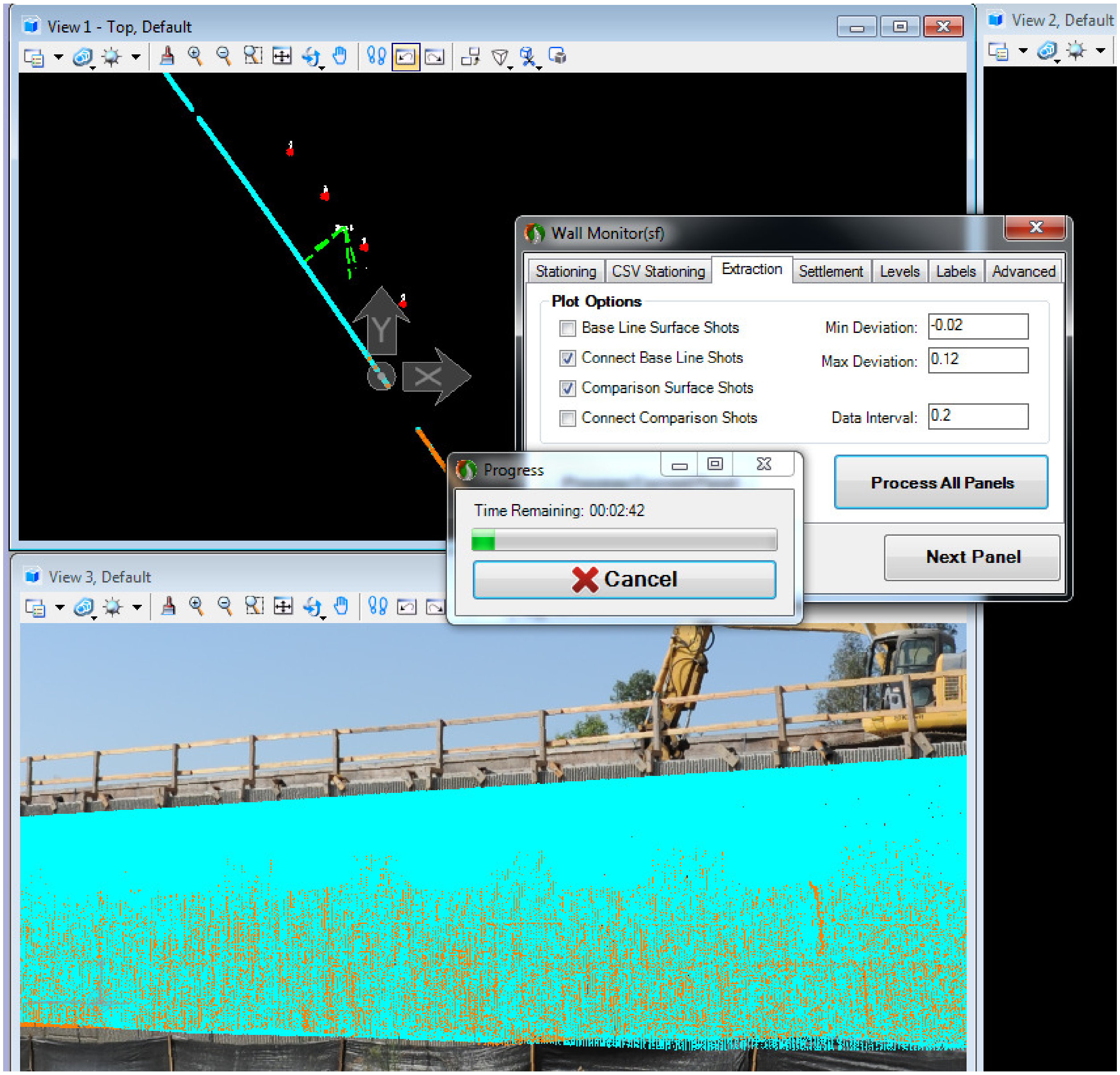


Figure 29: TopoDOT™ wall monitoring tool in "extraction" mode

<u>Step 4b: Review motion at each panel as described by extracted features</u>

The TopoDOT™ extraction tool selects a "strip" of data centered at each station (typically the column center). The surface of each point cloud is extracted automatically and represented by MicroStation™ elements, i.e. lines and points. The points are then colored as a function of the distance between the surfaces. The result is an easily interpreted view of the wall movement. In this case the higher panels have tipped away from their original position by approximately 0.04 feet.

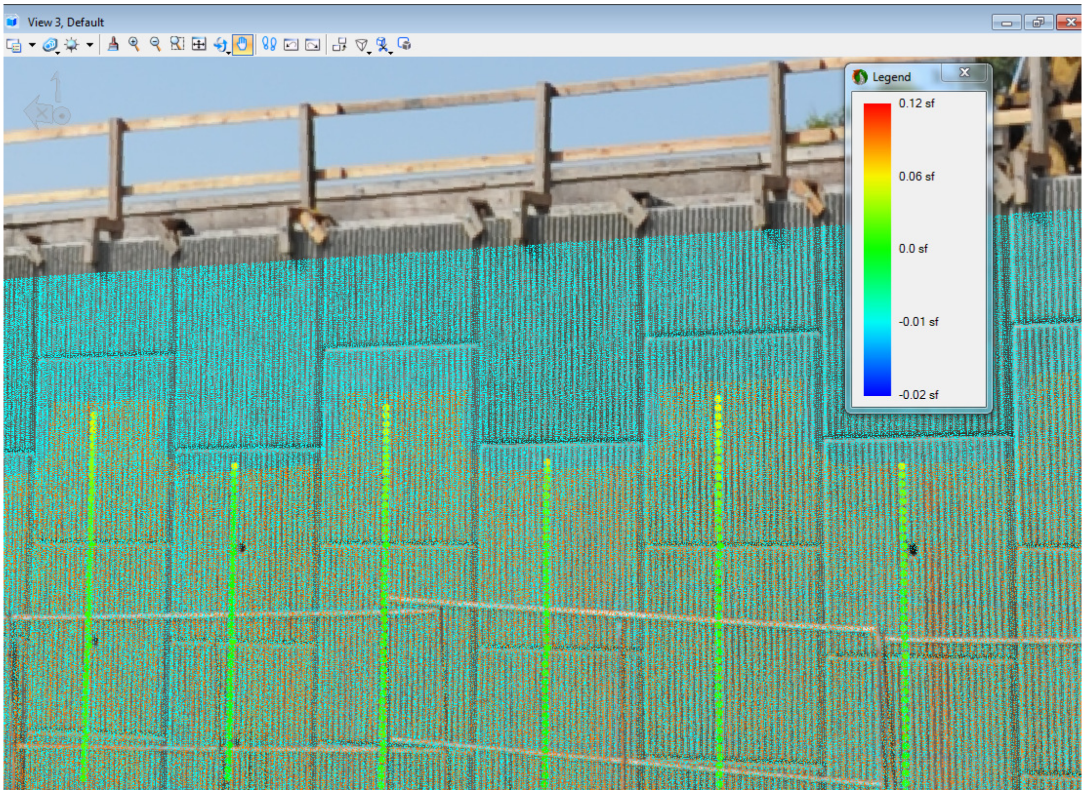


Figure 30: TopoDOT™ automatically measures, summarizes and communicates movement

Examination of a single cross-section demonstrates clearly how TopoDOT™ has automatically simplified the representation of the two surfaces as a brown line (baseline brown point cloud) and points (blue point cloud). The points are colored as a function of distance from the line; over 200 columns in less than 3 minutes.

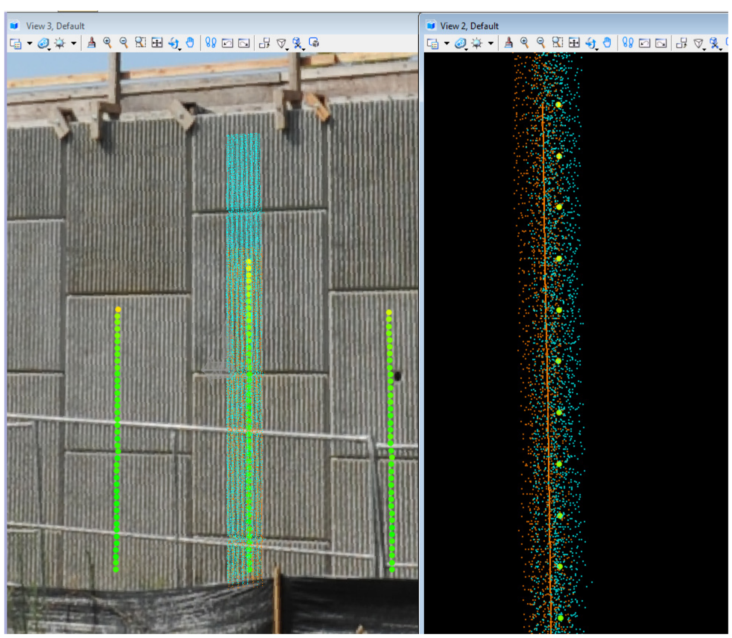


Figure 31: Vertical cross-section illustrates TopoDOT™ results

Step 4b: Review motion at each panel as described by extracted spreadsheet data

In addition, TopoDOT™ automatically extracts the point data representing these elements and exports them in individual spreadsheets for further analysis.

A	B	C	D	E
367.94	0.0522		370.8	0.136
367.8	0.0515		370.6	0.1369
367.6	0.0502		370.4	0.138
367.4	0.0478		370.2	0.1391
367.2	0.0461		370	0.1394
367	0.0446		369.96	0.1394
366.8	0.0428		369.8	0.1393
366.6	0.043		369.62	0.1357
366.4	0.0437		369.6	0.1335
366.2	0.0444		369.54	0.1194
366	0.0447		369.4	0.0772
365.8	0.0429		369.28	0.0592
365.6	0.0406		369.2	0.0746
365.4	0.0402		369	0.117
365.2	0.0401		368.8	0.116
365	0.0394		368.6	0.1131
364.8	0.0387		368.4	0.1093
364.6	0.0074		368.2	0.1061
364.4	-0.024		368	0.1032
364.4	-0.023		367.8	0.1002
364.2	0.0188		367.6	0.0977
364	0.0299		367.4	0.0951
363.8	0.0267		367.2	0.0923
363.6	0.0244		367	0.0866
363.4	0.0217		366.8	0.0805
363.2	0.0205		366.6	0.0817
363	0.0195		366.4	0.0813
362.8	0.0183		366.2	0.0788
362.6	0.0168		366	0.0766
362.4	0.0149		365.8	0.0739
362.2	0.016		365.6	0.0712
362.02	0.0134		365.4	0.069
362	0.0124		365.2	0.0672
361.8	0.0042		365	0.0653
361.6	0.0048		364.8	0.0625
361.4	0.0044		364.72	0.0588
361.2	0.0038		364.6	0.0356
361	0.0027		364.4	-0.002
360.8	0.0008		364.38	0.0003
360.6	-0.002		364.2	0.0372
360.4	-0.002		364	0.0528
360.2	-0.003		363.8	0.05
360	-0.004		363.6	0.0476
359.8	-0.01		363.4	0.044
359.6	-0.041		363.2	0.041
359.54	-0.046		363	0.0385
359.5	-0.044		362.8	0.0364
359.4	-0.026		362.6	0.0336
359.2	0.0029		362.4	0.031
359	0.0067		362.2	0.0306
358.8	0.0111		362	0.0284
			361.8	0.0215

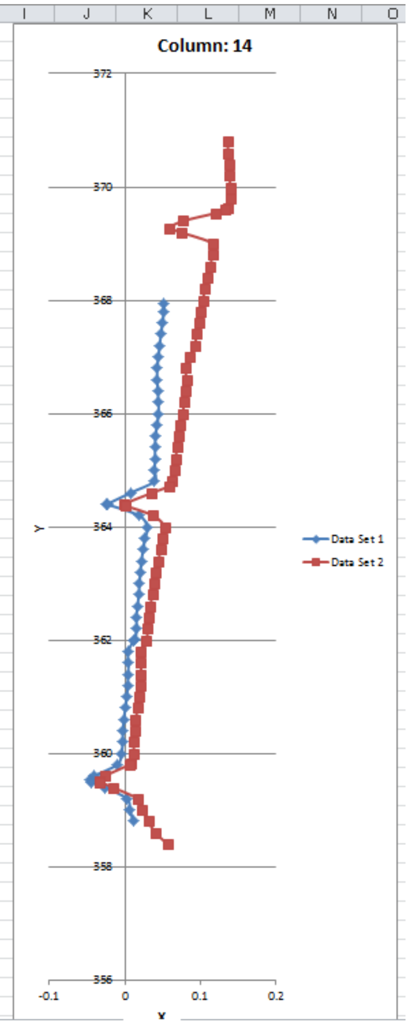


Figure 32: TopoDOT™ extracts data at each column

Step 5: Wall Monitoring Tool—Settlement

Step 5a: Process panels to monitor motion in local "Y" direction—vertical to wall

The TopoDOT™ Settlement tool automatically identifies the vertical joint locations at each station in each data set—brown and blue in our current example. The distance between the joints is automatically measured and represented by a directional arrow and magnitude of movement relative between the two data sets.

These elements mapped over a calibrated image provide a very intuitive and easily understood representation of the walls vertical movement at each column.

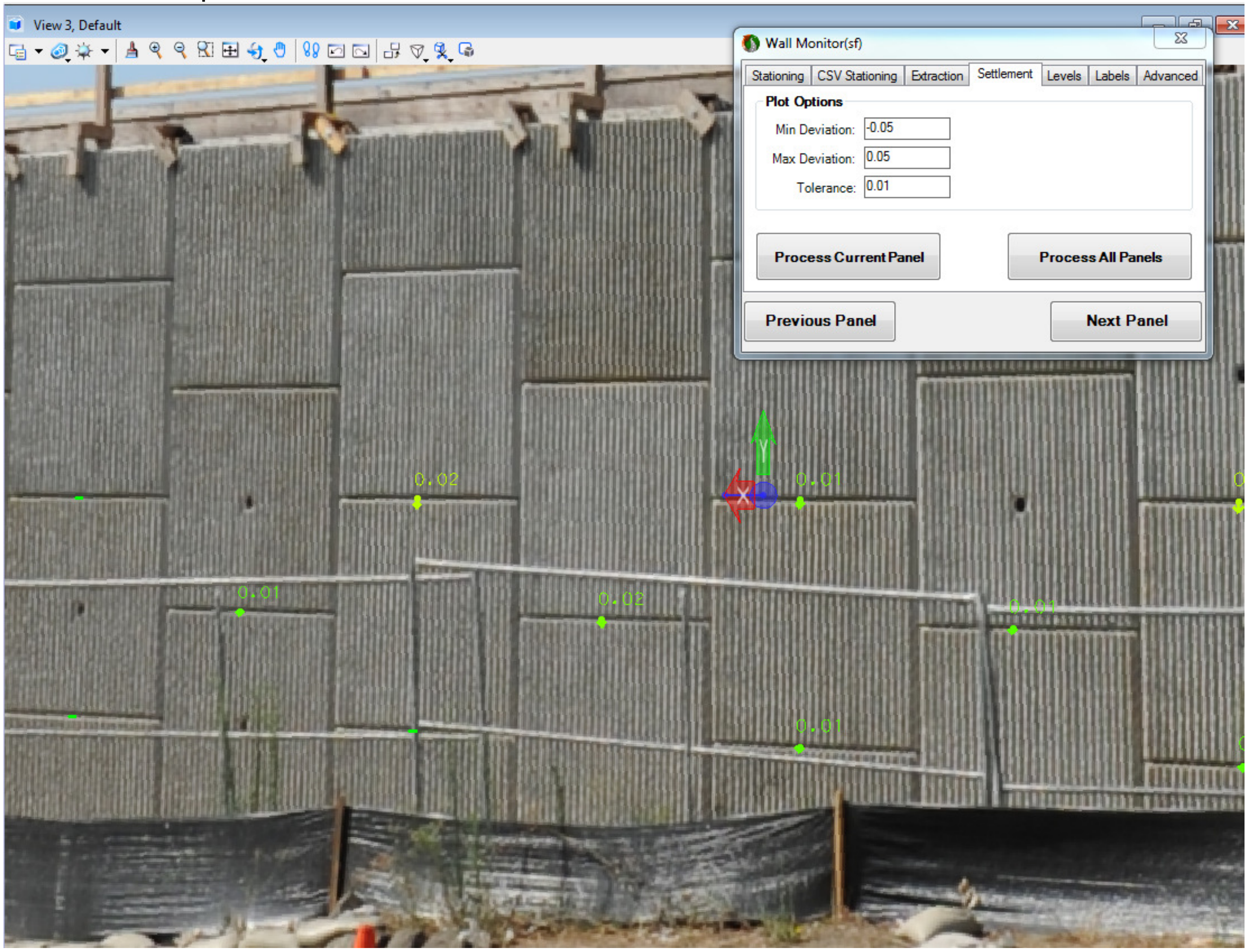


Figure 33: TopoDOT™ automatically locates joint in each data set and measures distance

<u>Step 5b: Review motion as indicated by extracted features</u>

A cross section of data taken at a single column and displayed in View 2 more clearly demonstrates the relative joint movement between the two data sets as well as the elements defining that movement, i.e. arrow and magnitude. Note that manual measurements of the point cloud movement using MicroStation™ measurement tools have been found to be very consistent with the results given by TopoDOT™ automated extraction tools.

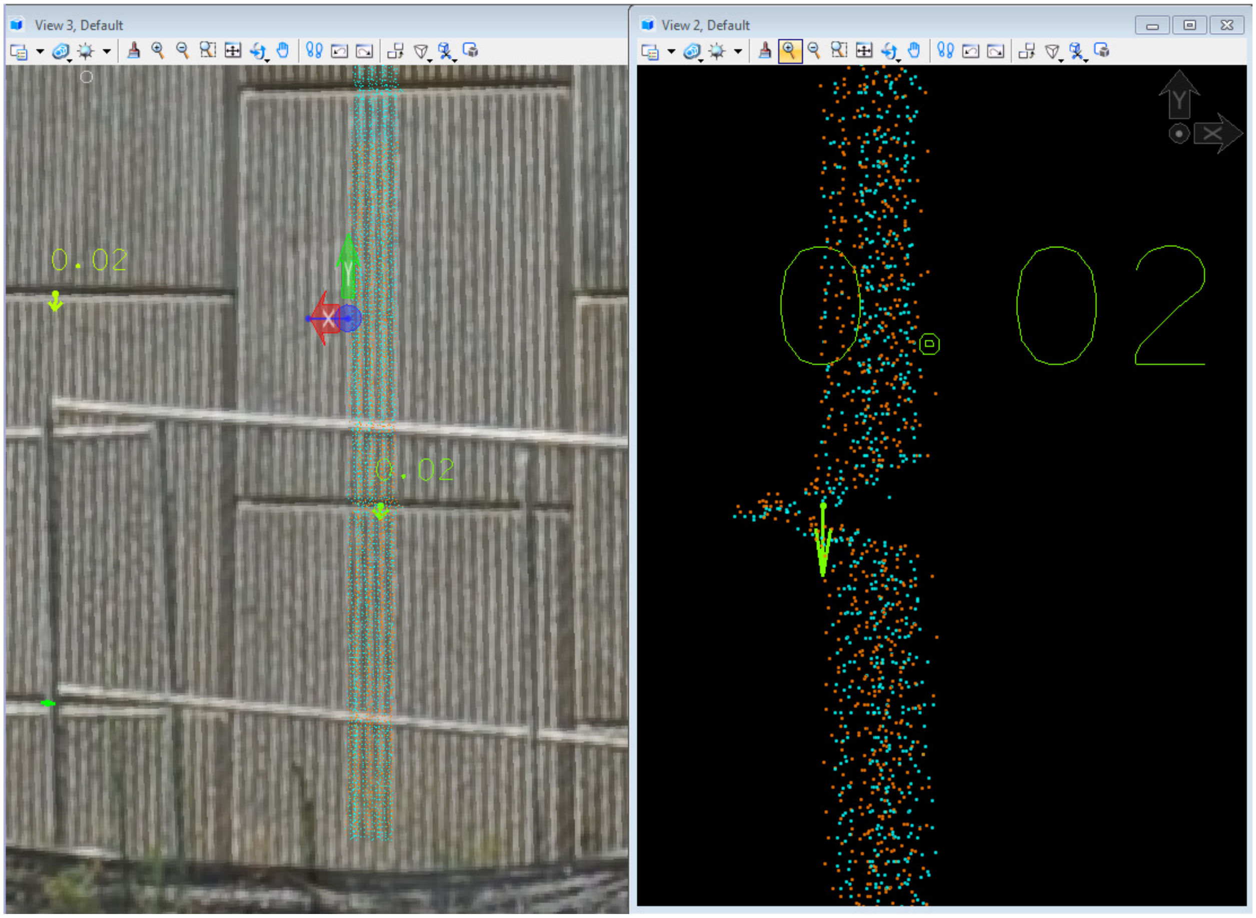
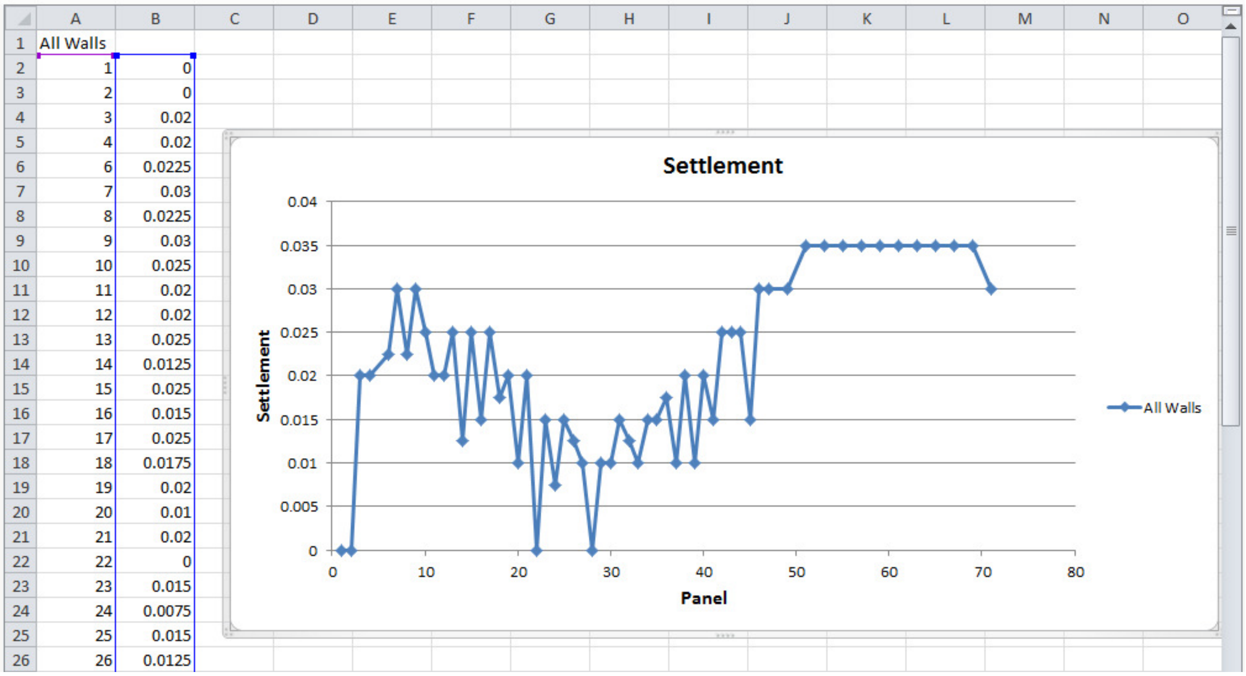


Figure 34: Vertical cross section illustrates TopoDOT™ automated settlement tool

Step 5c: Review motion as described in extracted spreadsheets

TopoDOT™ also automatically extracts each columns vertical movement and exports that data in a spreadsheet format for further analysis. Note that for multiple joints along a single column, TopoDOT™ will average the movements. While one would expect these movements to be equal, TopoDOT™ impose user specified quantization levels (typically 0.01 ft) so that joints on the boundary of that level may change. The average indicating half the quantization level has been determined to accurately indicate measurements at the very boundary of the level.

In the following spreadsheet, one notices movements of 0.005 indicating an average. These results are accurate. The trend of the wall movement is clearly evident along these 71 columns—all processed in about 2 minutes.



	A	B
1	All Walls	
2	1	0
3	2	0
4	3	0.02
5	4	0.02
6	6	0.0225
7	7	0.03
8	8	0.0225
9	9	0.03
10	10	0.025
11	11	0.02
12	12	0.02
13	13	0.025
14	14	0.0125
15	15	0.025
16	16	0.015
17	17	0.025
18	18	0.0175
19	19	0.02
20	20	0.01
21	21	0.02
22	22	0
23	23	0.015
24	24	0.0075
25	25	0.015
26	26	0.0125

Figure 35: TopoDOT™ summarizes settlement at each column in a single spreadsheet

Suggested Best Practices for Reporting

The following discussion suggests an approach to generating a comprehensive report summarizing the application of TopoDOT™ wall monitoring tools. Such a report should achieve the following objectives:

- Provide or at least reference all source data
- Establish lineage from the TopoDOT™ wall monitoring output to survey control
- Summarize intuitive and easily communicated results

In achieving these objectives, Certainty 3D suggests the following information be contained in each report. We note that these are only suggestions and it is left to the user to develop specific criteria meeting their project requirements.

Step 1: Provide Data Reference Sources

The first section should contain a summary list of all data associated with the wall monitoring operation. Such a list should include:

1. Reference control survey data and documentation
2. Wall design alignment file
3. LiDAR scanner project files
4. Relevant metadata

Step 2: Provide Overview of Scanning Operation

This section should provide a top level summary of the wall scanning operation. Of particular interest would be the layout of reference control and scanner position. Note that such information is easily extracted from the LiDAR scanner operating software and TopoDOT™. These results can typically be easily conveyed in the form of a screen shot from one or both sources.

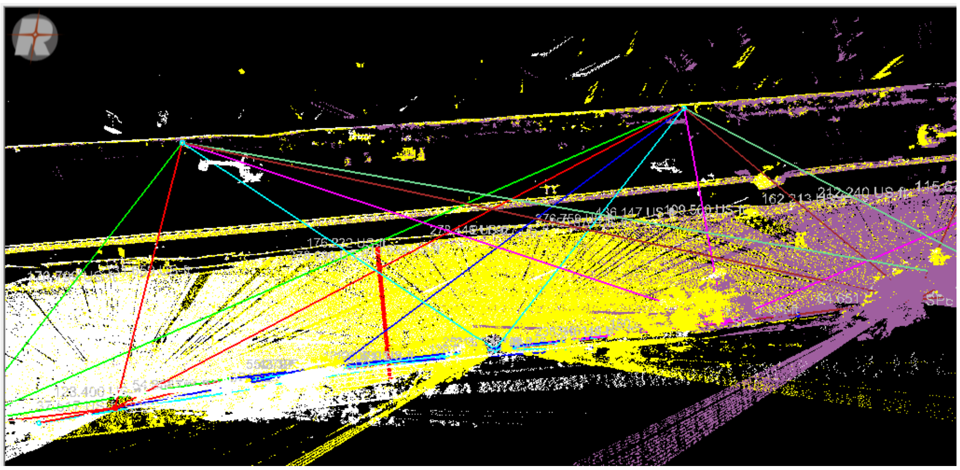


Figure 36: Scan to Target Vectors Quickly Indicate Stable Layout (RiScan Pro)

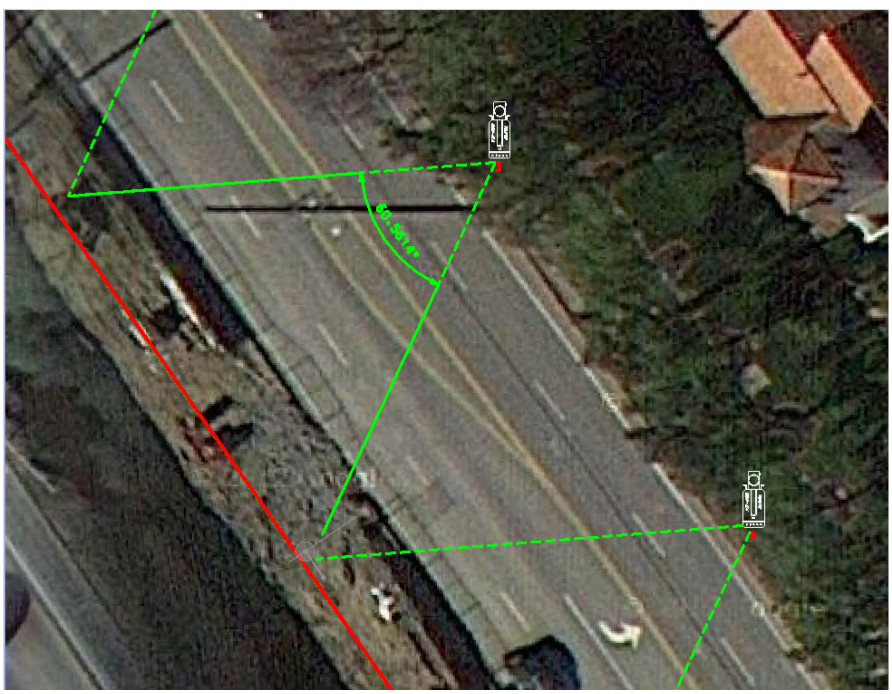


Figure 37: Top View Scanner Position-Wall Alignment (TopoDOT™)

Step 3: Record Lineage to Survey Control

LiDAR scanner data is typically oriented within the project coordinate system through resection from reference targets placed at known surveyed locations. Typically the scanner operating software will provide a summary table indicating the acquired targets, the matching control, standard deviation of fit as well as individual residual errors at each target. Thus for each scanner position there should be one summary report provided establishing the statistical fit between the located reference targets and corresponding control.

Corresponding tiepoints:	7	Avg. radial deviation [US-ft]:	0.0024
Standard deviation [US-ft]:	0.0073	Avg. theta deviation [US-ft]:	0.0007
		Avg. phi deviation [US-ft]:	0.0015

Name	Link	Ref...	F...	R...	S	P...	A...	R...	X	Y	Z	R	θ	φ	Δ X	Δ Y	Δ Z
tp001		1	t...	R...	0	2...	4...	2...	0.584	-19.390	0.207	1	8	2.	0.000	0.000	0.000
tp002	PRCS_002	0	t...	R...	0	1...	3...	2...	-144.7...	-24.154	-0.929	1	9	1.	-0.001	0.003	0.005
tp003	212	0	t...	R...	0	6...	3...	1...	-42.952	-5.362	1.868	4	8	1.	0.002	-0.010	-0.004
tp004	PRCS_003	0	t...	R...	0	9...	4...	2...	-42.811	-5.761	-0.477	4	9	1.	0.002	-0.004	0.002
tp005	516	0	t...	R...	0	2...	4...	2...	-55.032	-5.217	-0.207	5	9	1.	-0.009	-0.002	-0.008
tp006		0	t...	R...	0	5...	3...	2...	-65.866	105.932	18.027	1	8	1.	0.000	0.000	0.000
tp007	168862	0	t...	R...	0	2...	3...	2...	172.210	122.908	12.263	2	8	3.	0.013	-0.008	-0.001
tp008	514	0	t...	R...	0	1...	3...	2...	237.457	20.358	-2.932	2	9	4.	0.001	0.015	0.004
tp009	PRCS_004	0	t...	R...	0	1...	3...	2...	127.913	4.742	-2.228	1	9	2.	0.002	-0.001	-0.003

Figure 38: Summary of fit between scanner reference targets and survey control (RiScan Pro)

Step 4: Assessment of Relative Alignment

As described earlier, the relevant alignment of LiDAR scan data provides a clear indication of the overall data integrity given the enormous amount of common surfaces covered by adjacent scan positions. It should be noted that the wall itself would not be a reliable indicator of data alignment for comparing data acquired at different times—say several days or weeks apart. This is obvious as the wall is expected to move. However comparison of overlapping scan data over common surfaces such as buildings, roads, poles, etc. not expected to move between scanning operations provides a clear indication that the scan data is well aligned and consequently differences in the scan data at the wall result from actual wall movement.

Step 5: Summarize TopoDOT™ Wall Monitoring Results

The TopoDOT™ wall monitoring tool suite has been designed to automatically extract a comprehensive and easily understood summary of wall monitoring results. Extracted spreadsheets summarizing result at each panel will be key deliverables. Note that the report should clearly indicate which data sets are being compared along with relevant dates at which data was acquired.

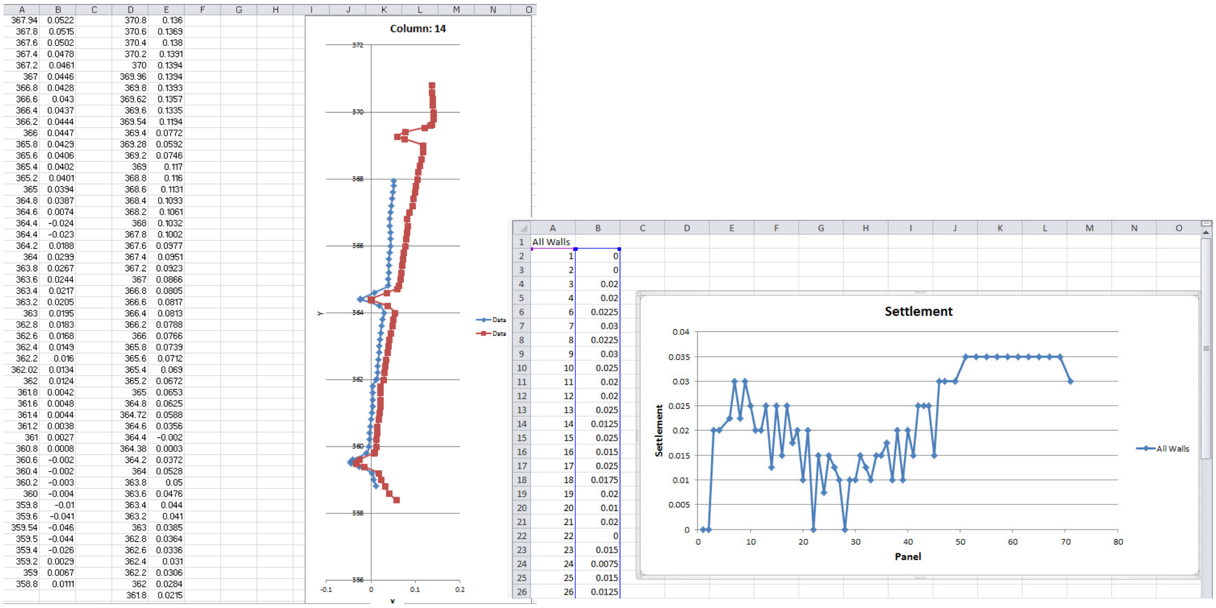
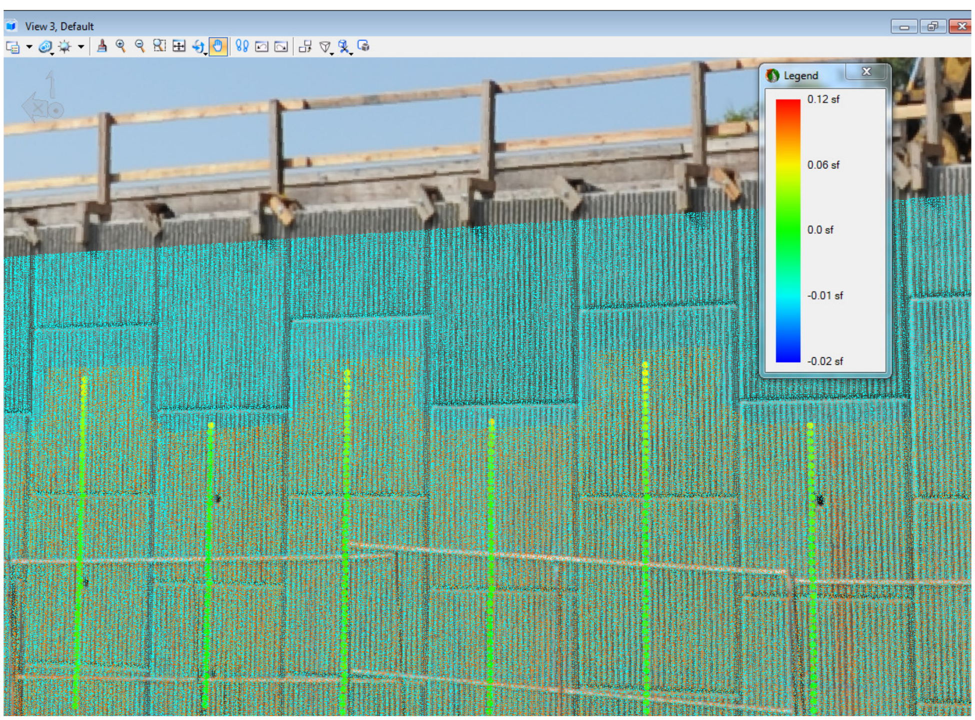


Figure 39: TopoDOT™ spreadsheet deliverables

In addition to the data represented in the spreadsheet format, TopoDOT™ offers very unique and useful deliverables in the form of encoded CAD elements projected onto calibrated images. Relevant images can be extracted and included as useful components of any final report.



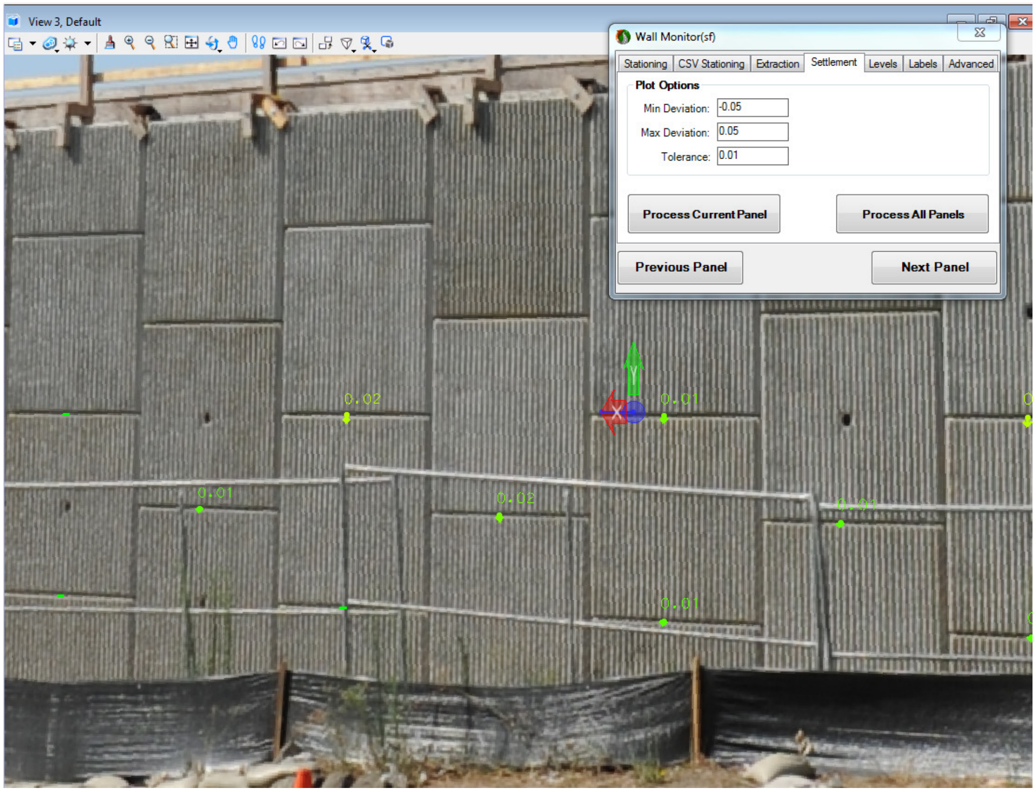


Figure 40: TopoDOT™ extracted elements projected onto calibrated image

Step 6: Conclusions

Any report should conclude with a summary of results based on the interpretation of the TopoDOT™ wall monitoring results. These results are fundamentally distance measurements. Thus these measurements should be evaluated within the context of time between data acquisition such that “rates” of movement are inferred.

One should note that given the inherent redundancy and coverage of LiDAR data, any inference of movement can be further validated by employing TopoDOT™ tools in supporting analyses.

For example, suppose TopoDOT™ extracts measurements indicating a wall “tilt” movement between two data sets. Several additional cross-sections might be made against buildings, roads, etc. between those data sets to confirm alignment. Close alignment on these common surfaces would further validate wall movement as one would not expect the scanner data to be exclusively misaligned on the wall only—hence the earlier recommendation of 360 scans at each position. Of course any misalignment of those common surfaces might indicate an overall data tilt necessitating a review of the original data.

Thus any report might end with conclusions and a brief comment on additional validation of results.

Certainty 3D offers this document as suggested guidelines for employing TopoDOT™ in wall monitoring operations. Final decisions as to the methods, processes, reporting, etc. are the sole responsibility of the TopoDOT™ user. Please contact Certainty 3D for training, recommendations or suggestions as to how these processes and TopoDOT™ might be improved.

Questions and/or Comments
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