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November 2019 Initial Deployment of LiDAR in the H-Canyon Exhaust Tunnel

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Executive Summary

The H-Canyon Exhaust Tunnel (CAEX) structure is periodically inspected under the Structural Integrity Program [1] using camera equipped crawlers or poles to remotely perform visual inspections. To explore the use of enhanced inspection methods a "Proof of Concept" using the Light Detection and Ranging (LiDAR) technology was performed over a 2-day period in November 2019. The purpose of the "Proof of Concept" deployment was to confirm whether a commercially available LiDAR unit could successfully operate and remotely transmit data from the tunnel CAEX environment and whether the data would provide quantitative information to establish baseline measurements. The LiDAR performance requirement was a measurement accuracy of ± 0.25-inches over a 30-foot distance [2].

This report documents the work activities leading to the deployment, the deployment and processing of data, lessons learned from the deployment and the post data processing methods that will be applied to future deployments.

The LiDAR system included a vendor customized pole with a Leica BLK360 LiDAR unit attached to the end which was deployed into the underground CAEX tunnel via a 6-inch pipe location referred to as the Pitot Tube location. The Leica BLK360 LiDAR system captures a full-color panoramic image overlaid on the high-accuracy point cloud. Prior to the deployment the assembly was tested at the vendor's shop and on-site in mock-up tunnel conditions. The LiDAR unit successfully operated on Day-1 of the deployment to perform 3 scans at 3 different elevations for a total of 9 scans. On Day-2 the LiDAR unit was not able to rotate and operate. No scans were performed. However, the information from Day-1 was sufficient to establish a baseline of interior surfaces.

Troubleshooting efforts were performed during the Day-2 and again one week after deployment, unfortunately these efforts did not resolve issues. Discussions with the Leica BLK360 LiDAR company suggested too much strain on the scanners' horizontal axis. Several factors such as the use of a slip ring to mount the LiDAR unit onto the pole, airborne debris and wind velocity in the tunnel may have contributed to this problem. It is unknown whether these items individually or collectively affected the LiDAR unit's ability to rotate and scan. Lessons Learned will be incorporated into future deployments.

Custom software provided with the Leica BLK360 LiDAR unit successfully obtained data and merged scans resulting in high accuracy point clouds. High resolution images and contour maps indicating surfaces features were obtained. However, the specificity required to compare wall and ceiling surfaces and establish a baseline with quantifiable interior measurements was beyond the Leica and Autodesk software capability. The publicly available opensource software CloudCompare, a 3-D point cloud processing program was used. The large amount of data collected from the 9 scans, over 500,000,000 points, overwhelmed the software and standard computer processing capability. Lessons Learned such as the selection of tunnel segments to compare point clouds, methods to determine interior dimensions, greater computer capability requirements and CloudCompare software limitations were identified. Knowledge obtained will be applied for subsequent post-processing.

Three methods to establish surface baseline measurements were developed: 1) Wall to Wall, 2) Horizontal Artificial Plane to Ceiling, and 3) Vertical Artificial Plane to Wall Comparisons. Subsequent deployments will use these methods to determine changes in the ceiling and walls. The results to-date provide a high confidence in baseline measurement values over a 19-foot distance in the tunnel.

Summary of Changes		
Revision	Description	Date
0	Initial	10/21/20

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1.0 Purpose

The 2019 deployment of the LiDAR technology in the underground H-Area Canyon Exhaust (CAEX) Tunnel Structure was a "Proof of Concept" to confirm a commercially available LiDAR unit could successfully operate and remotely transmit data from the tunnel CAEX environment and that post-processing would provide quantitative data of tunnel interior surfaces to establish a baseline from which a rate of change over multiple deployments will be determined.

The purpose of this Engineering Study Report (ESR) is to compile in a single document the:

1) Development,
2) Preparation,
3) Initial deployment of LiDAR,
4) The post processing of data to establish a benchmark of interior tunnel measurements for future rate of surface change determination,
5) Lessons learned from the deployment and post processing of data, and
6) Path forward for future LiDAR deployments and methods to determine a rate of surface change

Work activities were performed by Savannah River National Laboratory (SRNL) Research and Development Engineering (R&DE), SRNS Procurement, H-Area Operations and Engineering Organizations, and vendor James Fisher Technologies (JFT).

2.0 Background

2.1 Structural Integrity Program CAEX Tunnel Inspections (2014-2017)

The underground reinforced concrete CAEX Tunnel Structure is located between 221-H and 294-H and has been in service since the 1950's, see Figure 2.2-1. The Tunnel provides the Safety Class (SC) function to direct and confine 221-H Canyon process airflow to the Sand Filter System. As a passive design feature, the Tunnel is available 100% of the time.

The CAEX Tunnel is periodically inspected under the H-Area Structural Integrity Program (SIP) [1]. The SIP performs in-service inspections of SC and Safety Significant (SS) passive design features to confirm conditions can perform their credited safety function and provides assurance that if evidence of degradation is detected, corrective actions can be performed before the safety function is compromised. Inspection information is evaluated against qualification calculations to verify no change to the design feature qualification conclusions. If as-found conditions do impact design feature qualification conclusions, the Potential Inadequacy in the Safety Analysis (PISA) [3] process is initiated.

Due to chemical and radiological conditions in the tunnel, visual inspections are performed with remote crawlers equipped with video cameras that travel the entire tunnel route and with pole cameras inserted into existing pipe penetrations to view local areas. Interior surface degradation ranging from roughened surfaces with exposed aggregate to exposed interior reinforcement (rebar) have been observed. Degradation along the tunnel route is not consistent. Periodic inspections reinspect areas and compare with previous inspections looking for changes. Exposed interior rebar observed on the walls and ceiling during the crawler inspections has been documented on SIP reports since 2014 [4, 5, 6].

The degradation observed to-date and information from concrete core testing and soil testing led to the qualification calculation. Nonlinear Fragility Probabilistic Analysis [7] performed in 2019 to confirm the Tunnel can perform during normal operations and during a seismic event. The Tunnel is a reinforced concrete structure with 2 sets of rebar mats in the walls, floor and ceiling. An outer rebar mat is near the tunnel exterior and an inner rebar mat is near the tunnel interior. The Tunnel Nonlinear Analysis regards the tunnel interior reinforcement as ineffective, i.e. thus presuming the tunnel wall, floor and ceiling rebar surfaces are exposed. This condition is more conservative than current conditions. Visual re-inspections are assessed to:

1) Confirm conditions remain bounded by the qualification calculation [7] by visual observation of exposed interior rebar and
2) Determine a degradation rate of surface change to predict remaining service life.

While visual inspections do provide information to confirm tunnel conditions meet qualifications and it does not appear any significant changes have occurred since 2014, the inspections do not provide measurable information to predict a rate of change to determine tunnel remaining service life. The question of remaining Tunnel service life is important for H-Area Mission planning. Currently, only qualitative predictions can be made. Qualitative based predictions may be difficult to justify due to changes in crawler camera resolutions, lighting and angle views over multiple crawler inspections.

2.2 LiDAR Technology for Tunnel Use

Following the March 2017 SIP crawler inspection of the Tunnel, the need for an enhanced robotic platform and use of other inspection technologies beyond visual camera was identified. Although the 2017 robotic platform did complete the SIP inspection, the vehicle had difficulty traversing obstacles, the camera resolution was less than desired, and there was no ability to view the wall surfaces behind the abandoned-in-place duct. Also, the crawler could not travel over a 1-foot step to complete inspection of the 1970's CAEX Tunnel. The plan was to procure a new crawler for the 2019 SIP inspection.

The DOE-EM Office of Technology Development as part of the H-Canyon Collaborative Advanced Technology Demonstration (ATD) sponsored the Concrete Integrated Project Team, a panel of DOE complex wide and University personnel with input from H-Canyon personnel to evaluate enhanced robotic platforms and several sensor technologies such as 3-Dimensional (3-D) Mapping, Non-Destructive Examination (NDE) Concrete Mapping, Chemical analysis of degraded concrete, and a sensor changer/multiple axis arm to accommodate a second sensor. Of the sensors evaluated, 3-D Mapping via the LiDAR technology appeared to be the most promising and commercially available for the March 2019 SIP inspection. The purpose of 3-Dimensional Mapping is to provide measurable dimensions within the tunnel, any changes in tunnel interior dimensions between inspections would allow establishment of a rate of surface change. This knowledge along with H- Area Mission knowledge and visual inspections would be the basis for predicting the remaining tunnel service life.

In early FY2018, it became apparent that the DOE-EM Office of Technology Development ATD, would not be available to help fund a robotic platform with a multiple axis arm for several sensor technologies. SRNS developed a specification [8] and requested vendor quotes for an enhanced robotic platform. When no acceptable quotes were received that met the budget and schedule, the decision was made for SRNL to fabricate the 2019 crawler platform with higher resolution cameras, robust ability to traverse obstacles and the ability to elevate cameras to view wall surfaces behind the abandoned-in-place ducts. The new

2019 crawler would perform the visual inspection in March to satisfy the SIP requirement without LiDAR technology [9].

ATD did sponsor several graduate students in the Summer of 2018 at SRNL. The students evaluated several LiDAR 3-Dimensional Mapping Sensor suites; Hokuyo and Faro units. The results were encouraging for use in the Tunnel, however the following concerns required resolution before having high confidence in a successful LiDAR crawler deployment:

1. Does the wind/airborne debris/ moisture environment affect unit operation?
2. Will use of an external power source vs. battery power affect operation?
3. Can the unit reliably relay data from inside Tunnel to outside the Tunnel?
4. Are the measurements accurate within $\pm$0.25 inches over a 30 feet distance?
5. Are measurements consistent at different elevations?
6. What is the best elevation for the LiDAR to scan the entire tunnel surface?
7. How many scans are required at each location?
8. Does the number of scans affect accuracy?
9. What is the effect of the abandoned-in-place Stainless-Steel exhaust ducts on scans?
10. What are the software and hardware requirements for post-processing of data?

In early FY19, the decision was made to deploy LiDAR technology at a local area of the tunnel through an existing 6-inch pipe penetration known as the Pitot Tube location shown in Figure 2.2-1. This is the only accessible location along the tunnel route between 221-H and 294-H. This first-time deployment would be a “Proof of Concept” for LiDAR. A LiDAR unit would be attached to a pole or stick to insert into the CAEX Tunnel. The deployment would occur in November 2019 and would be separate from the March 2019 SIP crawler inspection. The team recognized that although deployment via a stationary pole is different from deployment on a crawler, many of the previously mentioned concerns could be evaluated.

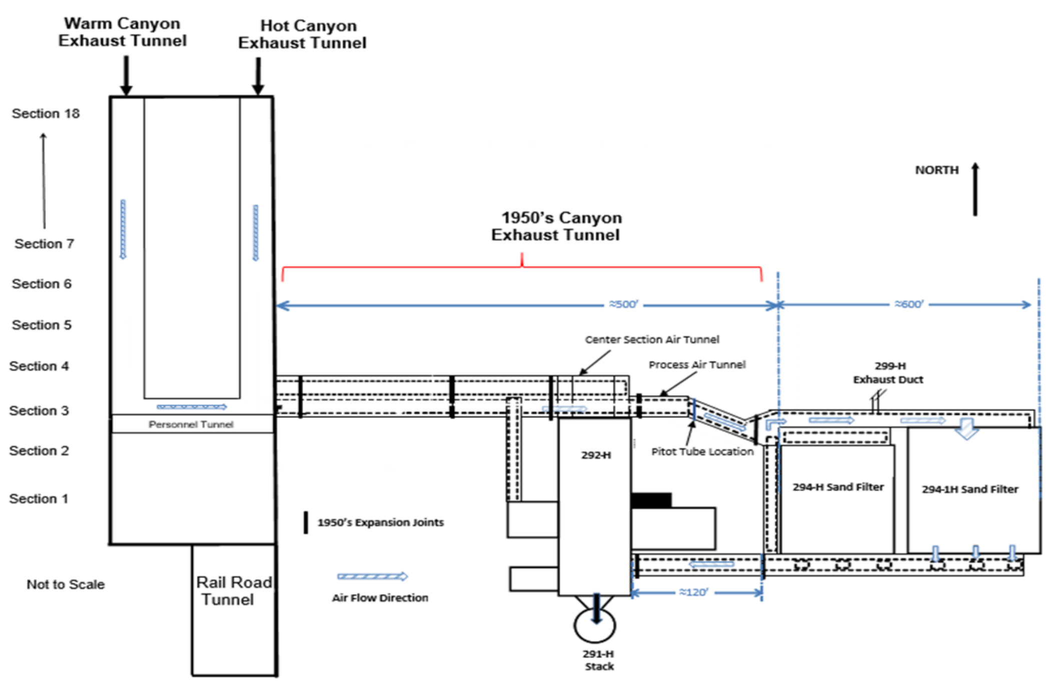


Figure 2.2-1 Diagram of CAEX Tunnel with Pitot Tube Location

SRNL and H-Area personnel developed a procurement specification [2] for "LiDAR on a Stick "(LiDS) that was competitively bid. Key technical and performance requirements included:

- Robust operation for multiple deployments
- Ability to produce a 3-D point cloud with an accuracy of 0.25-inches or better at 30 feet
- Ability to scan at 3 different and repeatable elevations
- Strong preference for data to be collected remotely and real-time vs. post-deployment data collection
- Strong preference for wired power over a short life battery requiring multiple battery change outs during deployment.

The subcontract to design, fabricate, assemble, and functionally test a LiDAR assembly was awarded to James Fisher Technologies (JFT), LLC in June 2019 [10]. JFT designed a pole that could be lifted with a crane, be inserted into the 6-inch pipe and be adjusted to three elevations within the Tunnel to scan the tunnel interior as shown in Figures 2.2-2 and 2.2-3. Data from the scanner would be remotely (wireless) transmitted to a computer located in a nearby temporary control area. JFT selected a commercially available Leica BLK360 LiDAR scanner unit to attach to the pole. The JFT selection of the LiDAR unit was limited by the physical configuration of the 6-inch pipe entry.

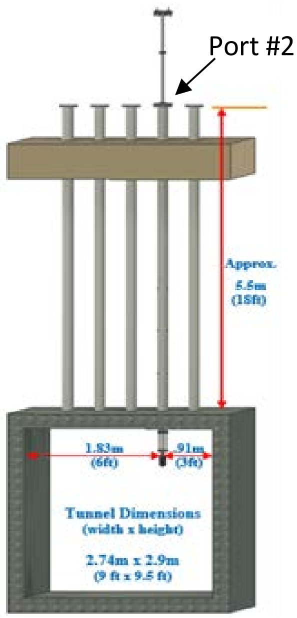


Figure 2.2-2 Conceptual LiDAR System shown inserted into pipe location and tunnel dimensions at Pitot Tube Location

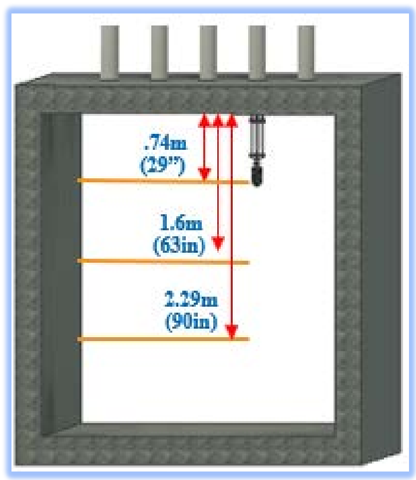


Figure 2.2-3 Three scan heights employed to reduce blind spots in results.

The Leica BLK360 LiDAR system captures a full-color panoramic image overlaid on the high-accuracy point cloud. The LiDAR is controlled remotely using an iPad Pro running the software, Autodesk Recap Pro Mobile. Scan data collected on the iPad Pro is then uploaded to a computer running Recap Pro software where the point cloud data can be registered, and, if desired, exported in common industry formats for alternative processing.

Due to the orientation of the Leica BLK360 LiDAR scanner in the tunnel, it was known that there would be blind spots as noted in Figure 2.2-4. Blind spots are areas that result in a point cloud with no points. The blind spots show as black regions on contour maps and images. Leica recommends a best scan distance from 3-feet to 10-feet. Objects within 2-ft will be in a blind spot. The BLK360 has a 60-degree angle cone facing the ceiling of the tunnel. This equates to a circular blind spot of approximately 32 inches in the ceiling of the resultant post-processed point cloud data.

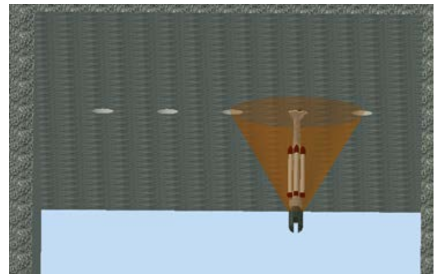


Figure 2.2-4 Blind Spot on the Ceiling due to configuration of LiDS

JFT customized the unit to provide continuous power for the Leica unit operations vs. reliance on battery power to eliminate the need to retrieve the pole due to low battery power. Additionally, at the end of the pole were four (4) dimmable Light Emitting Diode (LED) light strips for illuminating the light deprived environment and whose intensity is controllable from the above ground control station. A Wi-Fi access point is mounted at the top bottom section of the pole to bridge the communication network from the underground LiDAR to the above ground remote-control station where a second Wi-Fi access point is located. Centralizing wheels were located on the lower portion of the pole for scanner stabilization in the high wind velocity of the tunnel.

JFT design drawings, materials list and Functional Acceptance Test (FAT) procedure were reviewed by SRNS prior to JFT proceeding. Weekly in-progress telecons were held with JFT, SRNL, H-Area Operations and Engineering to status the JFT schedule, discuss any technical queries, and review of open action items. Technical topics discussed included SRNS field conditions, slip ring impact on LiDAR rotating operation, stabilization of pole in the tunnel wind environment, materials of construction, dust and moisture impact on scanner, and remote transmission of data. Figure 2.2-5 depicts the JFT LiDS assembly that entered the tunnel.

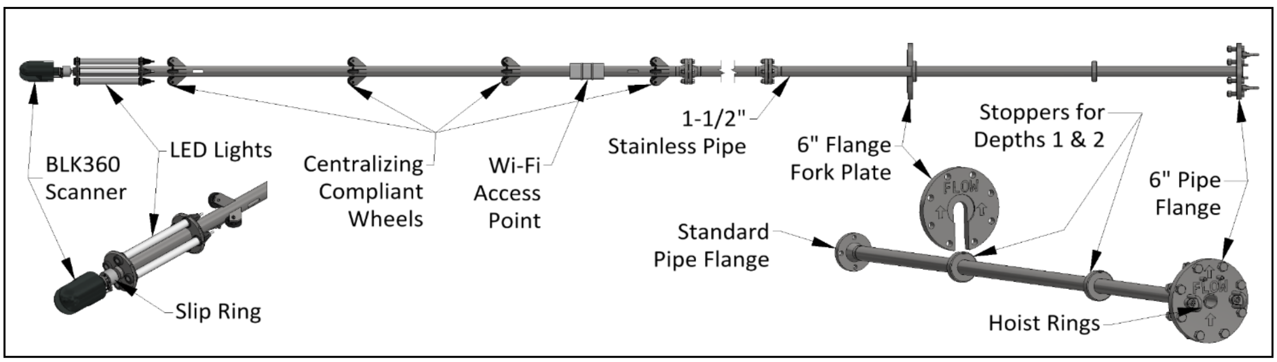


Figure 2.2-5 JFT Custom LiDAR on a Stick (LIDS) Assembly

The FAT was successfully performed in September 2019 at the JFT facility. Personnel from SRNL and H-Area Operations witnessed the test. The FAT simulated wind effects on the LiDAR unit with a fan and demonstrated the ability to remotely control and transmit data. The completed assembly was received by SRNL in early October 2019.

In parallel SRNL R&DE purchased a similar Leica BLK360 unit with SRNL funds to become familiar with the unit operation and software for data post processing. Experience gained from this unit and it's accompanied software package(s) was invaluable in technical discussions with JFT and later for mock-up testing of the JFT furnished assembly and deployment planning.

3.0 LiDAR Deployment Preparation

3.1 Mock-up Testing with SRNL BLK360

Given the short timeline between receipt of the JFT custom procured LiDAR system and the planned deployment date, a Leica BLK360 LiDAR unit with associated software was procured by SRNL R&DE to become familiar with the unit operation, software, and expected performance while JFT completed the custom system. To facilitate system familiarization and to obtain input for the field deployment plan, the BLK360 LiDAR was deployed in a mock-up of the H-Area CAEX Tunnel to test the performance of the unit. The goals of this performance test included:

- Simulate H-Area CAEX Tunnel surfaces
- Determine adequacy of software (Recap Pro Mobile and Recap Pro) to perform desired tasks
- Perform scans at simulated deployment heights
- Demonstrate LiDAR accuracy measurement to be within +/- 0.25-inch tolerance
- Test repeatability between scans
- Simulate erosion with an adjustable surface
- Examine interior wind (air flow) effect on measurements

<u>Mock-Up Test Setup</u>

A mock-up of the tunnel was located outside of 781-A, see Figures 3.1-1 and 3.1-2. Aluminum alloy 6105-T5 (80/20) was used to construct the frame of the mock-up tunnel. Faux stone walls made with veneer were affixed to the inside of Alumalite walls that served as the mock-up tunnel surface walls. The test setup included adjustable moving walls to simulate changes in interior dimensions. A tarp was draped over the tunnel frame to simulate the dark environment of the H-Area CAEX Tunnel. A piece of paper with a 3-by-3 matrix of circles with 1-inch horizontal by 1-inch vertical spacing was taped to both mock-up tunnel walls, see Figure 3.1-3. The vertical and horizontal placement of the paper on each wall was aligned using both a tape measure and a Bosch Blaze Pro 165’ Laser Distance Measure GLM 165-40. The Blaze Pro was used to measure the distance between the center circles on each wall prior to performing the initial test each day and after each LiDAR height change. The LiDAR was mounted upside down using a metal pole and Leica Art.-Nr.:853639, a tripod head. Illumination in the dark environment was provided by 4 Banner HLS27 LED strip lights on the maximum setting attached to the pole above the LiDAR.

The tests involved the mock-up LiDAR unit set-up at:

- 3 elevations (18”, 48” and 81” off the ground of the test area),
- Simulated tunnel air exhaust flow conditions, and
- Adjustment of the distance between walls to simulate changing interior dimensions

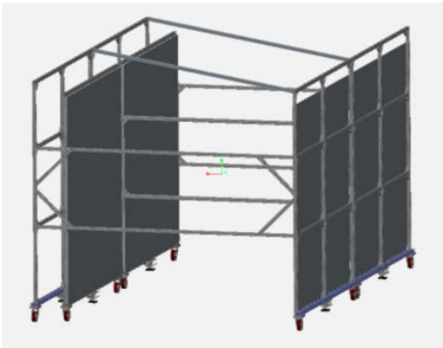


Figure 3.1-1 – Initial Tunnel Mock-up Design

Figure 3.1-2 – Photo of Tunnel Mock-up interior

Figure 3.1-3 – Photo of 3-by-3 Matrix Used to Take Measurements

Software Used

Software corporation, Autodesk and the LiDAR unit Leica company teamed together to provide an iPad application named Recap Pro Mobile for use with the BLK360 unit. Recap Pro Mobile software is used to obtain raw scan data. The data is then transferred to Recap Pro to merge scans. Autodesk provides Recap Pro for multiple imaging and surveying equipment including Leica products such as the BLK360 for use on a standard personal computer. These software packages were used for the demonstration.

Test Measurements

The LiDAR point cloud data was collected on an iPad Pro using Recap Pro Mobile software. A total of 26 test scans were performed over a two-day period. The distance between the center circles on each wall was measured in the LiDAR point cloud data for each test scan on the iPad Pro. A point in each center circle was selected by the user while utilizing the respective distance tool in Recap Pro Mobile and Recap Pro. The 26 individual test measurements are graphed in Figure 3.1-4. The distance between the center circles on each wall was measured in the LiDAR point cloud data for each test scan on the iPad Pro. All the data collected was within the ±0.25-inch tolerance except for 3 points. Wind gusts on the mock-up located outside contributed to these values being outside of the tolerance range.

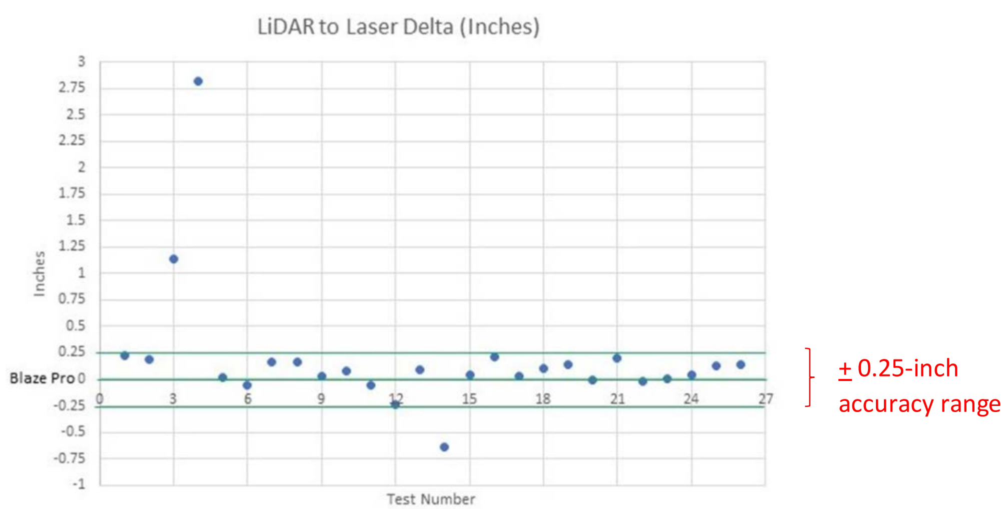


Figure 3.1-4 LiDAR Performance of 26 Individual Scans

Each of 26 test sets were then transferred from the iPad Pro to a laptop with Recap Pro. Distances between the center red circle on each wall were measured in the resulting Recap Pro merged point cloud sets. Scans were successfully performed at different heights. The previous wind impacted data had no noticeable effect on measurement accuracy. Figure 3.1-5, Merged Point Cloud chart depicts the results of the merged sets. Three tests with the variability of unit elevation were merged. The merged scans met the tolerance of ± 0.25-inches.

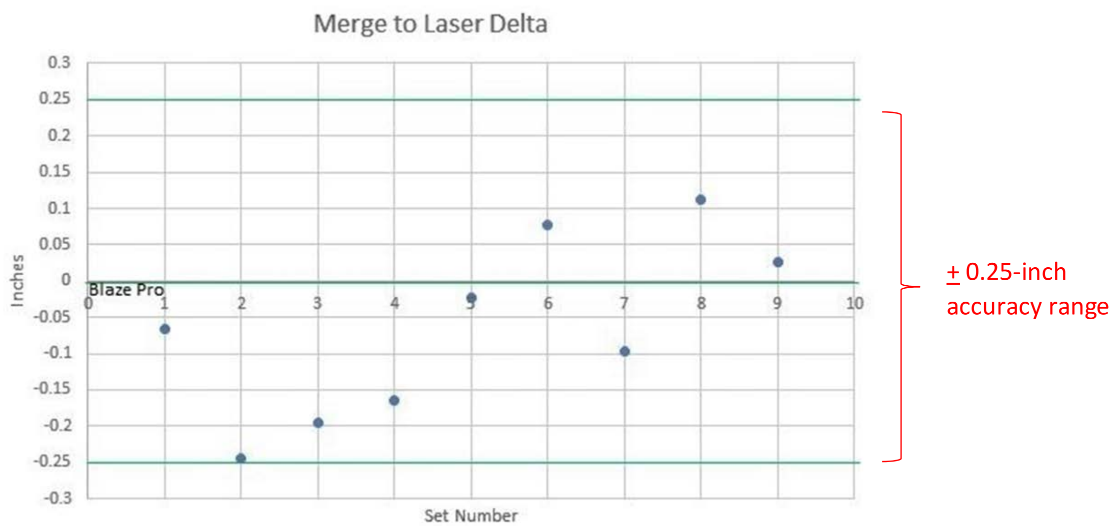


Figure 3.1-5 Merged Point Cloud LiDAR Performance

From the test, it was noted that individual scan values are not indicative of merged scan results. All merged point cloud measurements were within goal tolerance even though some sets had individual points that were out of tolerance. Test measurement data collected over the two-day period and merged scan data is provided in Attachment A.

The image quality in Recap Pro Mobile is sharper (higher resolution) than in Recap Pro, which made finding point cloud points within the target circle easier. This is a contributing factor to differences in the merged and individual scan measurements. The tools available within Recap Pro are not enough for deriving a correlation between individual scans and their respective merged sets. A software solution that can compare entire sections of uneven surfaces was still required.

3.2 Selection of Software and Requirements for the Computer System

Mock-up testing confirmed the need for additional software capable of performing point cloud comparisons to determine dimension changes. Several software suites were evaluated and CloudCompare was selected to provide the needed additional processing capabilities. CloudCompare is a publicly available opensource 3D point cloud processing software.

3.3 Vendor JFT Functional Acceptance Test

On September 17, 2019 JFT performed a Functional Acceptance Test (FAT) at their facility in Loveland, Colorado with SRNL and H-Canyon personnel in attendance. The JFT FAT set up included a plywood mock-up of the tunnel with a 6” pipe penetration through the ceiling and a fan to simulate tunnel wind conditions. The mock-up tunnel walls were moveable to simulate changing interior dimensions. A total of 6 scans at the three different elevations were successfully performed.

Table 3.3-1 lists the physical change measurements taken with a tape measure and the merged point cloud from the LIDs. The merged point cloud measurements were within the procurement specification accuracy tolerance requirement of $\pm$ 0.25-inches at 30 feet.

Table 3.3-1 Surface Depth Change Measurement (inches)

Block	Recap Pro	Tape Measure	Delta
A	1.371”	1.49”	-0.119
B	1.61”	1.79”	-0.18

The FAT demonstrated the LiDAR operation, ability to remotely transmit data, ability to deploy at three different elevations and operation of the LiDAR Recap Pro Mobile and Recap Pro software. Based on SRNS’s acceptance of the FAT, JFT prepared the LIDs for shipment. Appendix B contains additional information on the FAT performed at the JFT facility.

3.4 Receipt and Check-Out of JFT BLK360 System at SRS

On October 21, the LiDS System arrived in 781-A. All zip ties were replaced with larger zip ties. A First Article Inspection (FAI-51) was performed as well as an electrical safety evaluation on the vendor equipment. The LiDS assembly power and data system connectivity was tested with the unit in the horizontal position. A stand which also served as a stabilizer for the assembly was built out of aluminum alloy 6105-T5 (80/20). This stand was affixed to a Cotterman 10’ 450 lbs. load ladder. The LiDS lower assembly without the LiDAR attached was lifted and fastened to the stand. The LiDAR was attached to the rest of the lower assembly.

Figure 3.4-1 BLK360 with Slip Ring and Banner LED Lights

Figure 3.4-1 shows the LiDS lower assembly in 781-A. The JFT supplied power cable consists of four sections. All sections of the power cable were connected to confirm differing plug and socket configuration continuity. The power box was powered by an uninterruptable power supply (UPS). A scan was performed successfully while connecting to the BLK360 directly. A scan was initiated using the LiDS network setup and an error message was received. A browser was opened on the JFT supplied desktop and a connection to the BLK360’s intranet webpage was made. The firmware page was accessed. The “Search for Scanners” button was pushed in

Recap Pro Mobile on the iPad and a connection was established. A scan was successfully performed from a remote location to ensure transmission of data. A demonstration was performed for H-Canyon personnel.

Figures 3.4-2 and 3.4-3 show the LiDS power and Data system

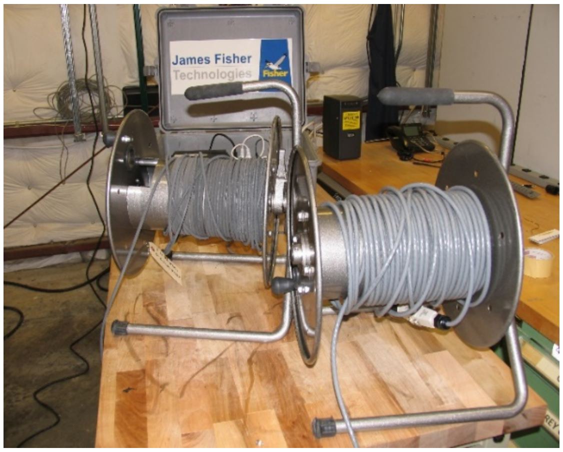


Figure 3.4-2 – LiDS Power and Data Cable Reels

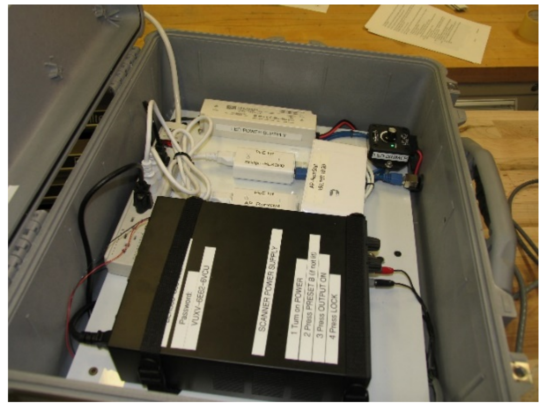


Figure 3.4-3 – LiDS Power and Data Box

Figure 3.4-4 is an image of an Ubiquiti NanoStation LocoM2 wireless repeater configured in station mode shown affixed to the deployment pole.

Figure 3.4-4 - NanoStation LocoM2

The BLK360 was left powered on overnight. A scan was successfully performed the following morning. A series of scans with different camera lighting settings were performed. The images obtained prompted the decision to perform a brief lighting test on the first deployment day with a low-resolution scan prior to performing high-resolution scans. SRNL also tested remote positioning the LiDAR to face a desired direction by starting a low-resolution scan and canceling that scan once the desired rotation was achieved. The desired rotation was obtained by viewing the images produced by the BLK360 in real time. This step was to confirm the ability to position the laser and mirror away from the face of wind to protect them from airborne debris when not in use between the 1st and 2nd days of deployments.

3.5 Deployment Planning

To determine the number of multiple scans at each deployment elevation, ten scans were performed at the same location using the SRNL LiDAR. The scans were merged into groups. By visual inspection and comparison of the data groups, it was determined that desired point density was not significantly affected when merging more than 6 scans. It was likewise determined 3 scans would provide the minimal point coverage desired for surveying the CAEX tunnel interior. Thus, a merged set with 3 scans performed at each deployment elevation would be performed one day and a merged set with 6 scans performed at each deployment elevation would be performed on the other day.

Due to the time it would take to perform the initial setup, the performance of 6 scans at each elevation was delayed until Day-2. Both days scans would be analyzed, and their accuracy compared using known dimensions of objects in the HCAEX tunnel. It would be determined during post data processing whether the 6 scans performed at the same elevation provided additional accuracy over the 3 scans performed at the same elevations. This evaluation would aid with future deployment planning.

4.0 Deployment

The deployment team consisted of H-Area Facility Operations, Maintenance, Quality Assurance and Engineering, Rigging, Radiological Protection, SRNL R&D Engineering and the JFT vendor should on-site technical support of the LiDS be required. A radiological contamination control windbreak was installed around the pitot tube entry platform, shown in Figure 4.0-1. The LiDS control equipment and LiDAR data acquisition iPAD and computer with real-time viewing were setup in a Mobile Mini trailer near the pitot tube location shown in Figure 4.0-2. A portable generator was temporarily installed next to the Mobile Mini trailer to provide power. The Leica BLK360 LiDAR was modified so that it could be remotely powered to eliminate the need to remove the LiDAR from the tunnel to swap batteries. The generator at the remote mini mobile location was used as the power source. A Tripp-Lite UPS unit was used between the generator and custom LiDAR system to provide conditioned power.

Deployment Day 1

On Monday November 4, 2019, after completing the pre-job brief, the team assembled at the pitot tube site to perform the LiDS checkout and startup. The BLK360 LiDAR required the power button located on the unit to be depressed to initially power on the unit. During the initial checkout, data communications could not be established between the LiDAR unit and the data collection iPAD located in the mini-mobile. Troubleshooting indicated that one of the four cables comprising the data and power feed had a bad connector. The power and data cables were designed in links to facilitate deployment. The defective cable was removed, and the communications link was established.

Figure 4.0-1 Staging of LiDS system for crane lift. Pitot tube radiological windbreak shown in background.

Once the LiDS system was operating correctly, the LiDAR scanner, which was mounted on a 25-foot pole, was lowered by crane through the 6-inch pitot tube pipe entry into the tunnel as shown in Figure 4.0-3. The crane positioned the LiDAR into the tunnel at the highest planned measurement location. Several low-resolution scans with the pole LED lighting set at various intensities were performed to determine the optimal lighting level. Low resolution scans can be collected in approximately 2 minutes versus the high-resolution scan collection time of approximately 11 minutes. It was determined that scans would be collected with the lighting intensity set at 100%. The LiDAR unit successfully collected the planned 3 scans at each of the 3 heights providing for a baseline data set.

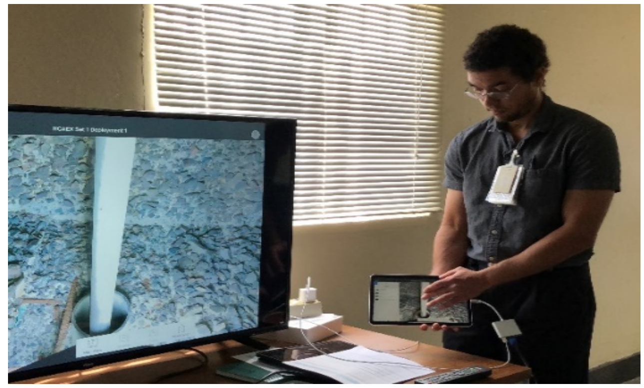


Figure 4.0-2 Live data feed from the LiDAR in the tunnel to iPAD located in Mini Mobile

At the end of the day, the deployment pole was maintained in the lowest deployment location allowing for the pole flange to cover the pitot tube opening to secure the system overnight. The LiDAR was remotely turned so that it's mirrors would face away from tunnel air flow with grit and be protected. The Mobile Mini generator remained operational to supply continuous power to the LiDAR unit as a loss of power would require the unit to be raised from the tunnel to manually power up the scanner.

Figure 4.0-3 LiDAR inspection pole being lowered into pitot tube.

<u>Deployment Day 2</u>

Upon returning on Tuesday November 5th morning the generator had shut down unexpectedly during the night. The LiDAR was lifted out of the tunnel and the power button depressed to turn on the unit. The Wi-Fi connection from the iPAD to the unit was verified and the LiDAR lowered into the tunnel. Once positioned in the tunnel, a scan was initiated from the IPAD. The LiDAR system would begin rotation of its 360-degree panoramic scan, stop after approximately 120 degrees then produce a "Slow Axis Stalled" error followed by a "Scan Aborted" error.

During the troubleshooting session, the LiDAR unit was removed and reinserted into the pitot tube several times along with the battery being installed into and out of the LiDAR device. Each time the LiDAR unit, slipring and cables were checked for visible degradation. The removal of the LiDS from the tunnel and the replacement of the LiDAR scanner battery in the hut proved to be easier than anticipated. After a series of failed troubleshooting efforts including contacting the Leica technical support, the LiDS was relocated to a radiological contaminated storage area and the pitot tube area resealed. The second day planned scans were unable to be obtained.

Appendix C documents the iPAD error messages received and the physical steps taken during troubleshooting.

5.0 Deployment Issues and Lessons Learned

Under the Leica service agreement, the company offered to send a replacement BLK360 if we would return the failed unit for troubleshooting at their facility; however, since the device had been introduced into a radiological and chemical environment, this was not a viable option. In order to assist in troubleshooting without having access to the device, Leica requested SRNL to download the activity log from the LiDAR and provide it to them for failure evaluation.

Figure 5.0-1 LiDAR troubleshooting and activity log acquisition

The log was acquired the week following the deployment along with several suggested but unproductive troubleshooting activities performed at the radiological controlled area where the LiDAR system was stored see Figure 5.0-1.

Leica responded after examining the logs that the "Slow Axis Stalled" errors indicate the horizontal rotation axis drives were not working and the factory suspects that the error was caused by too much strain on the scanner's horizontal axis. They stated that the system "is not very over designed and so any additional strain induced by the installed slip ring or wires could very easily cause this error." To emphasize this point, they noted that the system could be operated vertically, but even operating the unit horizontally could harm the LiDAR bearings and motors involved with the horizontal axis rotation.

The unrecoverable error was ultimately found to be the Leica BLK360 LiDAR unit. The team reviewed possible issues that affected the horizontal axis drives:

- Slip ring
- Airborne debris
- Tunnel airflow resistance to motor operation

A list of Lessons Learned from the Deployment that will be applied to subsequent deployments are noted in Table 5.0-1.

Table 5.0-1 Deployment Lessons Learned

Mitigation Actions for Future Deployments		
	Action	Basis
1	Power the BLK360 LiDAR using the battery versus modifying the scanner to operate on remote power.	Removing the pole from the tunnel to access the LiDAR scanner to install the battery as part of the troubleshooting process proved to be less onerous than originally thought. Operating on battery power means that the slip ring can be disconnected and any extra drag from the slip ring removed. The custom modification to the device required the addition of a slip ring to allow the device to rotate freely on the end of the pole while being remotely powered, it is thought that the force of the drag to the slipring on the internal axis of the device could have contributed to its failure.
2	Remove the LiDAR scanner from the tunnel into the pitot tube for protection when not scanning, lunch break, overnight.	It was known that the BLK360 LiDAR IP54 rating was not as robust as the specified IP64 rating requested in the RFP for the tunnel environment, however the pitot tube 6" diameter physically limited the choice of commercially available LiDAR devices that could be used, and it was accepted as a risk. The industry is rapidly developing LiDAR technology and hardware; it is believed that more robust LiDAR scanners will soon be available. Additionally, strategies to increase the robustness or better protect more sensitive equipment in hazardous environments should be developed and/or implemented.
3	Perform LiDS deployment in one day.	When possible a one-day deployment is preferred. 1) Reduces the time the system is in the tunnel 2) Reduces chances for logistics failures
4	Fabricate spare cables	This single point of failure was highlighted during the deployment.

6.0 Data Acquired and Post Processing

The LiDAR unit was able to scan a nearly 200-foot section of the tunnel interior as highlighted in tan on the tunnel cross-section shown in Figure 6.0-1. The western section included the 36" abandon-in-place HB-Line exhaust duct and the eastern section terminated at the 1950's-1970's transition. Water located in the transition area low point showed up as a blind spot, i.e. the water surface is black on the contour map shown in Figure 6.0-2.

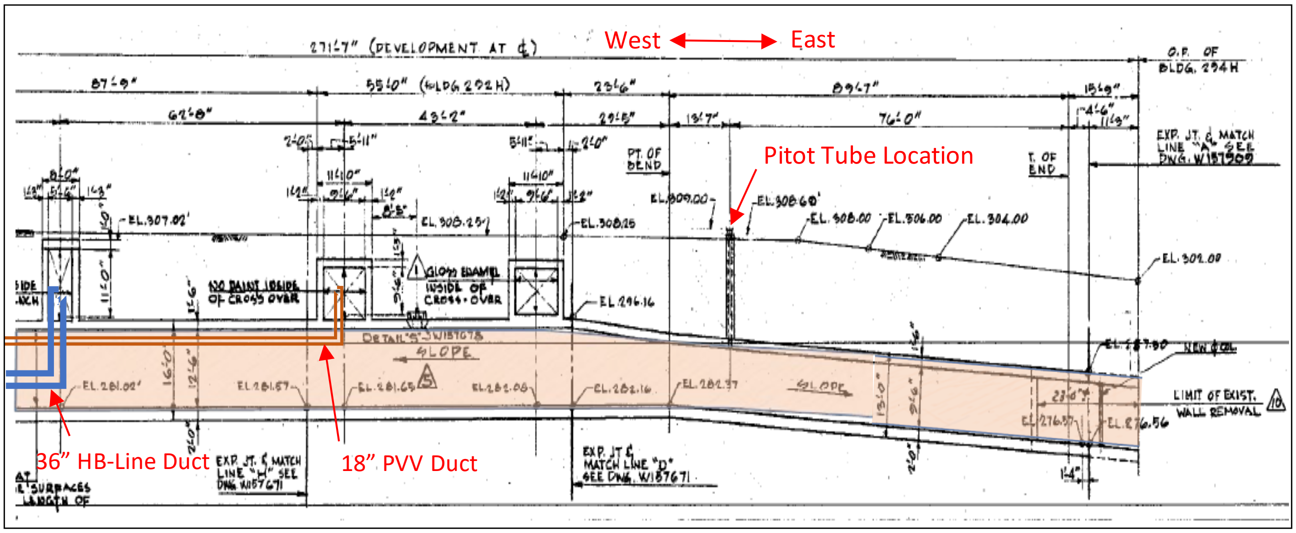


Figure 6.0-1- Cross-Section of Tunnel of LiDAR scanned area highlighted (excerpt from W157677)

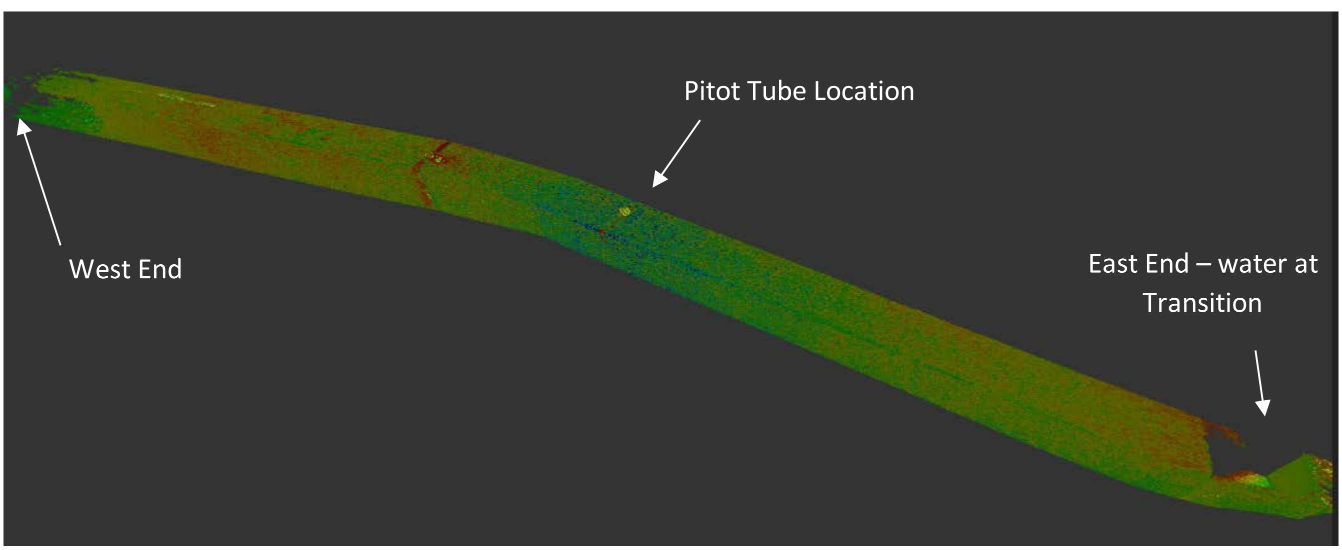


Figure 6.0-2 Contour Map of Scanning Limits

6.1 Data Acquired

Three high resolution LiDAR scans were completed at each of the three planned deployment heights, Figure 2.2-3, for a total of nine scans. With each scan, the Leica BLK360 LiDAR system captures a high-accuracy point cloud and a full-color panoramic image, as shown in Figure 6.1.-1. The point cloud range is limited by distance and laser line of sight to surfaces. The panoramic image is limited to the area lit by the deployment pole LED lights.

Figure 6.1-1 Partial view of 3D acquired point cloud (left) and High-resolution panoramic image (right)

The acquired point clouds are a set of data points in 3-dimensional space representing the surfaces being detected by the laser scanner. Each data point in the cloud has an X, Y and Z value based on the Cartesian coordinate system representing its location within the 3D space, Figure 6.1-2. In the tunnel point cloud, the X-axis is in the direction of the tunnel wall, the Y-axis is in the direction of the tunnel width and the Z-axis is in the direction of the tunnel height. The scanner software defines the coordinate origin of the point cloud (0,0,0) at the scanner location (top elevation for this case).

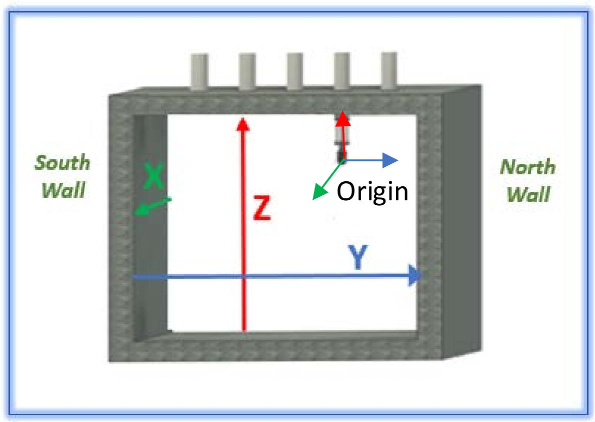
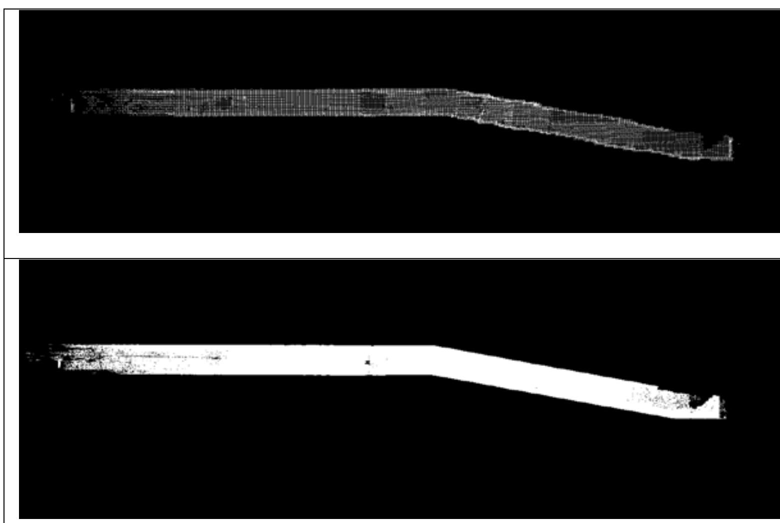


Figure 6.1-2 Tunnel Point Cloud Coordinate Orientation

The BLK360 LiDAR unit includes a camera system capable of collecting a 3D full-color panoramic image during the scan, this is not a feature of all LiDAR systems. These high-resolution images provide a valuable qualitative view of the tunnel walls. The BLK360 LiDAR processing software can overlay the visual panoramic image onto the point cloud data which facilitates user selection of points in the tunnel for measurements.

6.1.1 Point Cloud Distribution

Point cloud data from each scan are unevenly distributed points representing the surface of the surrounding objects. Blind spots exist and vary due to limitations of the scanner and physical features i.e., instrumentation, piping, duct, etc. obstructing clear views of tunnel surfaces. Scanned data can be merged by easily combining and accumulating groups of points into one single point cloud for further study. Recap Pro Mobile uses one origin for all scans in a project folder. As the first scan in the project establishes the origin. Subsequent scans are oriented to the initial cartesian coordinate system, point cloud data from each scan covers the interior surface along the CAEX tunnel within a length of approximately 200 ft. Multiple scans are required to accumulate points from single scans collected from three selected elevations to form a comprehensive point cloud. Figure 6.1.1-1 illustrates the density of point cloud with single scan vs. merged 9 scans. The figure of the point cloud with 9 scans illustrates how close points are spaced when all the points are accumulated. The total number of collected points for all 9 scans is 535,136,428 points. The individual scans have point totals of [59,399,550; 59,623,200; 59,334,171; 59,312,386; 59,595,903; 59,623,200; 59,617,740; 59,399,550; 59,230,728] points. The merged three scans consisted of 1 high resolution scan at each of the 3 elevations for a total of 178,329,676 points that were used for post processing data. The degree of point density along the interior surface is primarily related to the distance between the scanner and the point of interest. With a shorter distance, the points are spaced closer.



1 Scan (Above) vs 9 Scans (Below)

Figure 6.1.1-1 Point Density 1 Scan vs. 9 scans

Likewise, the point density on the north wall is proportionally higher than the point density on the south wall, as the scanner was 3 ft from the north wall surface and 6 ft from the south wall surface. Between 0 and 4.5 feet East and West from the scanner North wall point density is greater than South wall point density. At 4.5 feet East and West from the scanner North wall and South wall point density is equivalent. At East and West distances greater than 4.5 feet South wall point density is greater then North wall point density.

The theory of relationship between point distribution and distance is also quantitatively verified from the histograms generated along with the contour maps in Appendix D and F for the Wall to Wall Comparison and Artificial Vertical Plane to Wall Comparison Methods where:

Point density = (Total points / [(6 / 5) * (360 °)^2 / π]) * [tan $^{-1}$ (x_2 / y) - tan $^{-1}$ (x_1 / y)] * [tan $^{-1}$ (z_2 / y) - tan $^{-1}$ (z_1 / y)] / Segment Area.

Where y is either 3 feet or 6 feet,
x_2 is the eastern most edge of the segment in units of feet,
x_1 is the western most edge of the segment in units of feet,
z_2 is the highest edge of the segment in units of feet,
z_1 is the lowest edge of the segment in units of feet,
and Total points are the total points produced by the LiDAR system during a scan.

Point density is the number of points divided by the area. The area is simply the Segment area, Segment East-West span multiplied by segment height or for the ceiling segments East-West span multiplied by North-South span. The derivation for the calculated number of points on a given segment is a more complicated equation that depends on the distribution of points, the percentage of the point distribution that strike the segment, and the total point count.

Leica states that a high resolution scan produces 360,000 points per second and the LiDAR scan duration is 180 seconds. Therefore, Total points produced by the LiDAR during a scan is 64,800,000 points. The actual measured point counts for each scan are around 59,400,000 points. The difference is explained by the fact that the object being scanned is a tunnel that continues in both directions past the furthest returned signal and not an enclosed space as well as the absorbation of light by the liquid on the East end of the tunnel.

The distribution of points is described by the surface area equation, 4πr^2 for a sphere with r = 1 and the percentage of the sphere generating points. The amount of radians squared (steradians is 4π). The amount of degrees^2 in a sphere is 4π (180 °/ π)^2, which when simplified is (360 °)^2 / π. Leica states the BLK360 has a vertical view of 300 °, which provides the percentage of the sphere generating points, 300 ° / 360 ° = 5 / 6.

The angle tan $^{-1}$ (x_2 / y) is the angle from the LiDAR to one extrema of the segment in degrees (°) and likewise for x_1, z_2, and z_1. The difference [tan $^{-1}$ (x_2 / y) - tan $^{-1}$ (x_1 / y)])] is the horizontal LiDAR field of view of the segment. The difference [tan $^{-1}$ (z_2 / y) - tan $^{-1}$ (z_1 / y)] is the vertical LiDAR field of view of the segment. The amount of degrees^2 in a segment is given by [tan $^{-1}$ (x_2 / y) - tan $^{-1}$ (x_1 / y)])] * [tan $^{-1}$ (z_2 / y) - tan $^{-1}$ (z_1 / y)]. This is a smooth surface approximation. For an uneven surface this quantity is [tan $^{-1}$ (x_2 / y_2) - tan $^{-1}$ (x_1 / y_1)])] * [tan $^{-1}$ (z_2 / y_4) - tan $^{-1}$ (z_1 / y_3)] for y_i as the point dependent depth of the uneven surface. The percentage of spherical degrees^2 that strike the segment is thus given by 5 / 6 * [tan $^{-1}$ (x_2 / y) - tan $^{-1}$ (x_1 / y)] * [tan $^{-1}$ (z_2 / y) - tan $^{-1}$ (z_1 / y)] / [(360 °)^2 / π]. Furthermore, the number of points that strike a segment is (64,800,000 points / [(6 / 5) * (360 °)^2 / π]) * [tan $^{-1}$ (x_2 / y) - tan $^{-1}$ (x_1 / y)] * [tan $^{-1}$ (z_2 / y) - tan $^{-1}$ (z_1 / y)]. Simplified is (1250 * π / 3) [points / (°)^2] * [tan $^{-1}$ (x_2 / y) - tan $^{-1}$ (x_1 / y)] * [tan $^{-1}$ (z_2 / y) - tan $^{-1}$ (z_1 / y)].

The ratio of north wall point density to south wall point density is $[\tan^{-1}(x_2 / y_1) - \tan^{-1}(x_1 / y_1)] / [\tan^{-1}(x_2 / y_2) - \tan^{-1}(x_1 / y_2)]$. For smooth surfaces between 0 and 4.5 feet East and West from the scanner North wall point density is greater than South wall point density. At 4.5 feet East and West from the scanner North wall and South wall point density is equivalent using the smooth surface approximation. At East and West distances greater than 4.5 feet South wall point density is greater than North wall point density using the smooth surface approximation.

6.1.2 Determination of Number of Scans for Use in Baseline

Data points from multiple scans can be merged into a more completed point cloud providing a more detailed measurement with availability of additional points within a certain area, however, processing additional points require additional computation cost. For the point cloud generated from merging all 9 scans, it requires 18 hours of computing time to process data points from two matching surfaces on north and south walls. Each matching surface area is 18 inches by 84 inches (contour map). This wall surface area is above the debris field on the floor adjacent to the wall and below the ceiling. If larger areas (> 18-inch by 84-inch) are selected with more data points involved, CloudCompare will abort and exit automatically. With similar areas selected from a point cloud generated by merging 3 scans (1 top elevation, 1 middle elevation, and 1 bottom elevation), only 1.4 hours are required to process the selected data points. The size of the group of points to be processed is key in relation to computer capacity.

The BLK360 high-resolution point cloud data sets were very large and resulted in very slow software performance on our standard business desktop computing platform. To process the large volume of points, an existing SRNL high-performance computer was employed with the specifications listed in Table 6.1-1.

Table 6.1-1 Computer Specifications with Software CloudCompare

Intel® Core™ i7-6900K CPU @ 3.20GHz 8 cores 20 MB cache
63.9 GB RAM
64-bit operating system, x64-based processor
475 GB C Drive with ~approximately 100 GB of free

Although the higher end computer improved processing time, it still required hours to complete single area measurements. Future consideration should be made to procure hardware to further increase data processing performance; a computer with enhanced hardware such as dual processors, greater memory, additional cores, and hard drive space would reduce the computational time and improve the capacity to process a larger volume of selected data points. Due to the parallelism utilized in CloudCompare, a system with additional cores will speed up point cloud distance comparison processing time

An area identified for further evaluation is whether the ability to efficiently process greater than 3 merged scans at one time is possible and beneficial thru computer software or hardware enhancements.

6.1.3 Verification of LiDAR Unit Calibration and Acquired Data

Upon completion of the deployment and the collection of the point cloud data from the scans, the LiDAR calibration and data tolerance were verified by selecting and measuring several physical features in the tunnel with known dimensions, Figure 6.1.3-1. This verification of the BLK360 device accuracy was performed in addition to the initial calibration of the LiDAR unit completed by the manufacturer. The calibration and measurements performed are documented in SRNS-E1122-2019-00020, *Calibration Records of the LIDAR on a Stick Inspection System- November 2019 Inspection* [11]. All measurements were within the ± 0.25-inch tolerance.

Figure 6.1.3-1 - Interior measurement of a schedule 40 pipe; one of six known measurements taken from the acquired point cloud to verify device and data accuracy

6.2 Methodology to Establish Baseline

This section discusses the methodology applied to establish a baseline from which subsequent LiDAR deployment data can be compared against. The data processing steps used to establish the baseline are documented in SRNS-IM-2020-00087, *H-Canyon Exhaust Tunnel LiDAR on a Stick (LiDS) Data Post-Processing Guide* [12].

Section 6.2.1 introduces the concept of contour maps, histograms and images that all the methods employed.

6.2.1 Contour Maps, Histograms, and Images

The collected point cloud data of the interior CAEX tunnel spans from the east end of the 1950's single tunnel to the double tunnel section at the location of the 36-inch HB-Line Exhaust duct access point. This covers an approximate 200-foot length of tunnel highlighted in Figure 6.2-1. Within this 200 ft, there are several gross geometry transitions to include height variations, floor slopes, and curvature along the tunnel walls.

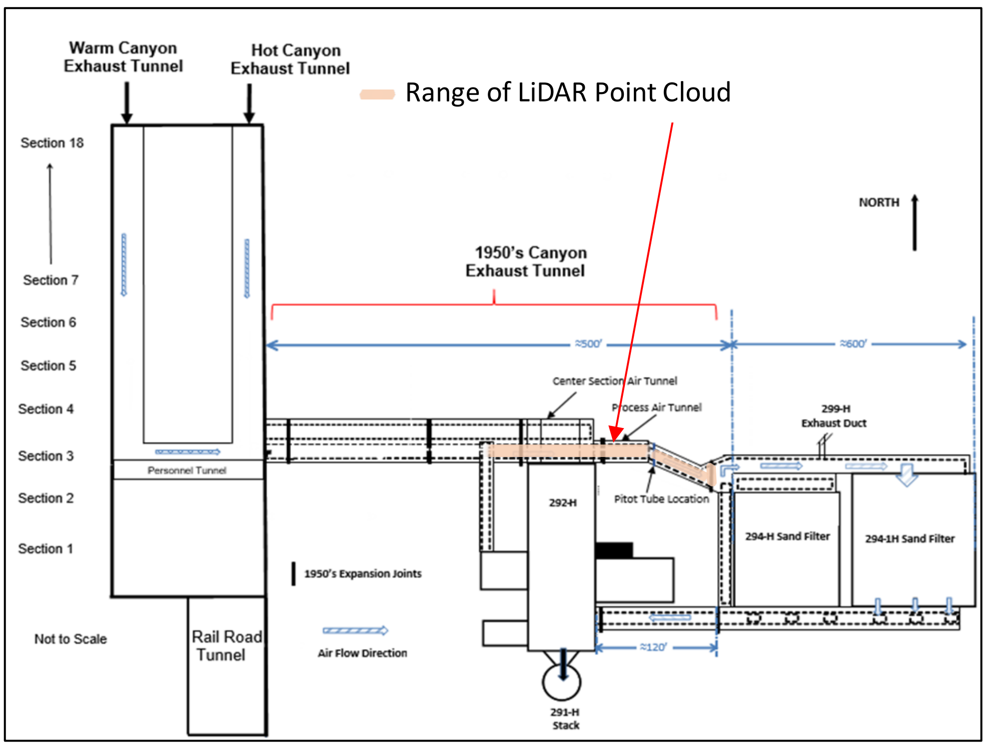


Figure 6.2.1-1 Range of LiDAR Point Cloud

Due to the tunnel configuration, the LiDAR point cloud is less dense farther away from the scanner on the west side vs east side which has less angle changes. It is ideal to divide the point cloud into smaller segments based on the variation of tunnel geometry and orientation to study the degradation at each different geometric section. Additionally, with understanding of the limitation of the computer capacity during data processing, the method used was to divide and process the point cloud in segments based on the volume of points being processed. For each segment selected a limit of approximately 5 million points between the North and South walls was used and processed without causing issues with the CloudCompare software or computer processing capability.

The range of the data points discussed in this report focused on the point clouds within 30 feet east and west of the scanner. The density of the points is is a function of the distance from the scanner. The density of the point cloud can affect the accuracy of the measurement. The procurement specification called for a LiDAR 3D point cloud accuracy of ± 0.25 inches (6.35mm) or better at 30 feet (9.144 m). The manufacturer of the BLK360 unit stated that the accuracy depends on the distance between the scanner and the object being scanned (6mm/0.236inch accuracy within 10 m/32.808 ft and 8mm/0.315in accuracy with in 20m/65.617ft). In addition, the manufacturer recommends an 18m (60ft) interval for each scan.

The software allows for two points to be selected on the point cloud and measured, Figure 6.2.1-2. Although it is interesting to perform point to point measurements, because of the uneven surface of the walls and ceilings and the likelihood that surface erosion is uneven throughout the tunnel, they can't be used to determine change of width and height. Instead tunnel segments of equal but opposite walls were defined for comparison, Figure 6.2.1-3. Additionally, ceiling segments were defined for comparison to an artificially defined floor plane. Using colored contour maps that denote differences in surfaces and the accompanying histogram that quantifies these distances an understanding of surface conditions can be evaluated. As the dimensions of the interior tunnel under current field conditions can be quantitatively measured by point cloud data, concrete loss at current conditions can be calculated. Furthermore, the degradation rate of concrete can be calculated with multiple deployments conducted periodically.

Figure 6.2.1-2 Point to point measurements shown on the point cloud with image

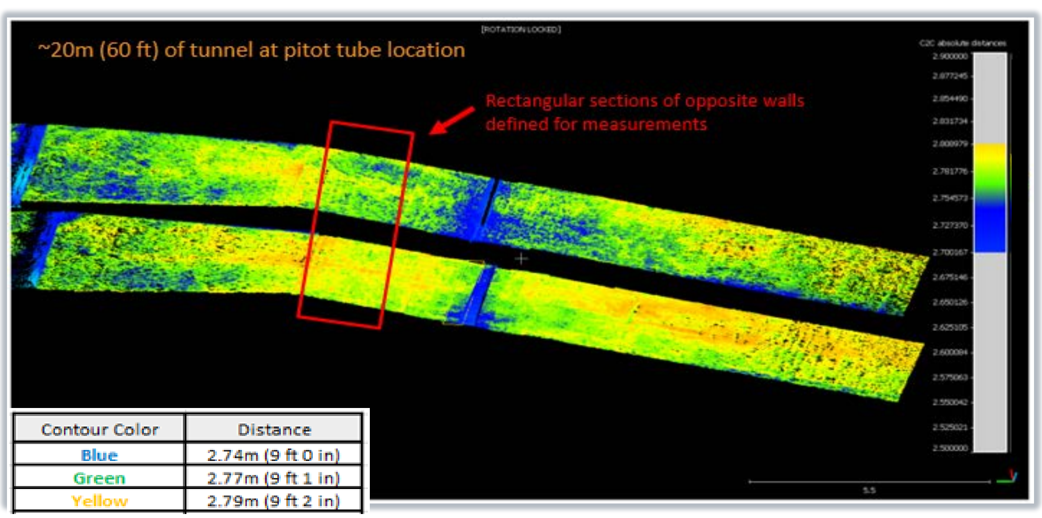


Figure 6.2.1-3 Selection of equal and opposite wall areas for comparison

Contour Map:

For each section selected by graphical user interface (GUI) from the data point cloud, measurements are from the clear distance distribution between 2 locations in the tunnel. Contour maps are generated for each segment by the method of the nearest neighbor distance concept. CloudCompare uses a nearest neighbor algorithm to calculate distances between a compared point cloud and a reference point cloud. The contour map includes contours on the matching areas. For example, in the comparison of the North Wall to South Wall method, the areas from North and South walls are defined as the compared side and reference side. The tunnel walls are a series of peaks and valleys due to the erosion on the tunnel walls. All points within a North wall valley may identify and use the same peak point in the South wall as its nearest point. Vice versa, when the South wall is compared to the North wall, the peak point mentioned above will use a peak point in the North wall that is near the valley as the reference point. The same principle is used when an artificial plane is inserted to evaluate an individual wall surface or the ceiling. Figure 6.2.1-4 provides an illustration of the nearest neighbor distance concept.

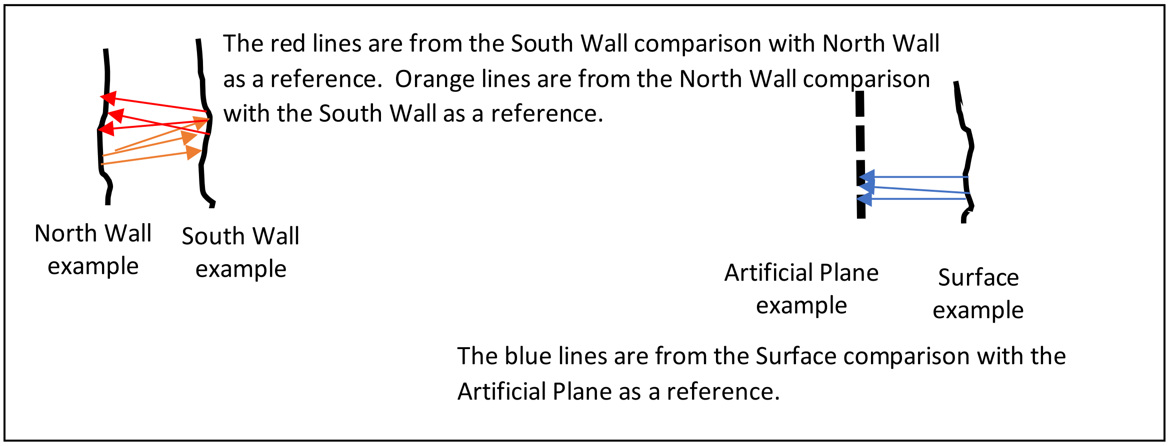


Figure 6.2.1-4 Surface to Surface Comparison –
"Nearest Neighbor Measurement" in a simplified 2- D profile

Therefore, the measurements are also performed on both sides are defined. The contour map displays the measured distance distribution through the "nearest neighbor distance" concept to assess the distance between corresponding surfaces of structural members named compared side and reference side. For a point selected from the compared side, the nearest point is found in the reference side and the distance is measured. For each point from compared side, distance calculated by nearest reference point is saved.

The final distance distribution is split into 256 bins, a scalar field. CloudCompare uses an 8-bit resolution for bins as a default, this value can be modified. Each bin is assigned a color that is defined by a scalar field color scale. It will result in a contour map with a colored scale bar, which is labeled with distance values. Figure 6.2.1-5 is an example of a contour map from a segment of the South Wall. The distribution of the contour lines shows how the clear distance changes across a segment of matching surfaces. Contour maps with colored distance labels are created to provide an overview of distance distribution between matching south wall and north walls inside CAEX tunnel. To have a reasonable scale and consistent distance label in contour maps of all the segments, a color code for the distance assigned for the contour is pre-defined in Table 6.2.1-1. The original design dimensions are color coded blue. Design dimensions are used as there is no available record of as-built dimensions.

Table 6.2.1-1 Pre-defined Color Scale

	Pre-Defined Color Code	Wall-Artificial Plane Distance	Wall-Wall Distance	Ceiling Distance	
	Cyan	4 ft 5 in	8 ft 10 in	9 ft 4 in	Design minus 2 inches
Original Design Width →	Blue	4 ft 6 in	9 ft 0 in	9 ft 6 in	Design
	Green	4 ft 7 in	9 ft 1 in	9 ft 7 in	Design plus 1 inch
	Yellow	4 ft 8 in	9 ft 2 in	9 ft 8 in	Design plus 2 inches
	Red	4 ft 10 in	9 ft 4 in	9 ft 11 in	Design plus 4 inches

The variation of distance reflected by different degrees of color shade is automatically calculated based on the value distribution and definition of the class and bin. The unit of the distance label is in inches. A rough distribution of concrete losses can be estimated from the distribution label. The Cyan indicates the presence of particulate captured by the LiDAR that was not segmented from the wall. The blue indicates the original concrete remaining with no loss. The red color indicates more concrete lost and a greater distance between north and south walls. For the spots with red color, further verification and investigation needs to be conducted by using the embedded full-color panoramic images.

As an example, the contour map, histogram, and image of the South wall, 2.1' to 3.7' west of the pitot tube segment is shown in Figures 6.2.1-5, 6.2.1-6, and 6.2.1-7.

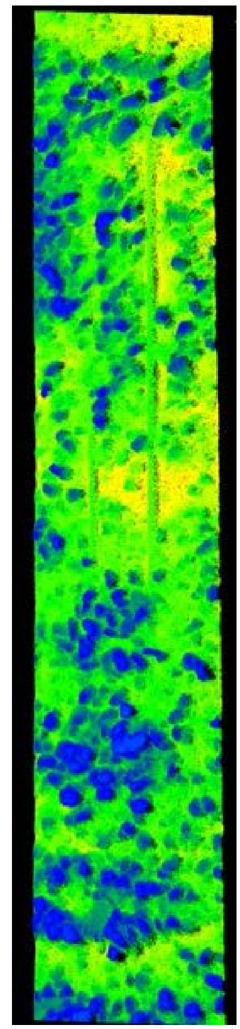


Figure 6.2.1-5 Segment West South Wall Contour Map Example

Histogram Curve

In addition to the colored distance label, a histogram curve is also provided along with the contour map at each segment providing a statistical conclusion. The curve is created to show the distribution of the data. The Mean Value and Standard Deviation are included in the default setting of the histogram curve. The values are important for further analysis when changes from data derived from future deployments are identified. The Value bar in the histogram curve can be moved to show a different percentile such as the median, 95%, etc. value desired. Figure 6.2.1-6 distance value is shown at 95%.

Furthermore, the data behind the histogram curve can be extracted from the CloudCompare program to convert into a spreadsheet program such as an excel file for further statistical analysis. The same mean distance and deviation values can be computed in these programs and be used as a consideration for input of concrete surfaces, needing further structural analysis.

Distances from points in the compared point cloud to the nearest neighbor in the reference point cloud are computed by CloudCompare. The median and the 95% values of these distances are recorded from the resulting histogram. The design distance is subtracted from the recorded values to give the erosion values.

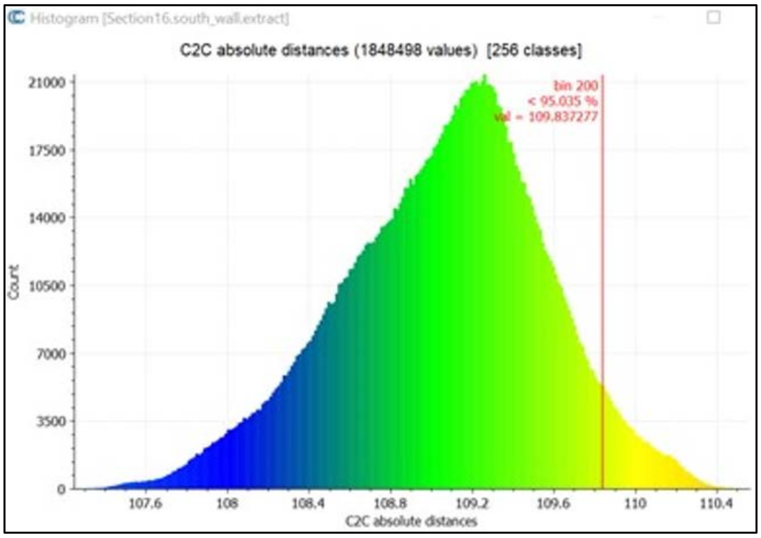


Figure 6.2.1-6 Segment Histogram Example at 95% value for West South Wall

Image

Full-color panoramic images were captured and can be used as a supplemental tool to further understand the field condition of concrete surfaces. It can also be used to visually inspect red colored areas shown on contour maps. The images at selected areas verify and offer additional explanation to the contour map. The high definition image itself is a good record to document the field condition.

Figure 6.2.1-7 is an example of an image taken of a segment. The corresponding contour map and histogram of the segment is shown in Figures 6.2.1-5 and 6.2.1-6.

Figure 6.2.1-8 is an example of image quality taken of the South wall. The area in the red box is of the West South Wall segment.

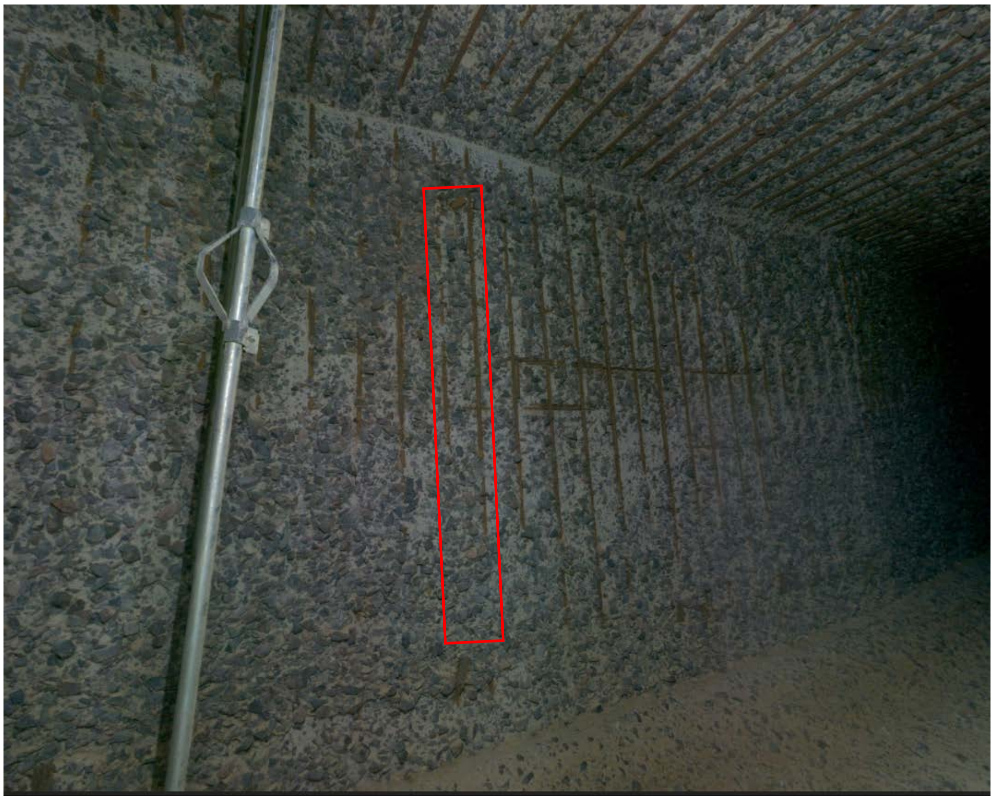


Figure 6.2.1-8 Image of South Wall, Red Boxed area shows location of Figure 6.2.1-7 Segment

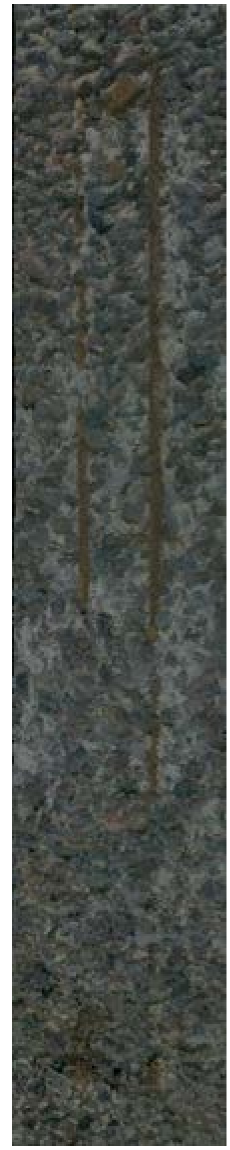


Figure 6.2.1-7 Segment Image West South Wall

6.2.2 Baseline Methods

Section 6.2.2 presents the methods that were evaluated to establish a baseline from which future deployment data cloud comparisons will be performed. The baselines are:

1. Comparison of North Wall to the South Wall
2. Creation of a Horizontal Artificial Floor Plane to compare with the Ceiling
3. Creation of a Vertical Artificial Wall Plane to compare each Wall individually

Although the range of scan data collected encompasses a 200-foot distance as seen in Figures 6.0-1 and 6.0-2, for the purpose of collecting useable interior measurements, the Leica BLK360 unit is calibrated from the manufacturer to a 6mm (or 0.25-in) accuracy up to 30 feet on a level plane with no changes in configuration. Twelve (12) segments, 30' east and 30' west of the pitot tube were selected for evaluation based on the Leica BLK360 accuracy. Figure 6.2.2-1 highlighted in green represents the location of the 12 Segments along the tunnel route.

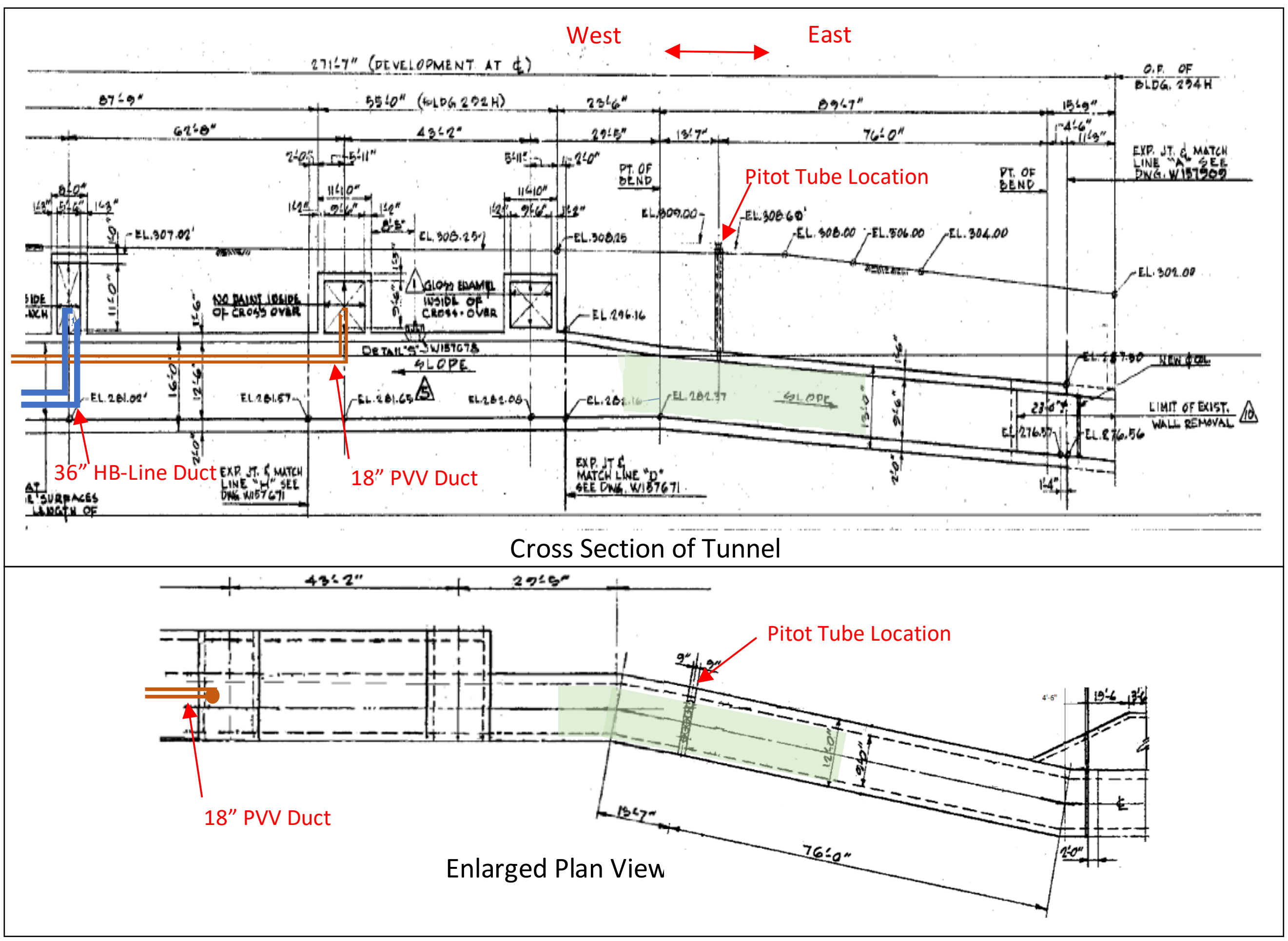


Figure 6.2.2-1- Representative Plan and Cross-Section View of location of the 12 LiDAR Segments highlighted in Green (excerpt from W157677)

Figure 6.2.2-2 shows the location of the 12 segments that were evaluated. Segment EWO is at the Pitot Tube location. Segments E1 through E5 are east of the Pitot Tube. Segments W1 through W6 are west of the Pitot Tube.

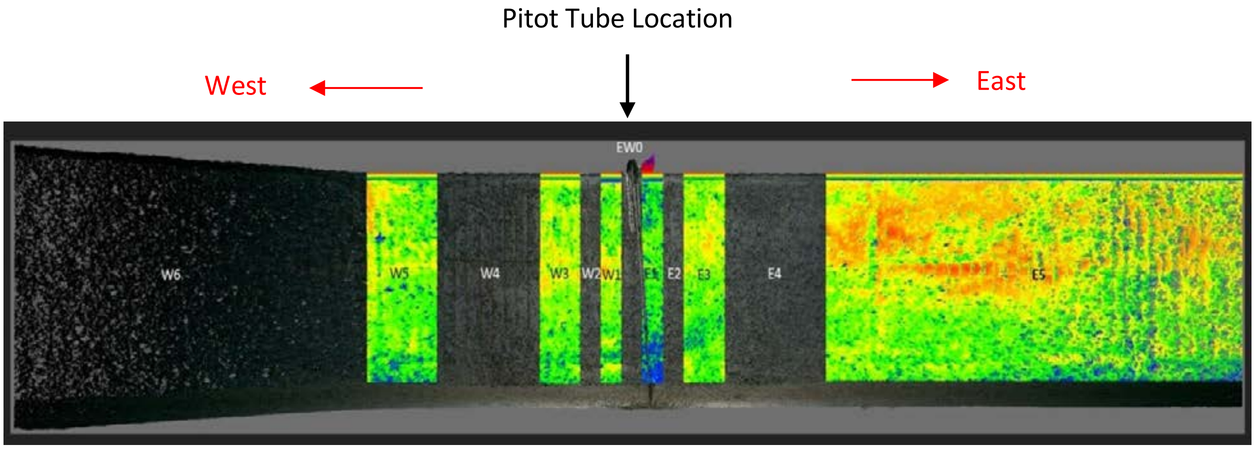


Figure 6.2.2-2- Location and Relationship of the 12 LiDAR Segments to Each Other

As previously discussed in Section 6.2.1, the point cloud density is related to measurement accuracy, generally the greater the density, the higher the confidence in measurement accuracy.

In the data collected from the 3 Baseline Methods summarized in Tables 6.2.2.1-1, 6.2.2.2-1**,** and 6.2.2.3-1, there is a noted reduction in point cloud density as the distance increases from the LiDAR unit. This was expected as the LiDAR manufacturer recommends a best scanning distance of 3-feet to 10-feet. Additionally, the number of blind spots, i.e. dark regions on the contour maps shown in Appendices D, E, and F, increased as the distance from the scanner increased. The LiDAR must have a line of sight to the surface being scanned to obtain an accurate distance, blind spots were caused by the uneven wall surfaces protruding into the laser path and obscuring areas located behind them causing shadowing, Figure 6.2.2.1-3. Blind spots cause no data points to be collected on a shadowed surface; not all surface points are included in calculating the median and 95% distance value, thus, the median and 95% distance values are less accurate. Figure 6.2.2.1-3 also illustrates as shown by red circles in the diagram, how blind spots increase as our distance and thus angle of incidence to the surface increases.

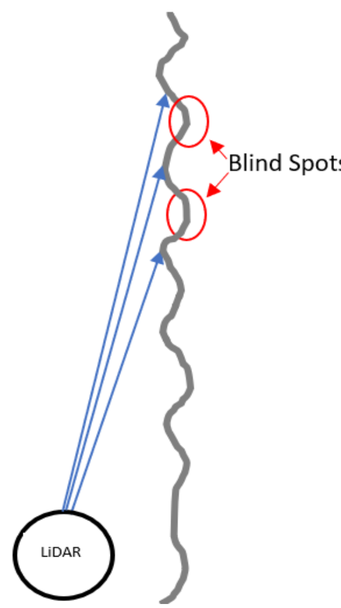


Figure 6.2.2.1-3
Blind Spots Illustrated

6.2.2.1 North Wall and South Wall Comparison Method

This method compares the North and South Wall to each other using the nearest neighbor measurement concept depicted in Figure 6.2.2.1-1. The 12 segments were taken above the floor debris and below the ceiling. Table 6.2.2.1-1 tabulates the Segment data and references the location from the LiDAR scanner using East (E) and West (W). The Contour Maps, Images, and Histograms for each of the segments are in Appendix D.

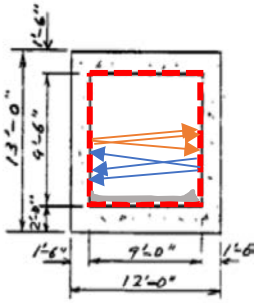
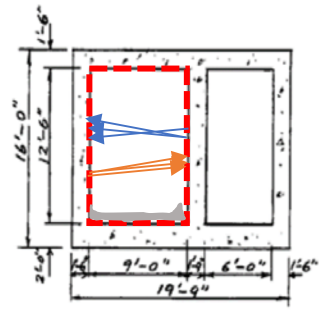
	
Single Tunnel Configuration	Double Tunnel Configuration

Figure 6.2.2.1-1 Nearest Neighbor Measurement for Wall Comparison

Table 6.2.2.1-1 Wall to Wall Comparison Data

Segment East (E) West (W)	X Location from Pitot Tube '(feet)		Z Location Below Pitot Tube Pipe '(feet)		Y Mean Value from North Wall inches	Y Mean Value from South Wall inches	Point Cloud Density North Wall* Points/in^2	Point Cloud Density South Wall* Points/in^2
			Top	Bottom				
W6	-30.13	-12.91	0.98	-8.74	109.64	109.62	38	21
W5	-12.92	-9.49	-0.09	-8.28	109.52	109.77	95	154
W4	-9.5	-4.47	-0.08	-8.32	109.31	109.6	353	406
W3	-4.48	-2.51	-0.08	-8.32	109.36	109.44	1190	832
W2	-2.5	-1.5	-0.11	-8.31	109.05	108.96	2153	1096
W1	-1.5	-0.49	-0.2	-8.3	108.75	108.68	3167	1224
EW0	-0.48	0.53	-0.21	-8.27	108.45	108.64	3394	1368
E1	0.52	1.54	-0.15	-8.3	108.98	108.73	3546	1232
E2	1.54	2.55	-0.15	-8.3	109.12	108.92	3014	1200
E3	2.55	4.56	-0.08	-8.28	109.2	109.08	1681	962
E4	4.56	9.5	-0.09	-8.27	109.16	109.36	470	479
E5	9.5	29.84	-0.09	-8.23	109.43	109.82	38	69

*rounded values

Segments East-West Origin (EWO), East 1 (E1) through East 4 (E4), and West 1 (W1) through West 4 (W4) with the higher point cloud densities and less blind spots in the contour maps give the team a greater understanding of the absolute value of the tunnel dimensions. While all the 12 Segments will be revisited and future deployment data will be compared with the November 2019 deployment for change, greater focus will be placed on change information from Segments EW0, E1 through E4, and W1 through W4. The most complete data of tunnel surfaces from the Wall to Wall Comparison Method covers a 19-foot distance vs. a 60-foot distance. Surface change between deployments will be based on a direct comparison of "Y" axis values which is the tunnel width.

The data from Table 6.2.2.1-1 is graphed in Figure 6.2.2.1-1. In this Figure the wall width dimensions obtained through this method are graphed against the tunnel width design. Tunnel design dimensions are used as as-built information is not available. The change from the 9' (108 inches) Design tunnel width ranges from 0.5" to 1.6" over the 19' distance.

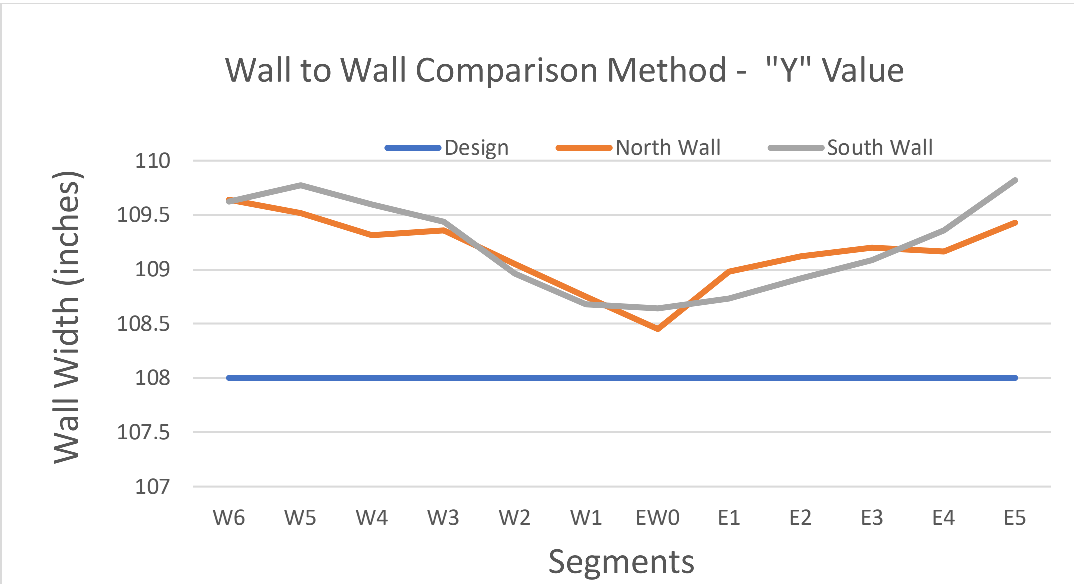


Figure 6.2.2.1-1 North and South Wall Measurements to Tunnel Design Width

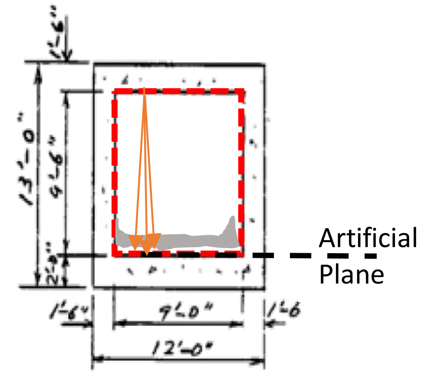
With the data generated on both compared and reference sides for each segment with similar distance distribution, the degradation rate of certain interested areas of the tunnel can be estimated from information provided by histogram curves and data from the following equation in addition to direct comparison of the tunnel widths (Y-values) discussed above. This method presumes that the erosion on both sides is symmetrical. While it is known from visual inspections, the degradation is not consistent along the tunnel this information would provide data to note change is occurring with the below equation:

$$Degradation\ Rate\ of\ the\ Wall = \frac{Shift\ of\ the\ Median\ of\ the\ Distance\ distributions}{Time\ Periodx2}$$

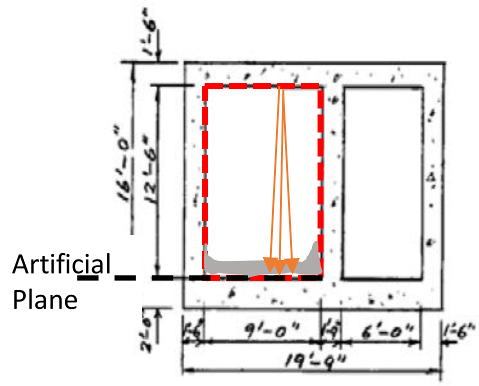
The degradation rate can be calculated directly from the shift of the mean value of the distance from contour map for each defined segment. Note the factor of 2 is used in above equation, considers the concrete loss as equal on both sides of the wall tunnel. This factor can be verified with the image. The difference calculated between measured distance and designed distance can be divided by 2 to calculate the erosion on each side of the wall.

6.2.2.2 Artificial Horizontal Plane to Ceiling Comparison Method

This method compares a horizontal artificial plane to the ceiling segments using the nearest neighbor measurement concept depicted in Figure 6.2.2.2-1 for the same 12 segments. The contour maps, images, and histograms for each of the segments are in Appendix E.



Single Tunnel Configuration



Double Tunnel Configuration

Figure 6.2.2.2-1 Nearest Neighbor Measurement for Artificial Plane to Ceiling Comparison

As observed from camera inspections, the floor of the CAEX tunnel is covered by a layer of debris from the erosion of concrete. The thickness of debris varies along the tunnel. The collected point cloud data displays a floor surface which represents the top surface of the debris on the floor. The reinforced concrete floor surface is protected from erosion by the debris. In addition, the thickness of the floor is greater than the thickness of the wall and the ceiling per original design documents. The floor has less structural concerns which are confirmed by the Non-Linear Analysis results.

Exposure of rebar was observed at many locations on the ceiling along the tunnel during visual camera inspections. To be able to evaluate the concrete loss and estimate the rate of change on the ceiling surface with the data points from the LiDAR inspections, an approach by introducing a horizontal artificial plane was investigated. An artificial plane for each segment is generated at the same location of design floor plane. The floor artificial plan is within ± ½ inch of the design floor plane. The generated data points are combined into the existing point cloud data to be used as points on the reference side. Distance distribution between ceiling and the artificial plane is plotted with the same contour map technique. Concrete degradation on the ceiling and rate surface change can be calculated by change of distance distribution from multiple deployments.

To establish the horizontal artificial plane, the ceiling and floor with debris of Segment E5 was compared by the same method as the North and South walls. The lowest height of the debris is at the middle section of the floor. The height is 1.976 inches (50.19 mm) based on original design. Under this case, the artificial floor plane is created 1.5-2 inches from the lowest point of each scanned floor surface. The elevation of the horizontal floor plane can be adjusted to a given elevation with an exposed rebar on the ceiling and the known design interior height.

In Figure 6.2.2.2-2, the left image is looking straight down. The right image shows a comparison of the horizontal artificial floor plane to the actual scanned floor.

Figure 6.2.2.2-2 Floor composite segment from West to East W3 to E3 without EW0.

Data for the artificial floor plane was generated by modifying the *Z* axis (tunnel height) of data points which of the current floor plan to the Z value per original design plane. As the artificial horizontal plane shown in Figure 6.2.2.2-2 is totally smooth on the surface, the deviation of the contour maps shown in Appendix E indicate the surface roughness of the ceiling. The hot spots (red color) next to the rebar indicate where the most concrete loss can be seen in the images. Distance distribution can be quantitatively analyzed with the histogram curve. The artificial horizontal floor plane established from this initial LiDAR deployment becomes the reference from which subsequent deployment data will be measured against.

Table 6.2.2.2-1 tabulates the data from the 12 segments.

Table 6.2.2.2-1 Ceiling-to-Artificial Plane Comparison

Segment East (E) West (W)	X Location from Pitot Tube '(feet)		Y Location from edge of furthest North Pitot Tube '(feet)		Z Mean Value from floor to Ceiling inches	Point Cloud Density Ceiling Points*/in^2
			North	South		
W6	-30.13	-12.91	1.94	-10.61	116.17	28
W5	-12.92	-9.49	1.96	-7.5	116.61	148
W4	-9.5	-4.47	1.94	-7.51	116.36	459
W3	-4.48	-2.51	1.91	-7.52	116.25	1050
W2	-2.5	-1.5	1.89	-7.5	116.47	1515
W1	-1.5	-0.49	1.9	-7.54	116.55	1932
EW0	-0.48	0.53	1.88	-7.59	116.4	2316
E1	0.52	1.54	1.92	-7.57	116.62	2131
E2	1.54	2.55	1.92	-7.51	116.5	1738
E3	2.55	4.56	1.91	-7.54	116.46	1341
E4	4.56	9.5	1.89	-7.57	116.41	529
E5	9.5	29.84	1.87	-7.66	116.35	59

*rounded values

Similar with the previous Wall to Wall Method evaluation in Section 6.2.2.1, Segments EWO, E1 through E4, and W1 through W4 with the higher point cloud densities and less blind spots in the contour maps give the team a greater sense of understanding the tunnel dimensions. While all the 12 Segments will be revisited and future deployment data will be compared with the November 2019 deployment for change, greater focus will be placed on change information from Segments EW0, E1 through E4, and W1 through W4. The most complete data of tunnel surfaces from the Artificial Horizontal Plane to Ceiling Comparison Method covers a 19-foot distance vs. a 60-foot distance. Surface change between deployments will be based on a direct comparison of “Z” measurement.

The data from Table 6.2.2.2-1 is graphed in Figure 6.2.2.2-1, are graphed against the Design Tunnel height of 114 inches or 9.5 feet. Over the 19-foot tunnel distance an average loss of 2.25” to 2.62” has occurred to the ceiling. Based on this data, full exposure of the ceiling interior rebar mat would be expected. The data is inconsistent with Appendix E contour maps and images indicating exposure of north-south rebar and very little exposure of the east-west rebar. Additional review of this Method and results is required.

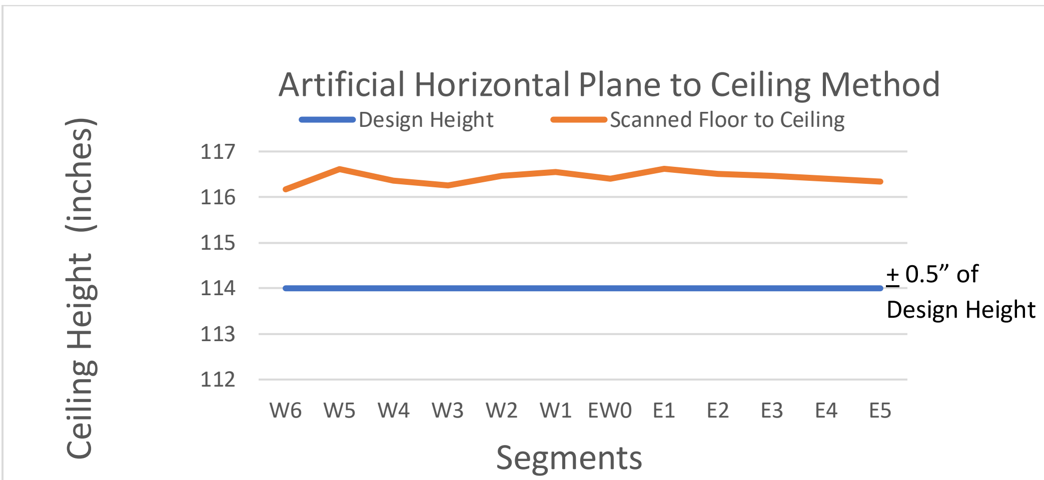


Figure6.2.2.2-1 Ceiling Measurements “Z” to Tunnel Design Height

In addition to a direct examination of data “Z” changes over time, the following Equation of the degradation rate of the ceiling is applicable:

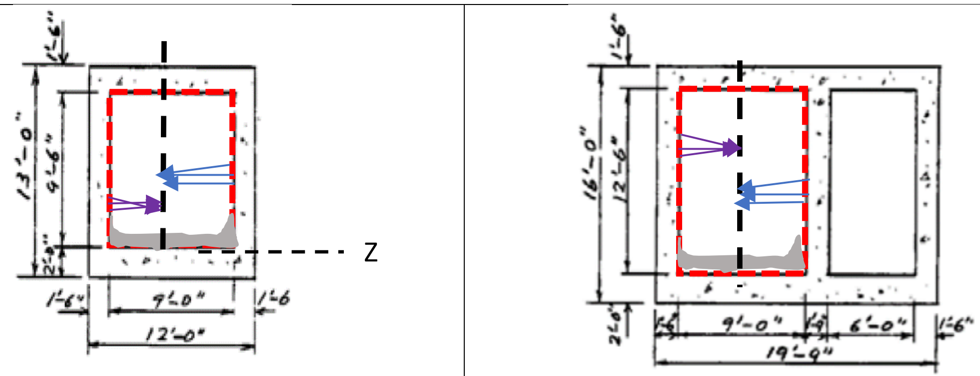
$$Degradation\ Rate\ of\ Ceiling = \frac{Shift\ of\ the\ Median\ of\ the\ Distance\ distribution}{Time\ Period}$$

The degradation rate can be calculated directly from the change of the mean value of the distance from contour map for each defined section to the internal original design height. Likewise, implementation of additional considerations can modify this equation.

The horizontal artificial floor plane can also be generated by generating a set of points as the coordinates of the ceiling are known. The approach requires effort to create data that can be minimized using the functions provided by a spreadsheet program. With the tunnel transition from the 12’-6” to 9-6” height shown on Figure 6.2.2.2-1, a trapezoid prism shape, the artificial plane must be a sloped plane parallel to the ceiling surface to plot the distance distribution. This will require a gradually varied Z vertical value along with the longitudinal Y value. This approach was not investigated for this initial deployment post data processing.

6.2.2.3 Artificial Vertical Plane with the South and North Wall Individually Comparison Method

This method compares a Vertical Artificial Plane to each wall individually using the nearest neighbor measurement concept depicted in Figure 6.2.2.3.-1. The same 12 segments were evaluated. Table 6.2.2.1-1 tabulates the data from the segments. The Contour Maps, Images, and Histograms for each of the segments are in Appendix F.



Single Tunnel Configuration | Double Tunnel Configuration

Figure 6.2.2.3-1 Nearest Neighbor Measurement for Artificial Vertical Plane to Wall Comparison

Data for the artificial vertical plane was generated by modifying the Y values of data points of the current tunnel width to the Y value per original design plane. The average Y value for each segment North and South walls were calculated. An approximate midpoint value was derived from the calculated averages. The graphed 11 derived midpoint values resulted in a best fit line that was used as the midpoint line. The vertical artificial plane is within ± 0.5 inches of design tunnel midpoint width.

Table 6.2.2.3-1- Wall-to-Artificial Plane Comparison

Segment East (E) West (W)	X Location from Pitot Tube '(feet)		Z Location Below Pitot Tube Pipe '(feet)		Y Mean Value from North Wall inches	Y Mean Value from South Wall inches	Point Cloud Density North Wall Points*/in^2	Point Cloud Density South Wall Point*s/in^2
			Top	Bottom				
W6	-30.13	-12.91	0.98	-8.74	55.48	55.16	38	21
W5	-12.92	-9.49	-0.09	-8.28	55.71	55.14	95	154
W4	-9.5	-4.47	-0.08	-8.32	55.46	55.24	353	406
W3	-4.48	-2.51	-0.08	-8.32	55.55	55.25	1190	832
W2	-2.5	-1.5	-0.11	-8.31	55.28	55.13	2153	1096
W1	-1.5	-0.49	-0.2	-8.3	54.95	55.17	3167	1224
EW0	-0.48	0.53	-0.21	-8.27	54.73	55.09	3394	1368
E1	0.52	1.54	-0.15	-8.3	55.37	55.00	3546	1232
E2	1.54	2.55	-0.15	-8.3	55.39	55.27	3014	1200
E3	2.55	4.56	-0.08	-8.28	55.44	55.20	1681	962
E4	4.56	9.5	-0.09	-8.27	55.20	55.32	470	479
E5	9.5	29.84	-0.09	-8.23	54.95	55.72	38	69

*rounded values

The artificial vertical wall plane established from this initial LiDAR deployment becomes the reference from which subsequent deployment data will be measured against.

As previously seen in the Sections 6.2.2.1 and 6.2.2.2, Segments EWO, E1 through E4, and W1 through W4 with the higher point cloud densities and less blind spots in the contour maps give the team a greater sense of understanding the tunnel dimensions. While all the 12 Segments will be revisited and future deployment data will be compared with the November 2019 deployment for change, greater focus will be placed on change information from Segments EW0, E1 through E4, and W1 through W4. The most complete data of tunnel surfaces from the Artificial Vertical Plane to Wall Comparison Method covers a 19-foot distance vs. a 60-foot distance. Surface change between deployments will be based on a direct comparison of “Y” measurement.

The data from Table 6.2.2.3-1 is graphed in Figure 6.2.2.3-2. In this Figure the tunnel interior midpoint width dimensions obtained through the Artificial Vertical Plane to Wall Method are graphed against the Design Tunnel midpoint width of 54 inches. Like the other methods previously discussed, the most complete surface data from the Artificial Horizontal Plane to Ceiling Method covers a 19-foot distance vs. a 60-foot distance. Over the 19-foot distance a loss in the range of 0.73 inches to 1.55 inches is identified.

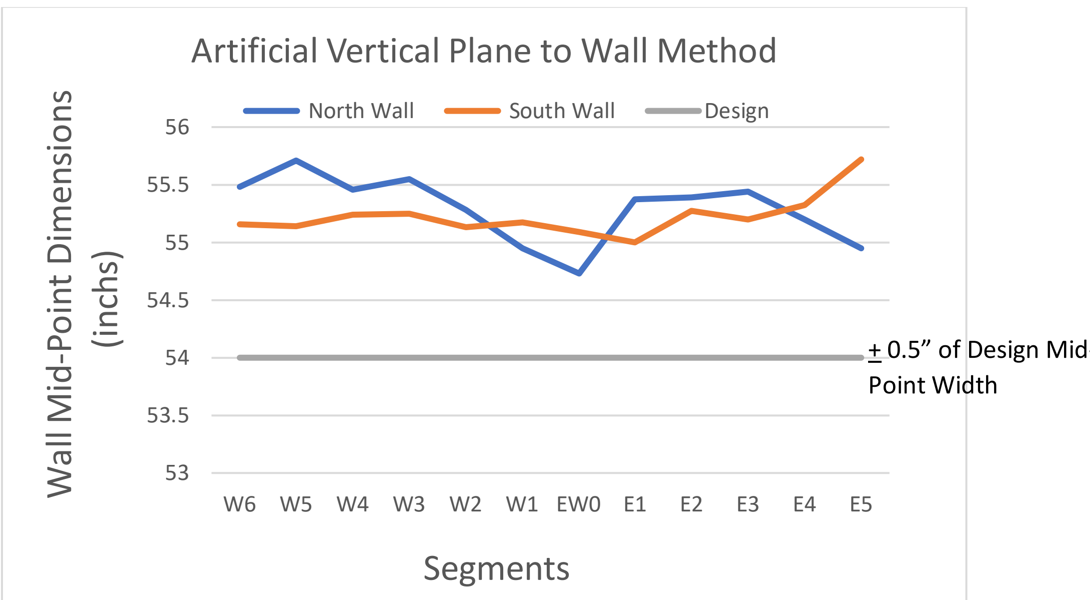


Figure 6.2.2.3-2 North and South Wall Measurements to Artificial Vertical Plane

In addition to a direct examination of data “Y” changes over time, the following Equation of the degradation rate of the wall is applicable:

$$Degradation\ Rate\ of\ Wall\ = \frac{Shift\ of\ the\ Median\ of\ the\ Distance\ distribution}{Time\ Period}$$

The degradation rate can be calculated directly from the change of the mean value of the distance from contour map for each defined section to the internal midpoint design width.

7.0 Summary and Recommendation

7.1 Summary

The November 2019 deployment of LiDAR at the Pitot Tube location to scan a local area in the CAEX Tunnel confirmed that a commercially available LiDAR unit could successfully operate and remotely transmit data from the tunnel environment, and that the data did establish quantitative baseline information that would be used in comparisons from future deployments to determine a surface rate of change.

The deployment and post-data processing presented challenges; the lessons learned are documented in this report and related to the:

- Physical configuration of the LiDAR assembly,
- Deployment activities and duration in tunnel environment, and
- Data post processing.

Three post-data processing Methods were developed. Baseline measurements were obtained from each Method and will be the basis for future deployment data comparisons to evaluate surface change over time. The three Methods are:

1. North Wall to South Wall Comparison
2. Artificial Horizontal Plane to Ceiling Comparison
3. Artificial Vertical Plan to Individual Wall Comparison

While the deployment resulted in a scan of nearly 200’ of the tunnel interior, from the data post processing, it was determined that the rough surface walls could only be scanned with little to no shadowing effect for total distance of 19’. Shadowing occurs when the line of sight laser measurement to each surface point becomes impossible due to obstructions, in this case the walls themselves being uneven.

All locations evaluated were within the measurement accuracy of the Leica BLK360 LiDAR, however as distance increases from the scanner to the wall, shadowing increases and point cloud density decreases causing baseline measurements to become more relative versus absolute. This was expected with this technology. Data post processing underscored the importance of understanding the impact of the physical configuration of the area, the scanner location and calibrated limits of the LiDAR scanner on shadowing and point cloud density and thus absolute versus relative measurements.

Lower density point clouds at further distances can affect the absolute measurement accuracy, however because the deployment baseline measurements are based on averages, it is believed that relative baseline measurements obtained at further distances from the scanner location still have value when compared to future scans obtained. At what distance the relative measurements lose value will need to be determined.

Of interest to the deployment was the potential value of including a LiDAR mounted on the inspection crawler which can be paused every 10’ -20’ in the tunnel and a scan collected. Such a deployment would provide a minimum of two views of each tunnel surface point from opposite directions which would significantly reduce shadowing effects and provide a much denser point cloud of the entire tunnel.

The deployment addressed some of the concerns identified in Section 2.2. that require resolution before the team is confident in a successful LiDAR crawler deployment. While it is apparent with this deployment that this Leica BLK360 lacked the robustness needed for a LiDAR crawler deployment, the use of this technology in the tunnel environment has merit. LiDAR instrument options for the pitot tube deployment were severely limited based on the size requirement that the system fit through the 6” pipe penetration. More robust LiDAR options for a crawler deployment exists. A successful LiDAR unit on a crawler would require robust ability to survive tunnel conditions and the time duration of crawler entries conducted over several days. Information from the gathered from this deployment is noted in the Table 7.1-1 below.

Table 7.1-1- 2019 Deployment Information for Future LiDAR Crawler Deployment

<table>
<tr><th>Concern</th><th>Deployment Information</th></tr>
<tr><td colspan="2">1. Does the wind/airborne debris/ moisture environment affect unit operation? Yes

The LiDAR unit is composed of rotating mirrors, camera and laser to scan surfaces. Performance is impeded if blinded by debris. Failure of the unit horizontal axis to rotate ended further deployment efforts on Day 2. The unit had been in the tunnel environment less than 24 hours. The unit had operated successfully at the JFT facility, during the SRNL Mock-up and during the Deployment Day 1. The failure to operate was attributed to too much strain on the scanners’ horizontal axis. It is unknown whether the environment or slip ring to maintain continuous power individually or collectively affected the LiDAR unit.

Consideration of protecting the unit during the 4-5 day crawler inspection duration when not scanning is required.</td></tr>
<tr><td colspan="2">2. Will use of an external power source vs. battery power affect operation? Yes

The use of an external power source required the use of a slip ring. It is unknown whether the slip ring and the tunnel environment together or individually contributed to failure of the scanner horizontal axis on Day 2. Operation on Day 1, the unit did not appear to be impacted. For a crawler inspection, a more robust unit with stronger horizontal rotating motors would be required or a stationary mountable LiDAR with internal scanning rotation. Either a battery the inspection duration would be required or a slip ring. A battery would require integration with the crawler platform.</td></tr>
<tr><td colspan="2">3. Can the unit reliably relay data from inside Tunnel to outside the Tunnel? Yes

The unit was able to reliably relay data from the Tunnel to the outside of the Tunnel at the Pitot Tube location. The distance was much shorter than what would be required for the crawler inspection, testing would be required to confirm transmission of data over a longer distance.</td></tr>
<tr><td colspan="2">4. Are the measurements accurate within $\pm$0.25 inches over a 30 feet distance? Yes for near field

Several objects in the tunnel with known dimensions were measured by the unit and unit accuracy was confirmed. As noted in Section 6.2.2, as distance increased from the unit, blind spots, i.e. areas of no information increased. A more complete point cloud of the tunnel surfaces is obtained over a 19-foot distance. During the crawler inspection, the crawler would stop at 10’ to 20’ intervals which is within the 19-foot distance and resolve this concern.</td></tr>
</table>

5. Are measurements consistent at different elevations? <u>Yes</u> Several objects in the tunnel with known dimensions were measured by the unit at different elevations. Unit accuracy and measurement consistency was confirmed during the verification performed.
6. What is the best elevation for the LiDAR to scan the entire tunnel surface? Though not confirmed, the middle elevation is believed to be the optimum elevation, due to reduced distance to ceiling and wall, and less blind spots.
7. How many scans are required at each location? This question has not been resolved due to difficulties encountered on Day 2. Three scans per each elevation were performed on Day 1, the planned six scans per elevation on Day 2 were not performed.
8. Does the number of scans affect accuracy? This question has not been resolved as the number of scans performed with this deployment is limited. It is expected with additional scans, the scans will provide a larger set of data points which should provide a higher accurate measurement.
9. What is the effect of the abandoned-in-place Stainless-Steel exhaust ducts on scans? No Stainless-Steel duct was in the immediate scanning location, a mock-up of these features would be required to determine affect. As seen in the EW0 Segment the duct would impact the ability of the LiDAR to scan the surface behind the duct.
10. What are the software and hardware requirements for post-processing of data? The software and hardware requirements are listed in Section 3.2. Post-processing computing time was very lengthy on the order of weeks, consideration should be made to upgrade the current computer platform. This would also assist in performing some of the additional computations of interest such as whether there is benefit of acquiring more scans at a location to obtain higher density comparisons.

7.2 Recommendation

This report concludes and recommends continued the deployment at the local Pitot Tube location. It is recognized that the tunnel degradation throughout the tunnel is not uniform, but this does provide a local 19-foot distance to monitor surface change with quantitative and qualitative (through contour maps and images) data. Additionally, the potential to use relative data at further distances to obtain surface change information exists. It is also recognized that with continued deployments, lessons learned can be applied and resolved relative to LiDAR technology in the Tunnel, computer software and hardware.

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12. SRNS-IM-2020-00087, H-Canyon Exhaust Tunnel LiDAR on a Stick (LiDS) Data Post-Processing Guide, Rev. 0

Attachment A SRNL BLK360 Demonstration Test Measurement Data

The LiDAR point cloud data was collected on an iPad Pro using Recap Pro Mobile software. A total of 26 test scans were performed over a two-day period. Tests 1-12 were performed on the first day of testing. Tests 13-26 were performed on the second day of testing.

The distance between the center circles on each wall was measured in the LiDAR point cloud data for each test scan on the iPad Pro. The measurements are in column 2 of Table A-1. are from Bosch Blaze Pro 165' Laser Distance Measure GLM 165-40. The distance between the center circles on each wall was measured in the LiDAR point cloud data for each test scan on the iPad Pro. These measurements are in the column 3 of Table A-1. Column 4 of Table A-1 is the difference between the Blaze Pro measurements in column 2 and column 3. Values in column 4 that are less than or equal 0.25" are highlighted green while values greater than 0.25" are highlighted red. The outliers in Lowest Height Delta, Figure 2 (red values in Table A-1, tests 3 and 4), are a result of outside wind pressure (an uncontrolled variable) on the Alumalite walls. All LiDAR individual scan measured values save for those affected by the outside wind pressure (Table A.1, tests 3, 4, and 14) were within the goal tolerance of 0.25". Test 3 and 4 were performed sequentially in the presence of high winds. Test 14 was performed on test day 2 during a brief high wind period. The LiDAR was positioned 18", 48", and 81" above ground level of the test area. The height at which each test scan was performed is annotated in column 5 of Table A-1. Tests 1, 2, 5, 6, 9, 10, 13-16, 19, 20, 23 and 24 were performed with an AquaFog TurboXE wind blower present but inactive while the remaining tests were performed with the wind blower active. Blower presence in all tests ensures similarity of point cloud scenes for all tests. Column 6 of Table A-1 shows target wind speed. A Kestrel 3000 anemometer was used to measure wind speed prior to the start of test 3. This is reflected in column 7 of Table A-1. Column 8 of Table A-1 contains abbreviated test set names such as W1S1 for Wall 1 Set 1. Wall 1 Set 1 corresponds to the first set of scans with blower inactive at the first wall position (tests 1, 5, 9). W1S2 corresponds to the second set of scans with blower inactive at the first wall position (tests 2, 6, 10). W1WS1 refers to the first scan set with blower active at the first wall position (tests 3, 7, 11). W1WS2 corresponds to the second set with blower active at the first wall position (tests 4, 8, 12). W2S1 corresponds to the first scan set with blower inactive at the second wall position (tests 15, 19, 23). W2S2 refers to the second scan set with blower inactive at the second wall position (tests 16, 20, 24). W2WS1 refers to the first scan set with the blower active at the second wall position (tests 17, 21, 25). W2WS2 corresponds to the second scan set with blower active at the second wall position (tests 18, 22, 26). W2C refers to ceiling scan set with blower inactive at the second wall position (tests 13 and 14).

Table A-1 BLK360 Mock-Up Testing Individual Scan Results

LiDAR Performance Testing							
Test #	Blaze Pro Laser Distance Meter (Inches)	BLK360 Point to Point Distance (Inches)	LiDAR to Laser Delta (Inches)	LiDAR Elevation Off Ground (Inches)	Required Wind Speed (mph)	Actual Wind Speed (mph)	Abbreviated Test Name
1	105.9	105.68	0.22	18	0	N/A	W1S1
2	105.9	105.71	0.19	18	0	N/A	W1S2
3	105.9	104.76	1.14	18	30	22	W1WS1
4	105.9	103.08	2.82	18	30	22	W1WS2
5	105.9	105.88	0.02	48	0	N/A	W1S1
6	105.9	105.96	-0.06	48	0	N/A	W1S2
7	105.9	105.73	0.17	48	30	22	W1WS1
8	105.9	105.73	0.17	48	30	22	W1WS2
9	105.9	105.87	0.03	81	0	N/A	W1S1
10	105.9	105.82	0.08	81	0	N/A	W1S2
11	105.9	105.96	-0.06	81	30	22	W1WS1
12	105.9	106.14	-0.24	81	30	22	W1WS2
13	106.46875	106.38	0.08875	81	0	N/A	W2C
14	106.46875	107.11	-0.64125	81	0	N/A	W2C
15	106.46875	106.43	0.03875	81	0	N/A	W2S1
16	106.46875	106.26	0.20875	81	0	N/A	W2S2
17	106.46875	106.44	0.02875	81	30	22	W2WS1
18	106.46875	106.36	0.10875	81	30	22	W2WS2
19	106.46875	106.33	0.13875	48	0	N/A	W2S1
20	106.46875	106.47	-0.00125	48	0	N/A	W2S2
21	106.46875	106.27	0.19875	48	30	22	W2WS1
22	106.46875	106.49	-0.02125	48	30	22	W2WS2
23	106.46875	106.46	0.00875	18	0	N/A	W2S1
24	106.46875	106.43	0.03875	18	0	N/A	W2S2
25	106.46875	106.34	0.12875	18	30	22	W2WS1
26	106.46875	106.33	0.13875	18	30	22	W2WS2

Table A-2 displays data for each merged set. Test sets 1-8 consists of one measurement at each height (18”, 48”, and 81”) with the same value of controlled variables. Controllable variables included wind blower on or off and movable wall at position 1 or at position 2. Addressing repeatability concerns two sets were taken for each combination of controlled variables. Set 9 consists of tests 13 and 14, which depict material change on the ceiling and was performed at wall position 2. Wall position 2 was 0.56875” from wall position 1 in the direction away from the opposite wall as measured by the Blaze Pro. Each set was transferred from the iPad Pro to a laptop with Recap Pro. Distances between the center red circle on each wall were measured in the resulting Recap Pro merged point cloud sets. This data is in column 3 of Table A- 2. Column 4 of Table A-2 is the difference between the Blaze Pro measurement and the merged point cloud measurement. The same value highlighting color scheme is used as described above. Column 5 of Table A-2 lists the full set names.

Table A-2 - Merged Point Cloud Data

Merged Scan Measurements							
Merge #	Blaze Pro Laser Distance Meter (Inches)	Recap Pro Merge Distance (inches)	Merge to Laser Delta	18 inches	48 inches	81 inches	Test
1	105.9	105.966	-0.066	0.22	0.02	0.03	Wall 1 Set 1
2	105.9	106.1444	-0.2444	0.19	-0.06	0.08	Wall 1 Set 2
3	105.9	106.095	-0.195	1.14	0.17	-0.06	Wall 1 Wind Set 1
4	105.9	106.064	-0.164	2.82	0.17	-0.24	Wall 1 Wind Set 2
5	106.46875	106.492	-0.02325	0.00875	0.13875	0.03875	Wall 2 Set 1
6	106.46875	106.391	0.07775	0.03875	-0.00125	0.20875	Wall 2 Set 2
7	106.46875	106.565	-0.09625	0.12875	0.19875	0.02875	Wall 2 Wind Set 1
8	106.46875	106.357	0.11175	0.13875	-0.02125	0.10875	Wall 2 Wind Set 2
9	106.46875	106.443	0.02575	0.08875	-0.64125		Wall 2 Ceiling

Figure 3.1-3, LiDAR to Laser Delta (Inches) is a chart depicting the results of all 26 tests in Table A-1. Figure 3.1-1, Merge to Laser Delta is a chart depicting the results of the merged sets, which correlates to the data in Table A-2.

Attachment B - James Fisher Technologies (JFT) Functional Acceptance Test

The FAT began with participant introductions, a discussion of facility safety, and personal protective equipment (PPE) requirements. The test procedure was reviewed and expectations for each stage of testing. The JFT FAT procedure involved

- transport of the assembly to the mock-up flange,
- system operation checks,
- system positioning,
- scanning,
- physical adjustments of near tunnel and target (30' away) tunnel mock-ups,
- repeat of transport through scanning steps,
- system degradation checks,
- verification of data requirements met,
- and system measurement checks.

The participants inspected the equipment on the shop floor and the test area setup. The height adjustment flange in Figure B-2 was measured and confirmed to match the SRS pitot tube flange.

Figure B-1 LiDAR and Lights Attached to Deployment Pole

Figures B-1 through B-3 show components being inspected prior to transport of the assembly to mock-up flange. The tripod connector as well as the Moog AC6438 slip ring are displayed in Figure B-3 with guide pin and power connection wire. The power connection wire was placed between the guide pin and the tripod connection above the LiDAR to protect the wire.

Figures B-4 through B-7 show the assembly being inserted and the assembly stationary at all 3 deployment elevation positions. The test setup was outside the JFT hanger facility in Loveland, Colorado. The test was performed on a calm day with air temperature between 80 ^{o}F and 85 ^{o}F, low wind conditions, and low humidity. A fan on a pallet was adjusted using a forklift to replicate the LiDAR assembly operation in an air flow. The air speed was measured using two separate anemometers. The air speed was approximately 34 mph. The LED lights were set to a low setting. The LiDAR operation was tested in the vertical position prior to lifting the LiDAR assembly into the mock-up tunnel. Images were received and image quality was assessed (30.5 megapixel). The LiDAR assembly was lifted with a JLG lift truck.

Deployment heights were measured as 87", 54", and 25" from the mock-up floor. Following the first scan there was a slow data transfer rate compared to previously observed transfer rates during unofficial testing of the LiDAR unit. The scan finished the transfer process successfully. Due to slow transfer rate of the first full scan, all subsequent scans were timed. The FAT test was paused for lunch with the LiDAR assembly at the 87" position.

Figure B-2 Pole Height Adjustment Flange

Figure B-3 LiDAR Moog AC6438 Swivel Joint

Figure B-4 Deploying Test Pole for FAT (missing middle section)

Figure B-5 First Deployment Position in Test Rig

After lunch, the assembly and the fan were lowered to the 54” position to resume testing. The iPad would not connect to the LiDAR unit. The LiDAR was rebooted. Rebooting did not resolve the issue.

Figure B-6 LiDAR in Mid Position in Test Rig

Figure B-7 LiDAR in Lowest Position in Test Rig

Additionally, the NanoStation LocoM2s were restarted. A time-out error notification appeared after attempting to reconnect to the LiDAR. JFT personnel changed the IP address on the iPad, and the connection was reestablished. The test continued. These troubleshooting efforts caused approximately an hour delay.

The first attempt at acquiring a third scan on the iPad at an elevation of 25” was electronically aborted 3 minutes and 15 seconds into the scan due to radio frequency interference caused by welding equipment less than 15’ away from the LiDAR and nearest NanoStation LocoM2. The following actions were performed:

1. The wireless connection between iPad and LiDAR was disconnected.
2. Restarted access point NanoStation LocoM2—no affect.
3. Remotely restarted LiDAR from desktop computer—no affect.
4. Restarted Recap Pro Mobile—no affect.
5. Disconnected from and reconnected to iPad Wi-Fi—no affect.
6. Refreshed iPad IP address—no affect.
7. Discovered LiDAR powered off—may not have powered back on after remote restart.

Connection was reestablished. Test continued. The iPad at this point had two successful transferred scans. The attempt to acquire a third scan was recommenced. The second attempt at acquiring a third scan was aborted after 2 min and 30 seconds due to insufficient power required for current spike of approximately 1.5 A. The BK Precision 9103, a programmable multi-range DC power supply, was set to 7.4 V per the rating on the battery label provided by Leica when the power fault occurred.

Set BK Precision 9103 voltage to 7.7 V. The third attempt to acquire a third scan on the iPad commenced and completed successfully.

Four small blocks were attached one to each mock-up tunnel wall at approximately 4' from the mock-up floors. Due to prior events during the test it was decided to turn the LED lights to full power to test if the increased system load would cause additional issues. The first set of three scans were performed with LED lights on a low setting the second set of three scans were performed with LED lights on full.
A scan at each height was repeated. Current fluctuations were monitored during the scanning operation. During the last transfer, the iPad went into sleep mode and Recap Pro Mobile shutdown. Recap Pro Mobile was restarted, and the last scan was successfully retransferred. Measured scan times are indicated in Table 3. All scan times are in mm:ss format. Times are cumulative from start to finish. Scan time is the time from the start of the scan until "transferring" appears in Recap Pro Mobile. Transferring time is the time from the start of the scan until "processing" appears in in Recap Pro Mobile. Processing time is the time from the start of the scan until "registering" appears or the progress bar disappears in Recap Pro Mobile. Registering time is the time from the start of the scan until the progress bar disappears in Recap Pro Mobile.

Table B-1 - Scan Times

Scan	Height	Scan Time	Transfer Time	Process Time	Register time
#1-1	87"	NA	NA	NA	NA
#1-2	54"	5:27	8:00	10:15	11:00
#1-3a	25"	3:15			
#1-3b	25"	2:30			
#1-3c	25"	5:30	10:20	10:55	
#2-1	87"	5:28	11:15	1330	NA
#2-2	54"	5:15	11:00	13:22	14:00
#2-3	25"	5:20	11:13	14:15	14:40

LiDAR assembly was lifted out of the mock-up tunnel and placed back on stands. Centralizer wheels were examined along with integrity of connections and zip ties.

All 6 scans were transferred from the iPad to a desktop, from Recap Pro Mobile to Recap Pro. The outdoor target tunnel was obscured in the scans due to the fan placement and thus was not used in the deployment comparison. Each set ([1-1, 1-2, 1-3c], [2-1, 2-2, 2-3]) of scans were merged in Recap Pro. Measurements were taken in Recap Pro to verify data accuracy. Depths of a block near the scan point, A, and of a block 30' away, B, were measured. Table B-2 displays the measured depth of the blocks both from a physical measurement and using the merged point cloud. Both merged point cloud measurements were within the accuracy tolerance requirement.

Table B-2 - Surface Depth Change Measurement

Block	Recap Pro	Tape Measure	Delta
A	1.371"	1.49"	-0.119
B	1.61"	1.79"	-0.18

Attachment C Troubleshooting Steps Performed on Day-2

Once positioned into the tunnel, a scan was initiated from the iPAD. The first set of photos at the first position were received at the iPAD, followed by a scan aborted message. The LiDAR device was rebooted from the desktop to clear the error and the wireless connection between iPad and BLK360 was lost. The system was removed from the tunnel and the LiDAR, slipring, and cables were checked for visible degradation. Cycled the LiDAR power with and without fully disconnecting power and attempted low resolution scans from iPad; the scan would start and the initial turning of the LiDAR to collect the panoramic picture was observed, however after turning approximately 120 degrees the unit would stop and a slow axis error would be received at the iPAD followed by the scan aborted message.
Error Msg 1 – Slow axis stalled

The BLK360 could not complete the request because it encountered a hardware error. Message: panorama shoot failed: device blocked: slow axis stalled	Additional details: Code: Unknown Status: lgs_status_device_error **OK**

Error Msg 2 - Aborted

The BLK360 could not complete the request because it was aborted. Message:	Additional details: Code: Aborted Status: lgs_status_aborted **OK**

To address a concern of debris impacting scanner movement, personnel manually rotated the LiDAR and slipring, LiDAR only, and slipring only through full rotation. Continued to observe same results when attempting a scan where LiDAR would initially start to rotate then stop and the iPAD would receive error msg 1, slow axis stalled.

Further actions were stopped, the team discussed options, contacted JFT Leica vendor support agent who offered several suggestions and we determined a path forward.

Following the pause, these actions were performed:

1) Tried initiating a scan directly by depressing the power button on the LiDAR unit versus initiating via the iPAD.
    a. Held button for 1 second and green ring at top of LiDAR immediately came on, waited 50 seconds.
    b. Pressed button again for 1 second to initiate scan. Ring on LiDAR blinked green then blinked yellow then went to a solid yellow (note it is difficult to tell ring color in video, so this is best interpretation).

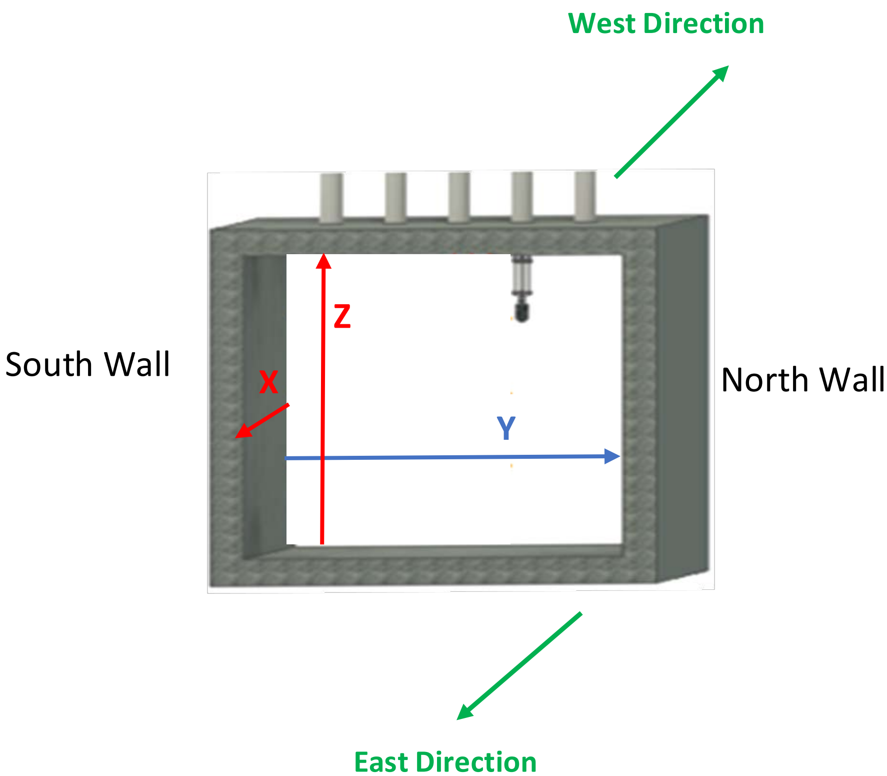
c. Turned off unit by holding in power button for 5 seconds.
d. Held button for 1 second to start. LiDAR blinked yellow then went to a solid green waited about 12 seconds.
e. Pressed button again for 1 second to initiate scan. Ring on LiDAR blinked green then blinked yellow then went to a solid yellow then a light green (note it is difficult to tell ring color in video, so this is best interpretation).
f. Pressed button again for 1 second. Ring on LiDAR turned dark green.

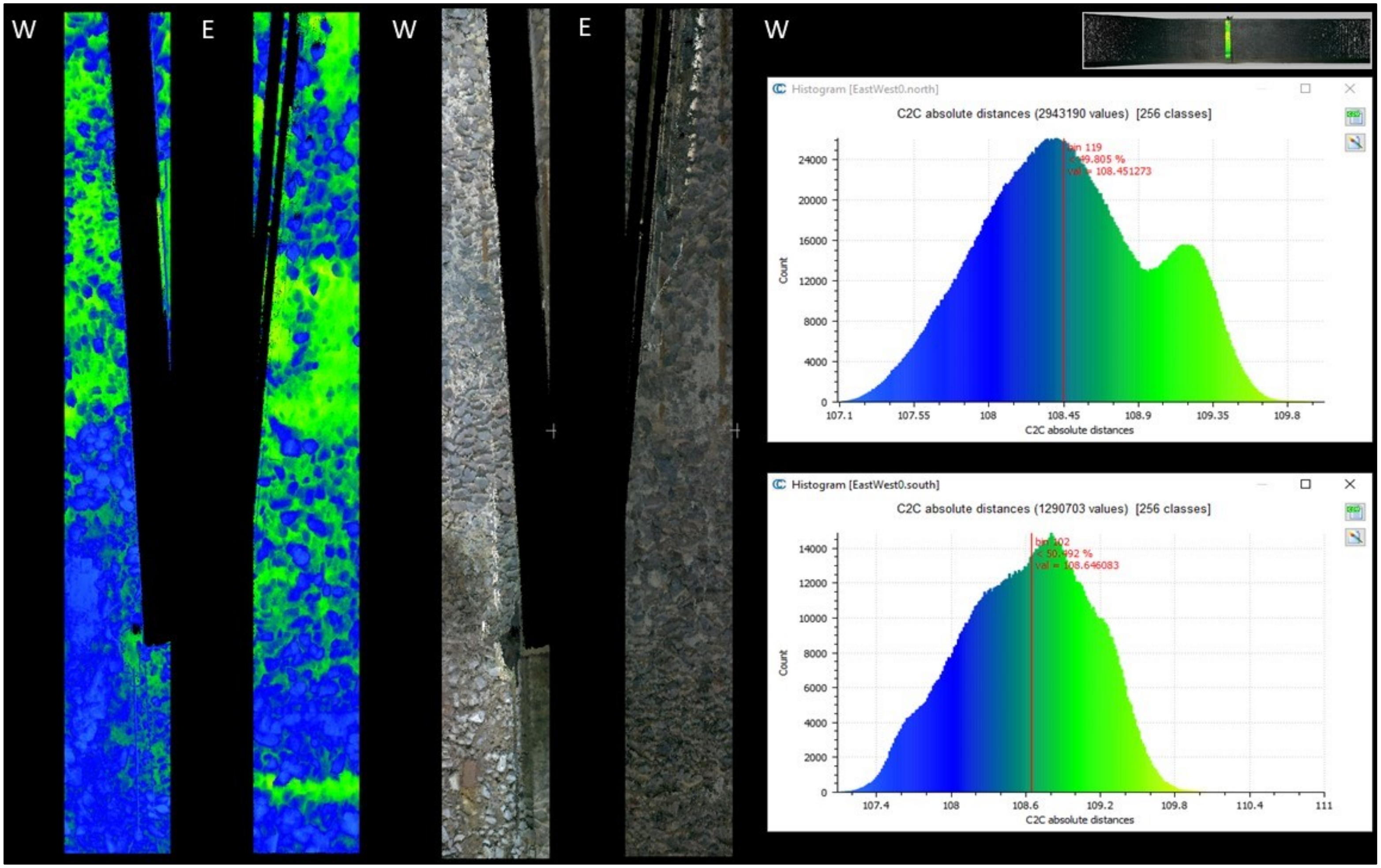
2) Turned off panorama view on iPAD (settings low, photo off, HDR off) and started a scan. Immediately received Error Msg 1 – Slow axis stalled. No turning of LiDAR observed. Tried a second time with same results
   a. Theory that maybe slow axis is the scanning axis versus panorama axis

3) Removed “fake” battery and installed real battery. Initiated scan from iPAD, immediately received Error Msg 2 – Aborted.

Attachment D Wall to Wall Comparison Method

Appendix D provides the contour maps, histograms curves and images for each of the 12 Segments. Contour maps, histogram curves and images are provided side by side for each group of data points.
With this method, the "Y" measurement, the distance between the North and South Walls is obtained. A figure depicting the coordinates, and an image of a Segment EWO with the "X" and "Z" coordinates is noted below.





North South North South

Figure D-1 Contour Map of Segment EW0 using wall-to-wall comparison (4.23M points)

Segment EW0 is located parallel with the pitot tube deployment location, 0.48’ West and 0.53’ East. The segment has a length of 12.21”. The segment extends from 0.21’ to 8.27’ below the pitot tube pipe. The segment has a height of 96.65”. The mean and 95% erosion values are North 0.45”, 1.34” and South 0.64”, 1.39”. This segment has [North, South] point density of [3393.55, 1367.73] points per square inch.

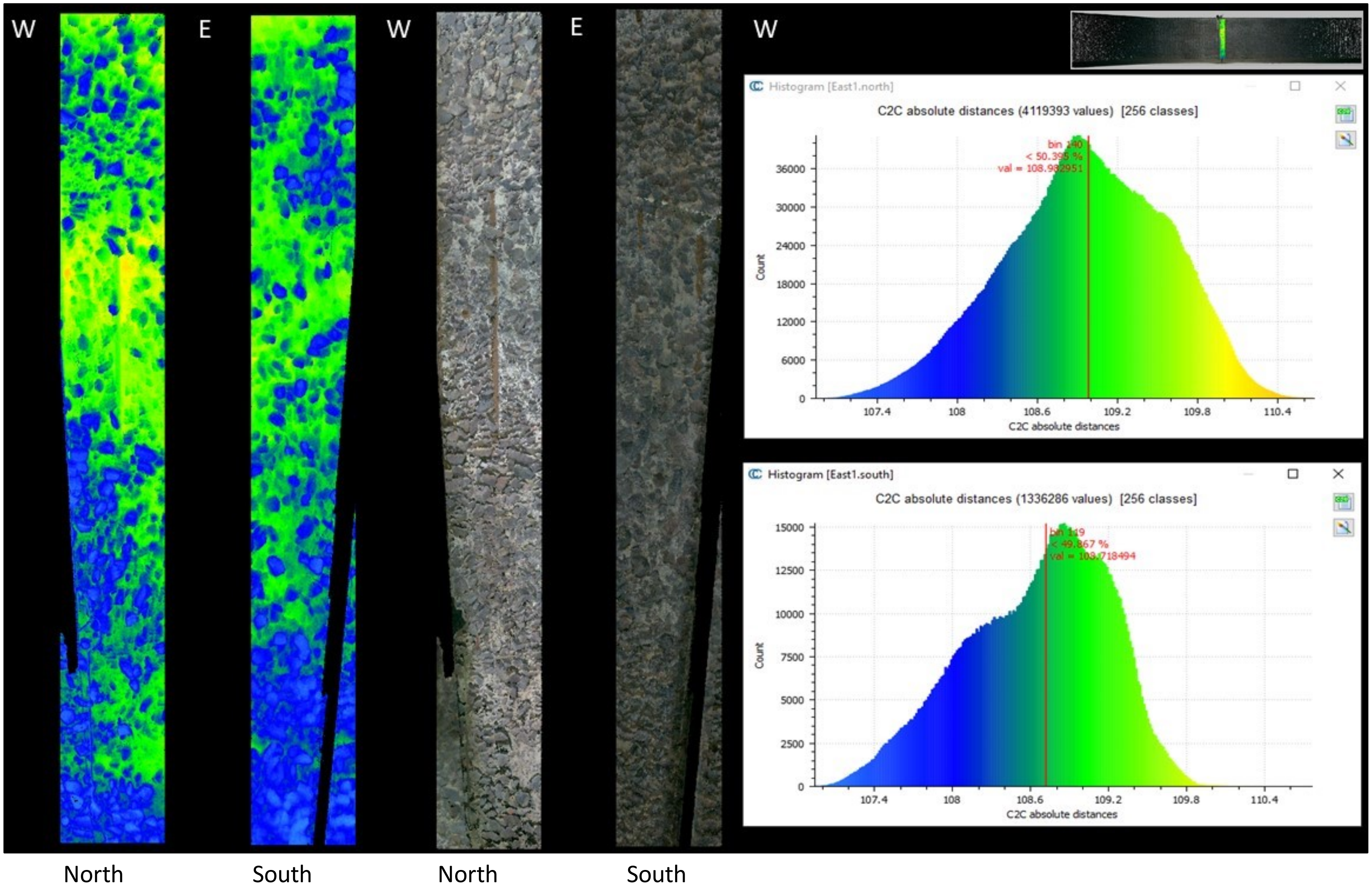


Figure D-2 Distribution of Segment E1 using wall-to-wall comparison (5.46M points)

Segment E1 is located 0.52’ to 1.54’ on the East of the LiDAR scanner. The segment extends from 0.15’ to 8.30’ below the pitot tube pipe. The segment has a height of 97.80”. The mean and 95% erosion values are North 0.98”, 1.9” and South 0.73”, 1.43”. This segment has [North, South] point density of [3545.91, 1231.57] points per square inch.

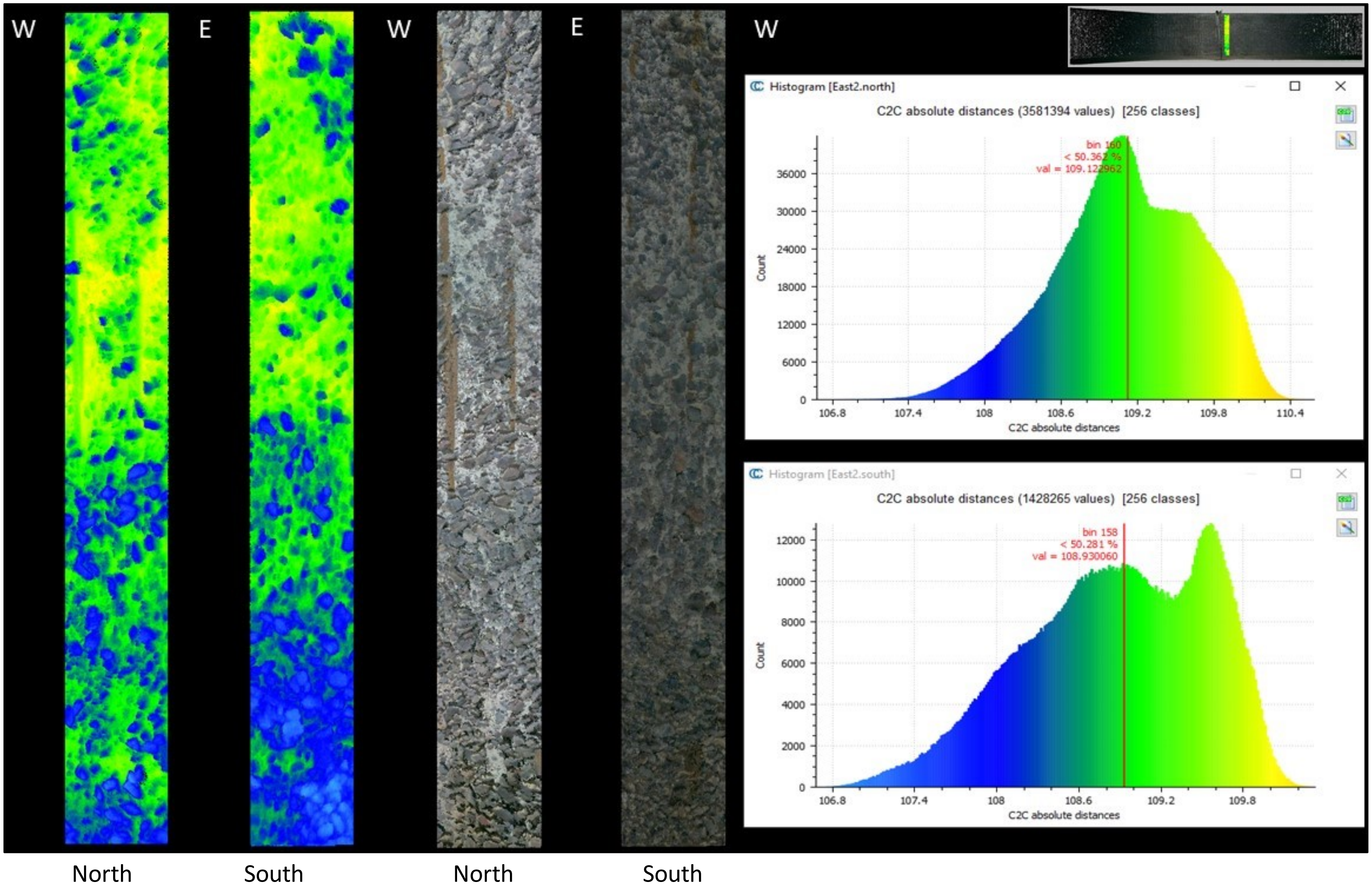
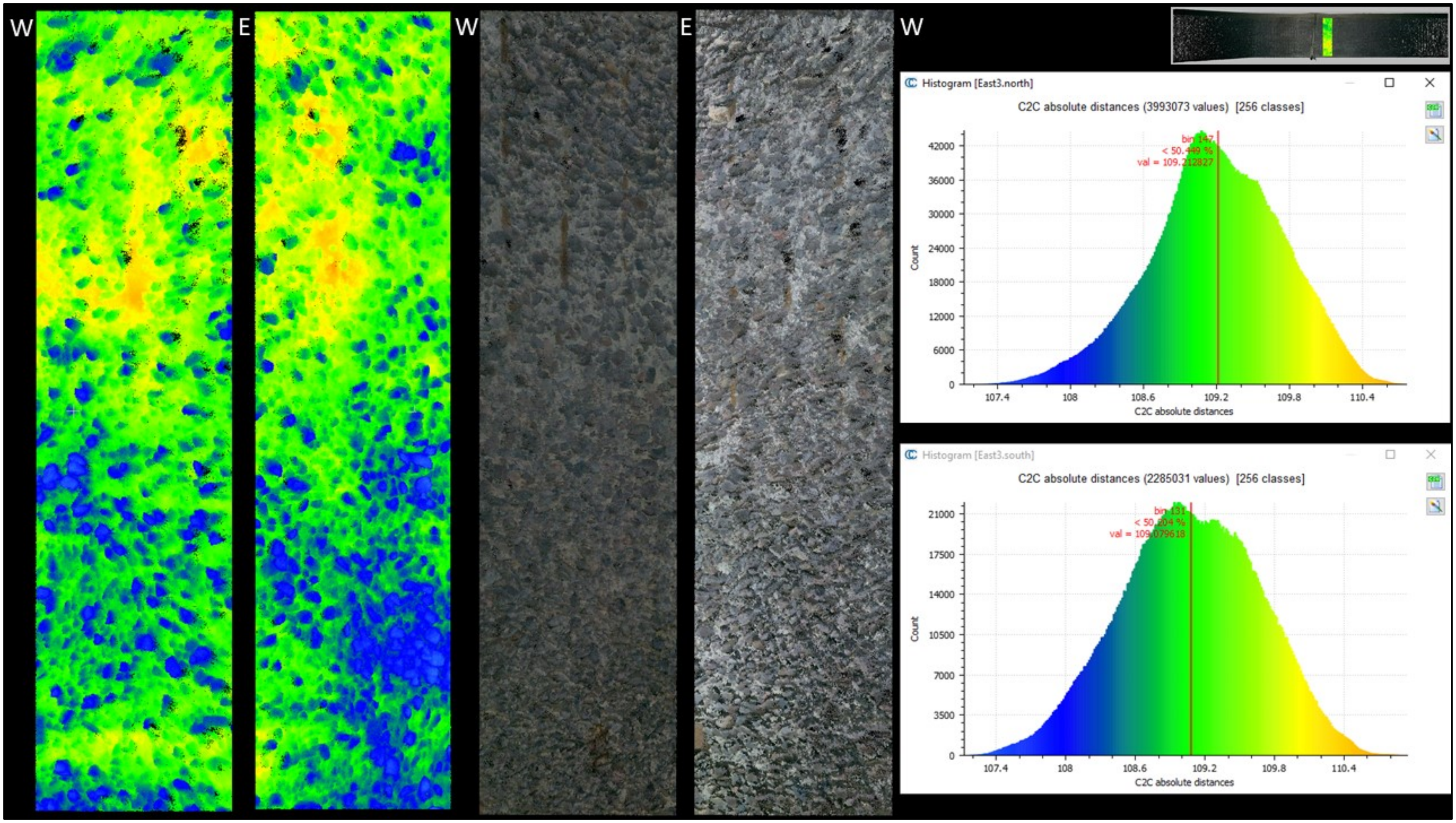


Figure D-3 Distribution of Segment E2 using wall-to-wall comparison (5.01M points)

Segment E2 is located 1.54’ to 2.55’ on the East of the LiDAR scanner. The segment extends from 0.15’ to 8.30’ below the pitot tube pipe. The segment has a height of 97.83”. The mean and 95% erosion values are North 1.12”, 1.97” and South 0.92”, 1.81”. This segment has [North, South] point density of [3014.22, 1200.07] points per square inch.



North South North South

Figure D-4 Distribution of Segment E3 using wall-to-wall comparison (6.28 M points)

Segment E3 is located 2.55’ to 4.56’ on the East of the LiDAR scanner. The segment extends 0.08’ to 8.28’ below the pitot tube pipe. The segment has a height of 98.64”. The mean and 95% erosion values are North 1.20”, 2.07” and South 1.08”, 2.03”. This segment has [North, South] point density of [1680.72, 961.84] points per square inch.

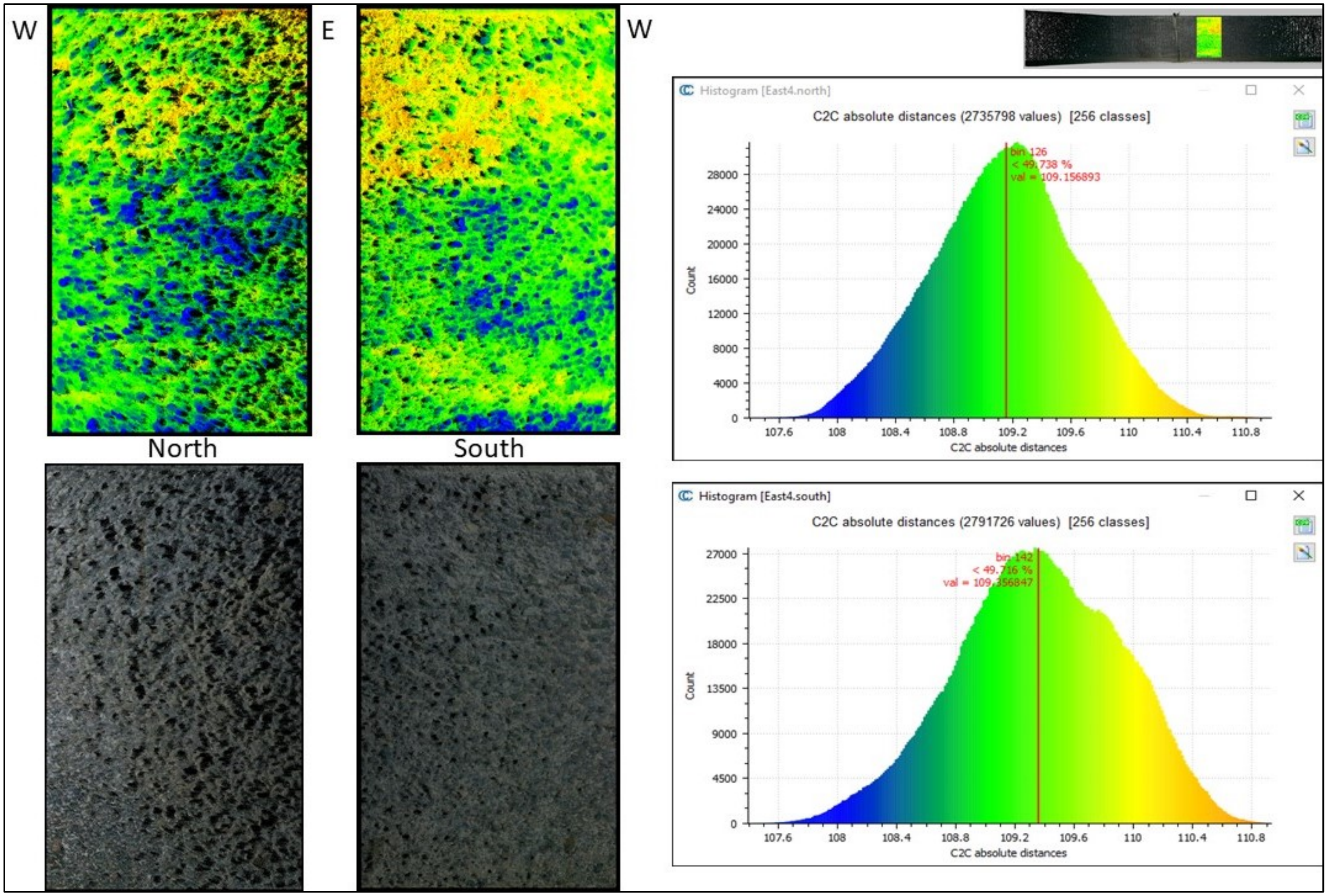


Figure D-5 Distribution of Segment E4 using wall-to-wall comparison (5.53 M points)

Segment E4 is located 4.56’ to 9.50’ on the East of the LiDAR scanner. The segment extends from 0.09’ to 8.27’ below the pitot tube pipe. The segment has a height of 98.31”. The mean and 95% erosion values are North 1.16”, 1.97” and South 1.36”, 2.23”. This segment has [North, South] point density of [470.29, 478.81] points per square inch.

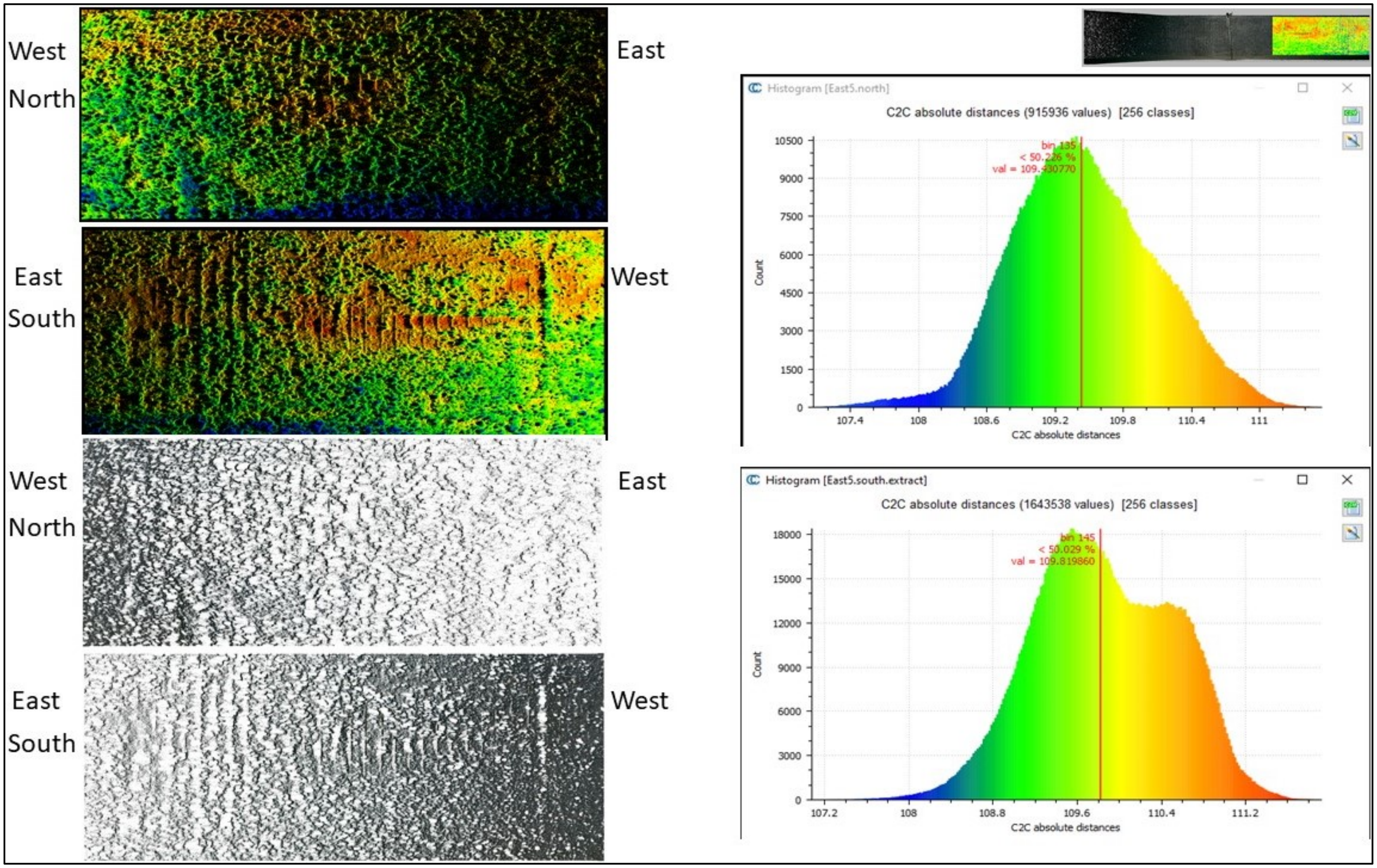
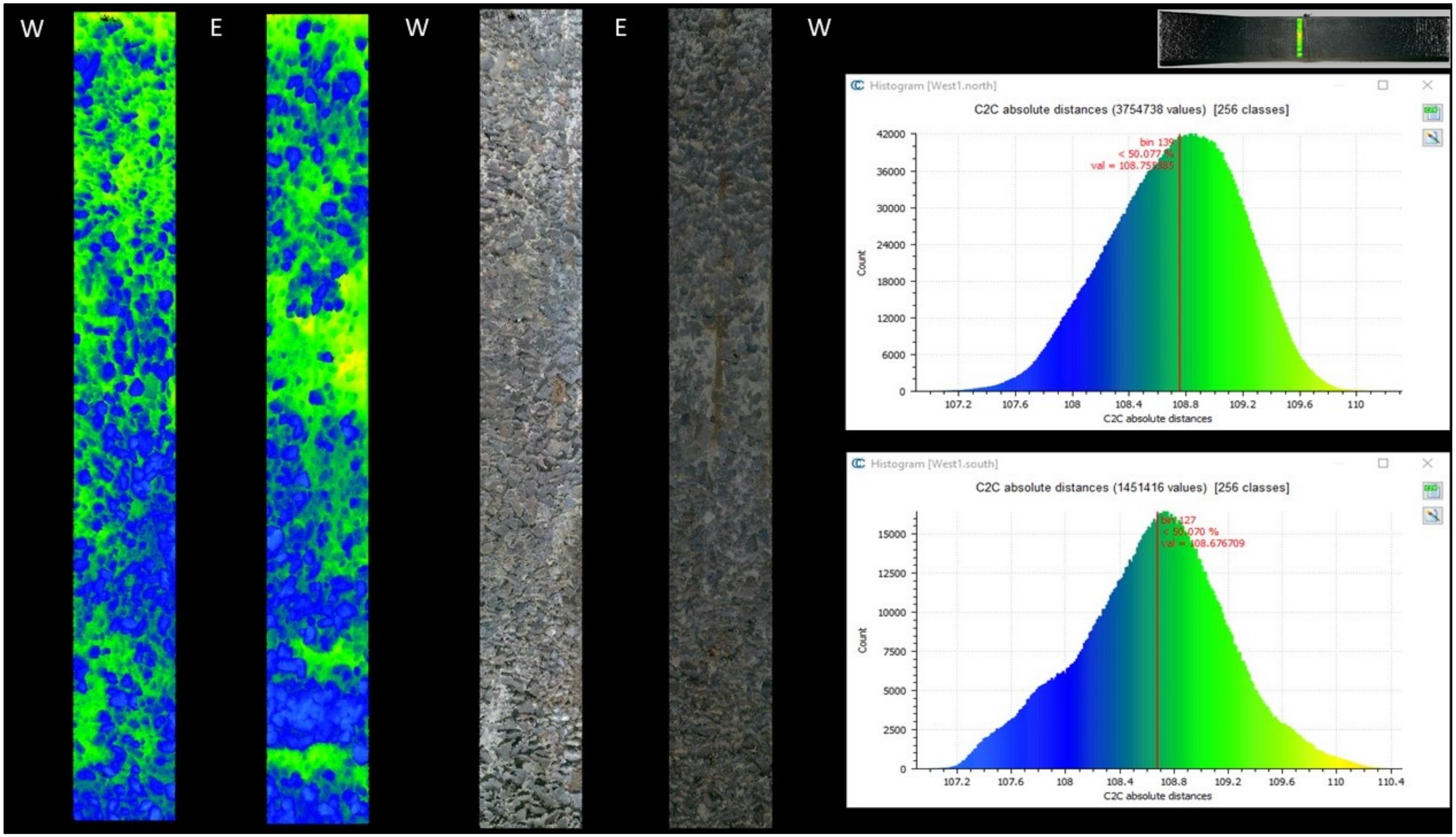


Figure D-6 Distribution of Segment E5 using wall-to-wall comparison (2.56 M points)

Segment E5 is located 9.50’ to 29.85’ on the East of the LiDAR scanner. The segment extends from 0.09’ to 8.23’ below the pitot tube pipe. The segment has a height of 97.63”. The mean and 95% erosion values are North 1.43”, 2.52” and South 1.82”, 2.90”. This segment has [North, South] point density of [38.44, 68.96] points per square inch.



North South North South

Figure D-7 Contour Map of Segment W1 using wall-to-wall comparison (5.21M points)

Segment W1 is located 0.48’ to 1.51’ West of the LiDAR scanner. The segment extends from 0.20’ to 8.30’ below the pitot tube pipe. The segment has a height of 97.29”. Rebar on the right side (South wall) shows lesser distance than the surrounding concrete. This indicates the surrounding concrete surface is lower than the exposed rebar. The mean and 95% erosion values are North 0.75”, 1.42” and South 0.68”, 1.53”. This segment has [North, South] point density of [3167.15, 1224.01] points per square inch.

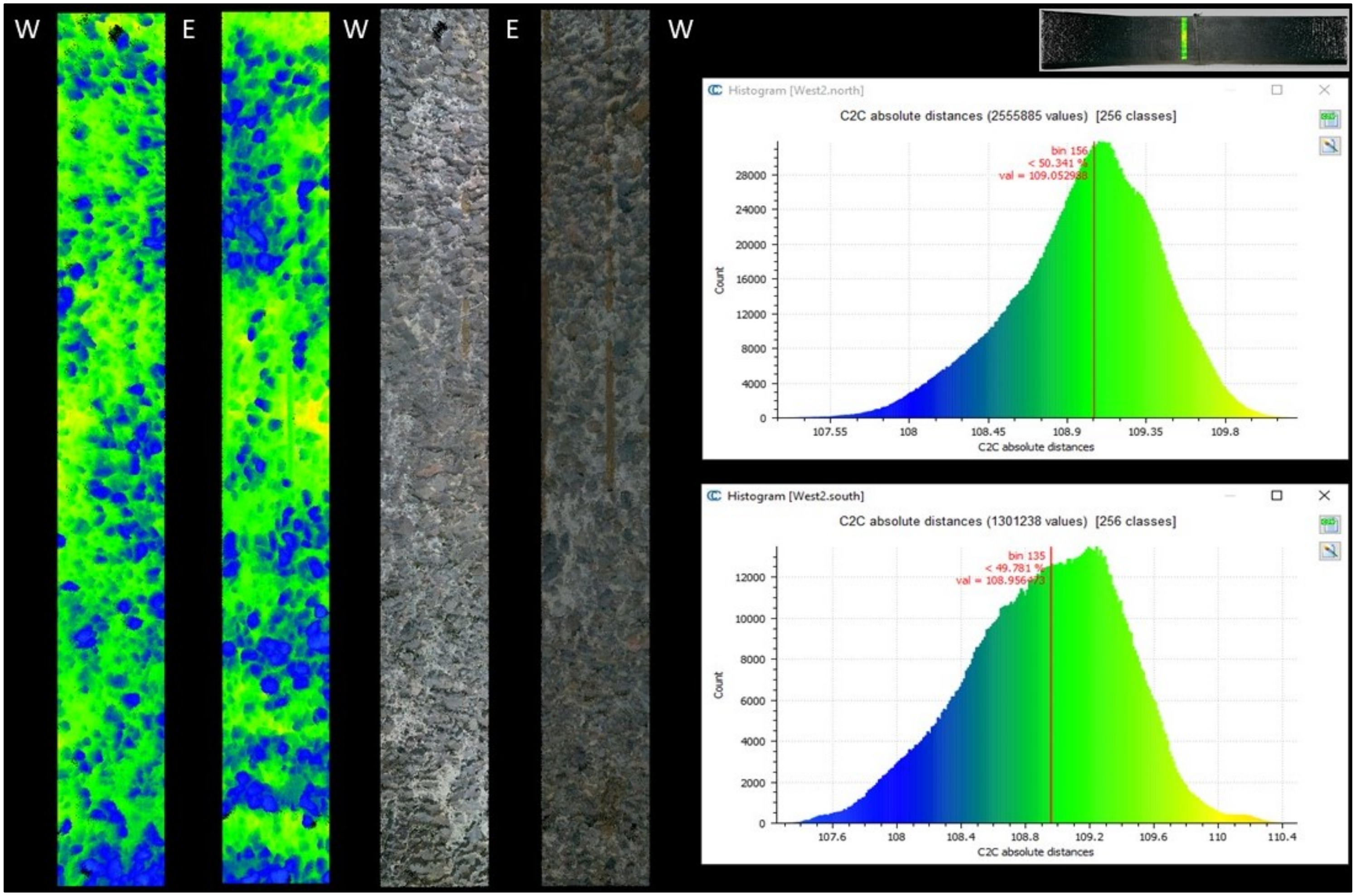
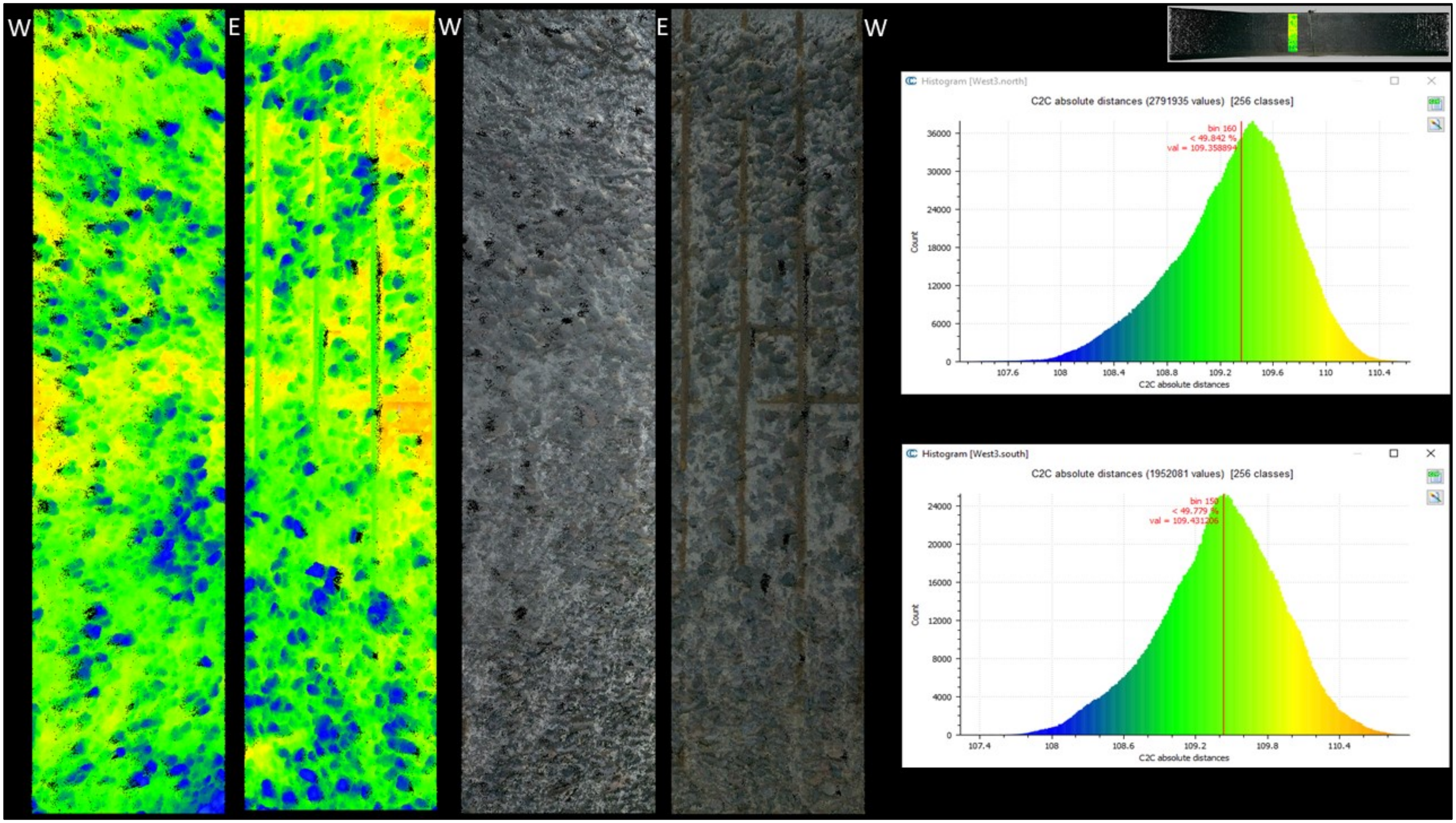


Figure D-8 Contour Map of Segment W2 using wall-to-wall comparison (3.86M points)

Segment W2 is located 1.50’ to 2.51’ West of the LiDAR scanner. The segment extends from 0.11’ to 8.31’ below the pitot tube pipe. The segment has a height of 98.34”. The mean and 95% erosion values are North 1.05”, 1.63” and South 0.96”, 1.64”. This segment has [North, South] point density of [2153.29, 1096.40] points per square inch.



North South North South

Figure D-9 Contour Map of Segment W3 using wall-to-wall comparison (4.74M points)

Segment W3 is located 2.50’ to 4.48’ West of the LiDAR scanner. The segment extends from 0.08’ to 8.32’ below the pitot tube pipe. The segment has a height of 98.85”. The mean and 95% erosion values are North 1.36”, 1.96” and South 1.44”, 2.18”. This segment has [North, South] point density of [1190.01, 831.95] points per square inch.

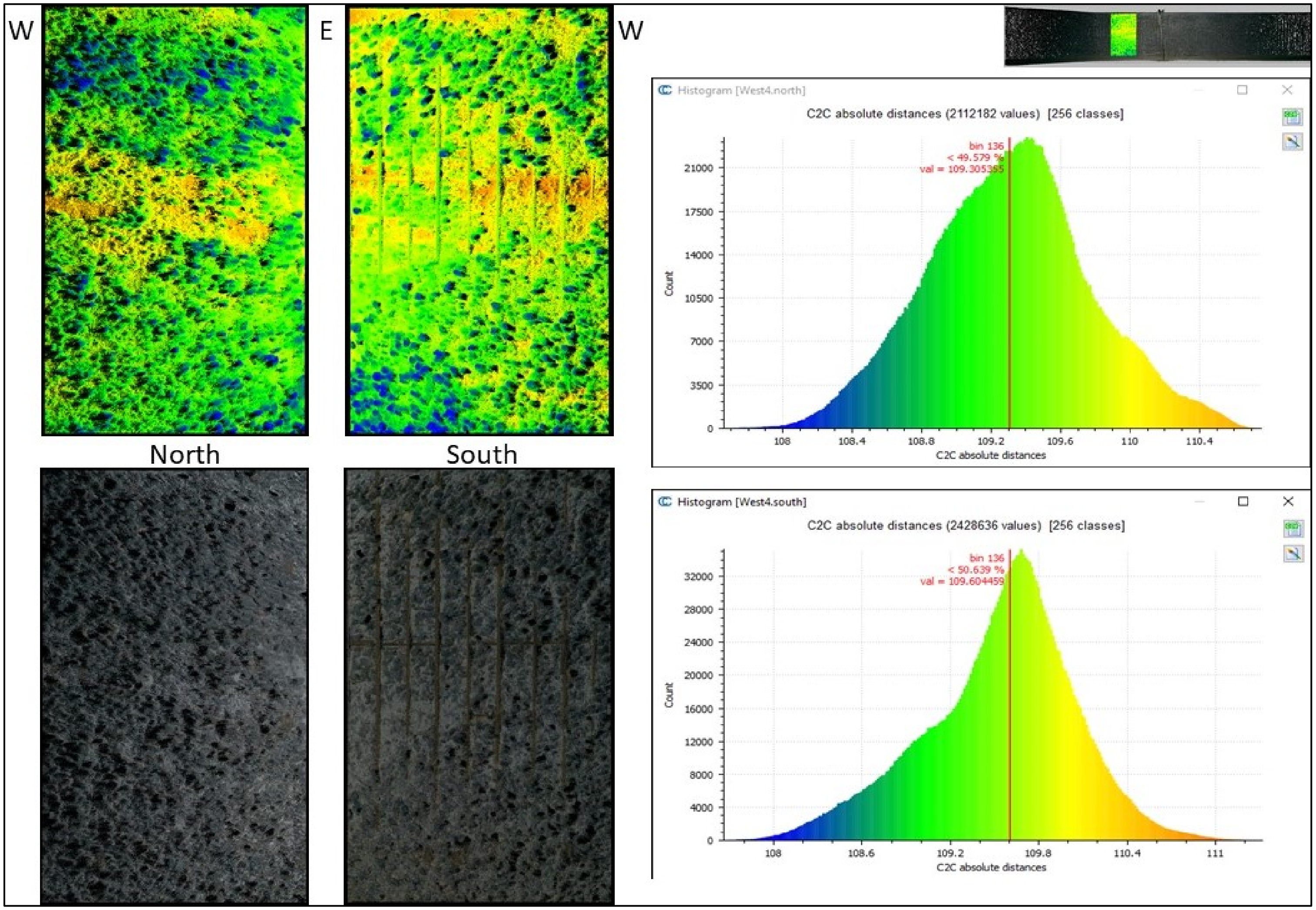


Figure D-10 Contour Map of Segment W4 using wall-to-wall comparison (4.54M points)

Segment W4 is located 4.46’ to 9.51’ West of the LiDAR scanner. The segment extends from 0.08’ to 8.32’ below the pitot tube pipe. The segment has a height of 98.90”. The mean and 95% erosion values are North 1.31”, 2.10” and South 1.60”, 2.37”. This segment has [North, South] point density of [352.88, 405.73] points per square inch.

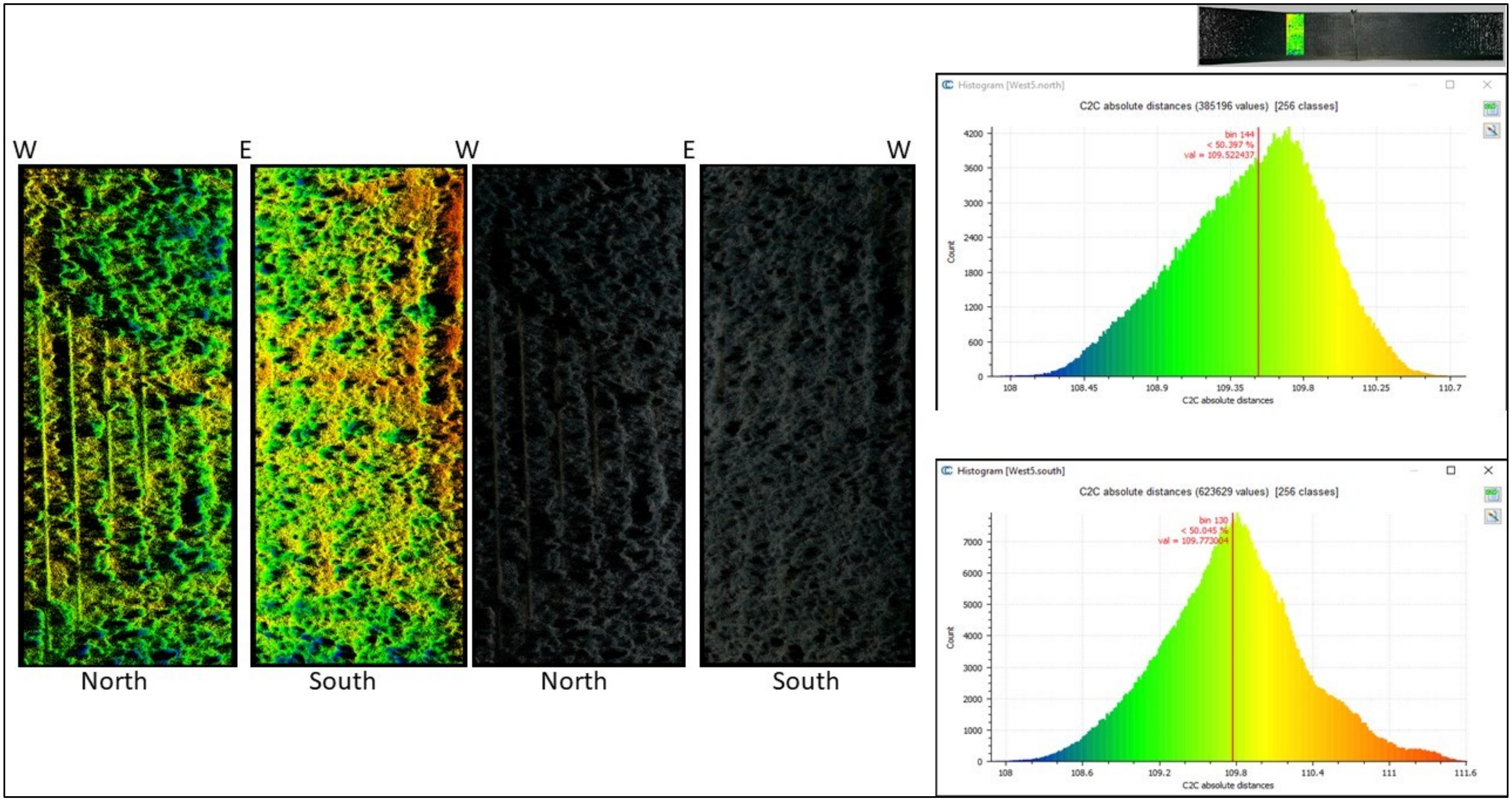


Figure D-11 Contour Map of Segment W5 using wall-to-wall comparison (1.01M points)

Segment W5 is located 9.49’ to 12.93’ West of the LiDAR scanner. The segment extends from 0.09’ to 8.28’ below the pitot tube pipe. The segment has a height of 98.26”. The mean and 95% erosion values are North 1.52”, 2.14” and South 1.77”, 2.72”. This segment has [North, South] point density of [95.20, 154.00] points per square inch.

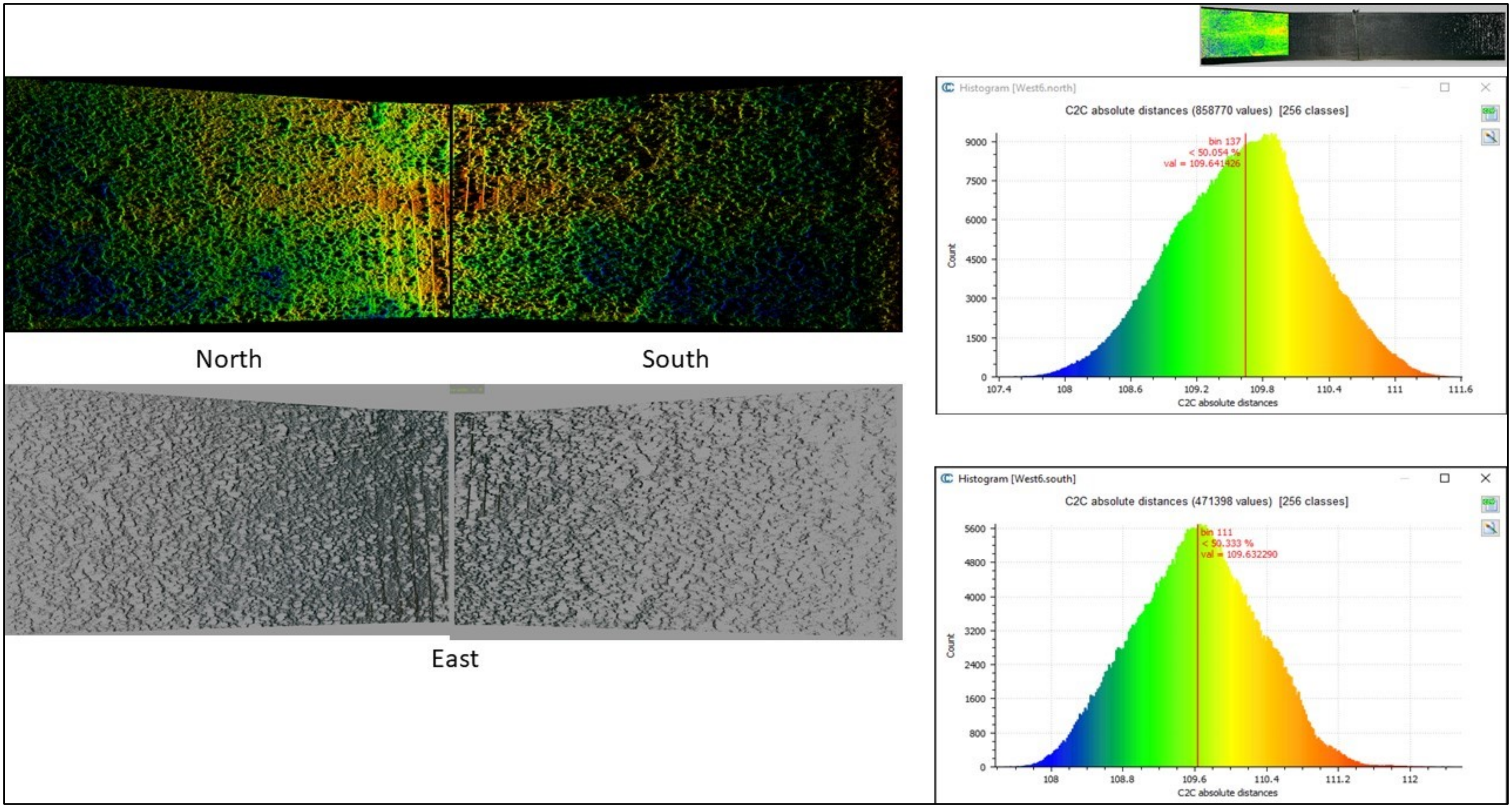


Figure D-12 Contour Map of Segment W6 using wall-to-wall comparison (1.33M points)

Segment W6 is located 12.91’ to 30.14’ West of the LiDAR scanner. The segment extends from 1.00’ above to 8.74’ below the pitot tube pipe. The segment has a height of 98.64”. The left most 0.14’ of W6 is outside calibration range based on manufacturer specification. The mean and 95% erosion values are North 1.64”, 2.64” and South 1.62”, 2.73”. This segment has [North, South] point density of [37.98, 20.83] points per square inch.

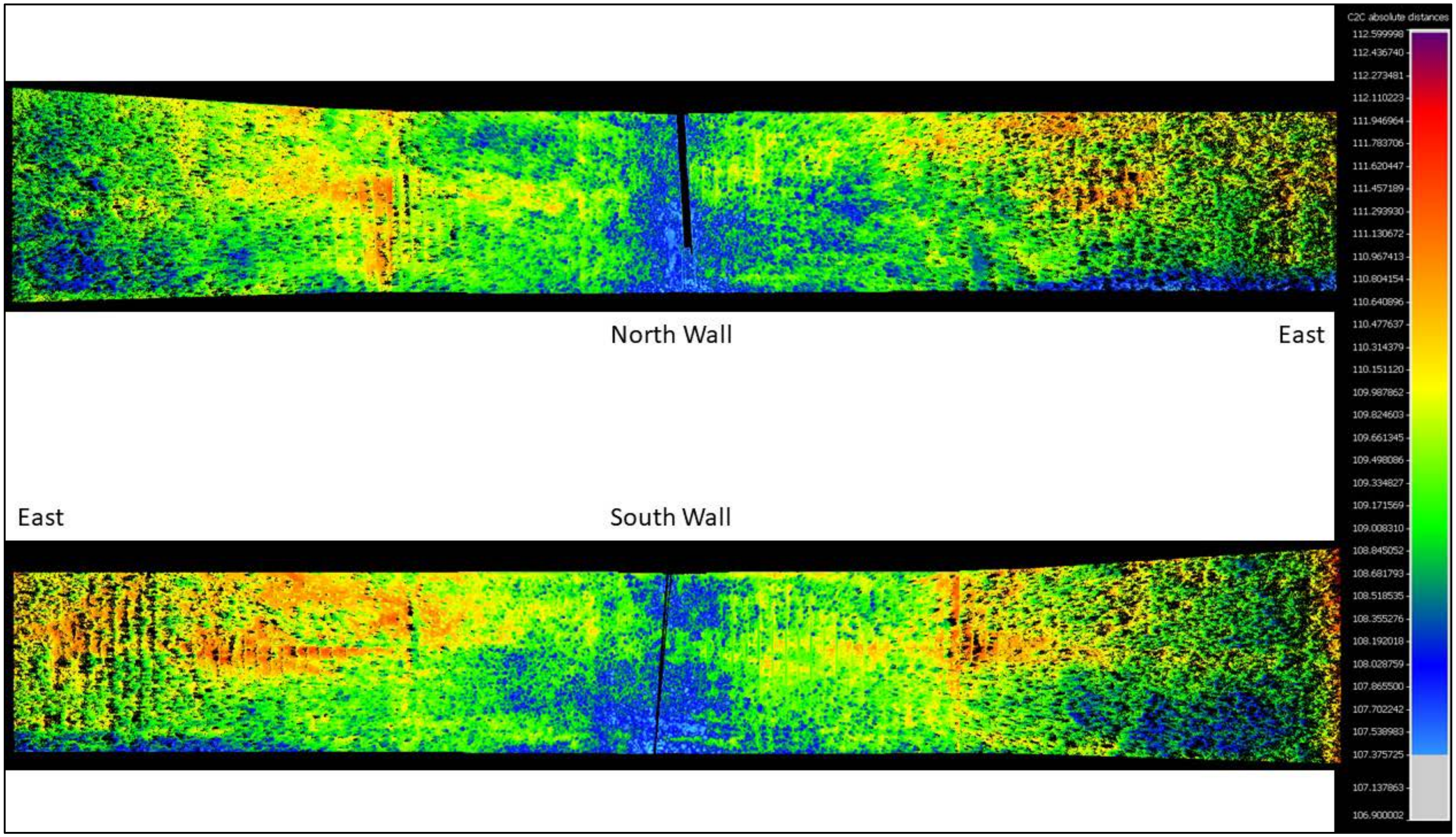
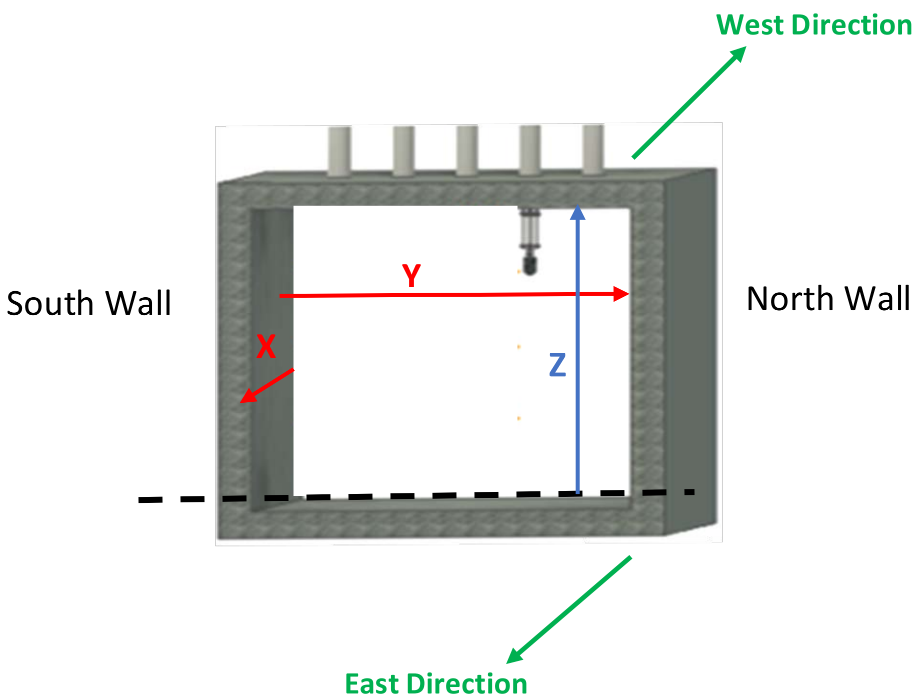


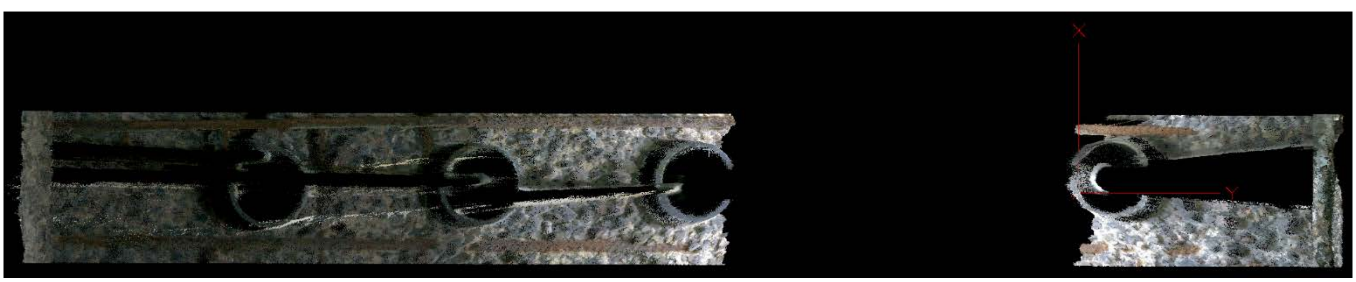
Figure D-13 Contour Map with Distance Distribution within ± 10 Meter from BLK360 scanner using wall-to-wall comparison.

The above contour map displays 12 segments combined. This contour map shows an overall view along the tunnel where the data point cloud covered. Gaps in the maps are due to blind spots produced by the environment and LiDAR capabilities. Cloud to cloud (C2C) absolute distances are shown on the right with the same scalar field color scale as the contour maps. The C2C absolute distance bar is a visual aid to view the same data as the contour map. More distance values are displayed on the bar than the contour map including minimum and maximum calculated distances.

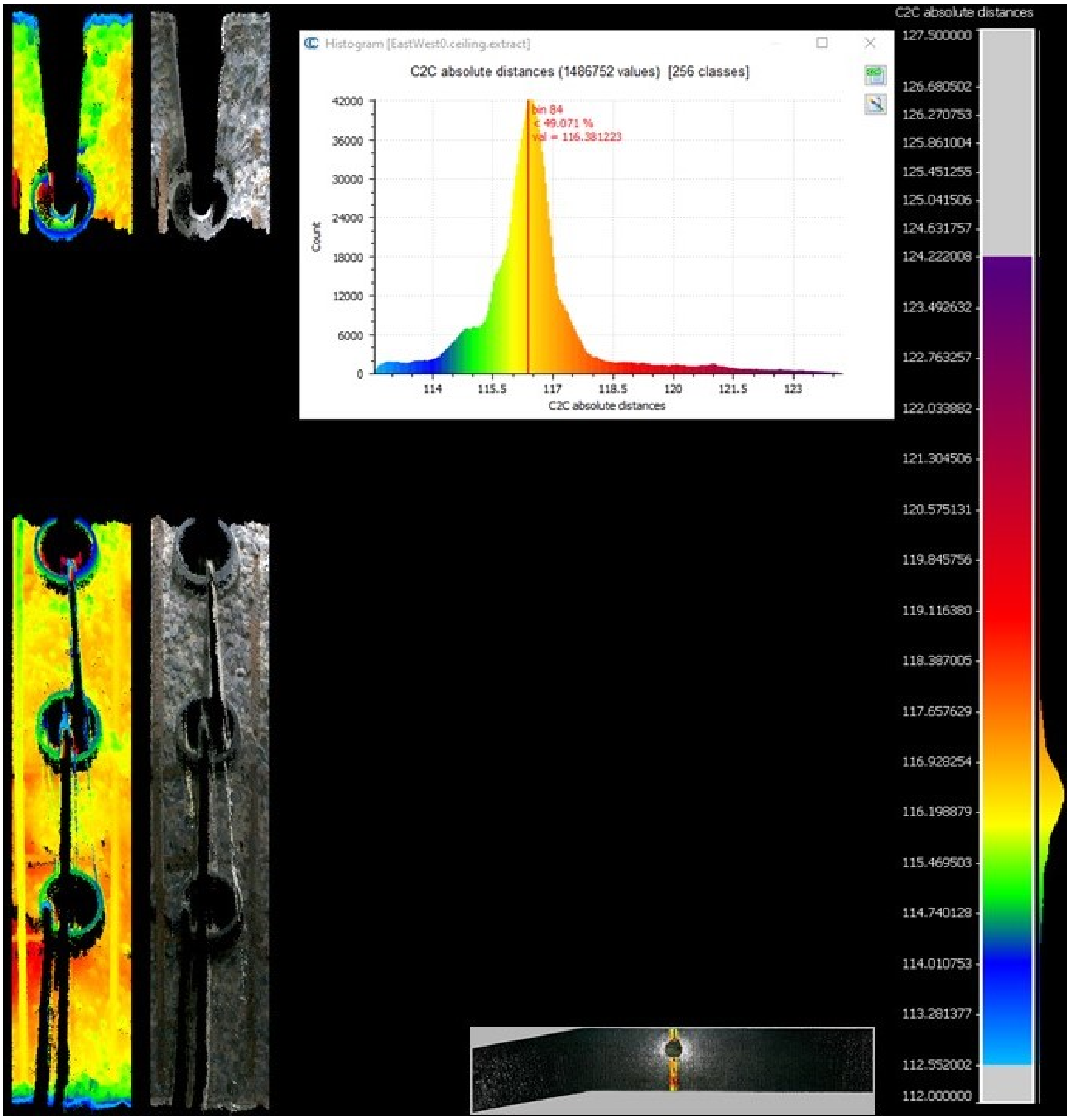
Attachment E Artificial Horizontal Plane to Ceiling Comparison Method

Appendix E provides the contour maps, histograms curves and images for each of the 12 Segments. Contour maps, histogram curves and images are provided side by side for each group of data points. With this method, the "Z" measurement, the distance between the Artificial Horizontal Floor Plane and Ceiling is obtained. A figure depicting the coordinate and an image of a Segment EWO with the "X" and 'Y" coordinates is noted below.





East

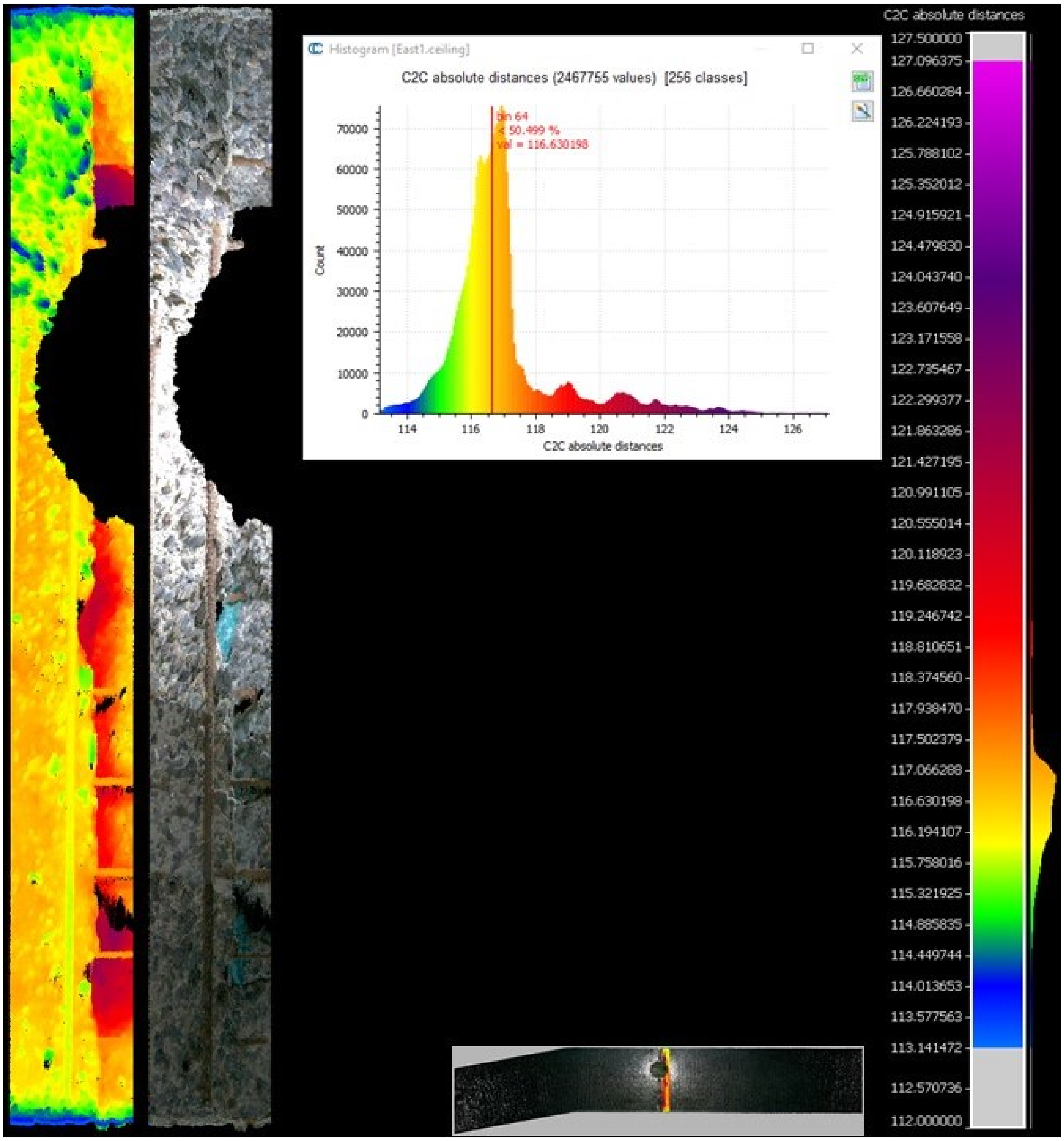


South

Figure E-1 Ceiling Contour Map of Segment EW0 (1.49M points)

Segment EW0 is located parallel with the pitot tube deployment location, extending 0.48’ West and 0.53’ East. The segment has a length (West to East) of 12.21”. The segment extends 1.88’ North and 7.59’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 112.81”. The missing areas in the contour map are blind spots due to a pipe holding a section of concrete (Coupon) on the North side (top), abandoned in place instrument piping from other sensor deployments hanging down in the tunnel on the South side of the deployment location, the blind spot from the device design of the BLK360 at the deployment location, and occluded spots from the other pitot tubes. The mean and 95% erosion values are 2.40”, 5.48”. Particulate and wall sections are responsible for calculated distances less than 114”. This segment has point density of 2316.29 points per square inch.

East

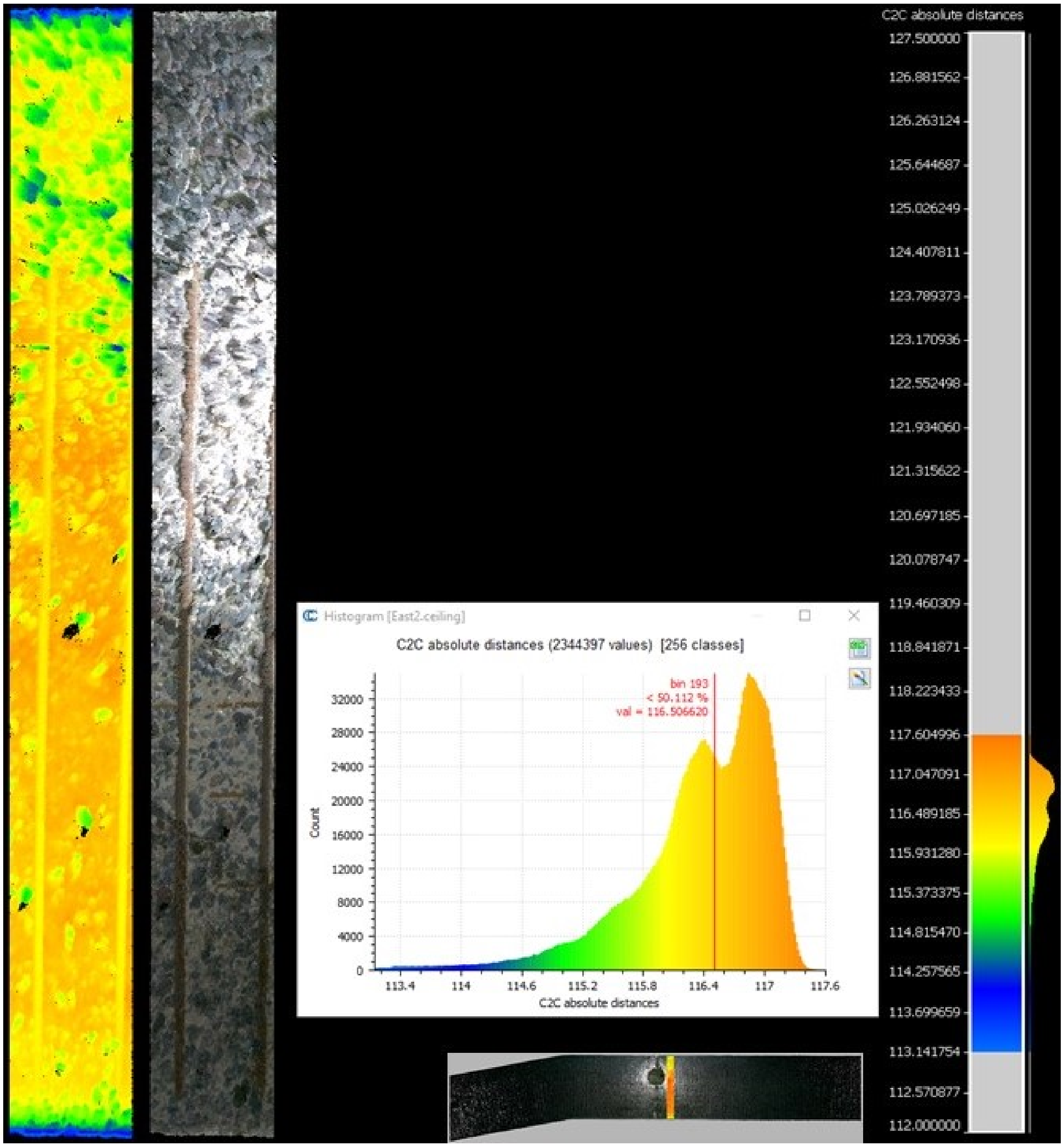


South

Figure E-2 Ceiling Contour Map of Segment E1 (2.47M points)

Segment E1 is located 0.52’ to 1.54’ on the East of the LiDAR scanner. The segment extends 1.92’ North and 7.57’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 113.63”. The missing areas in the contour map are blind spots due to the device design of the BLK360. The mean and 95% erosion values are 2.62”, 6.83”. This segment has point density of 2130.83 points per square inch.

East

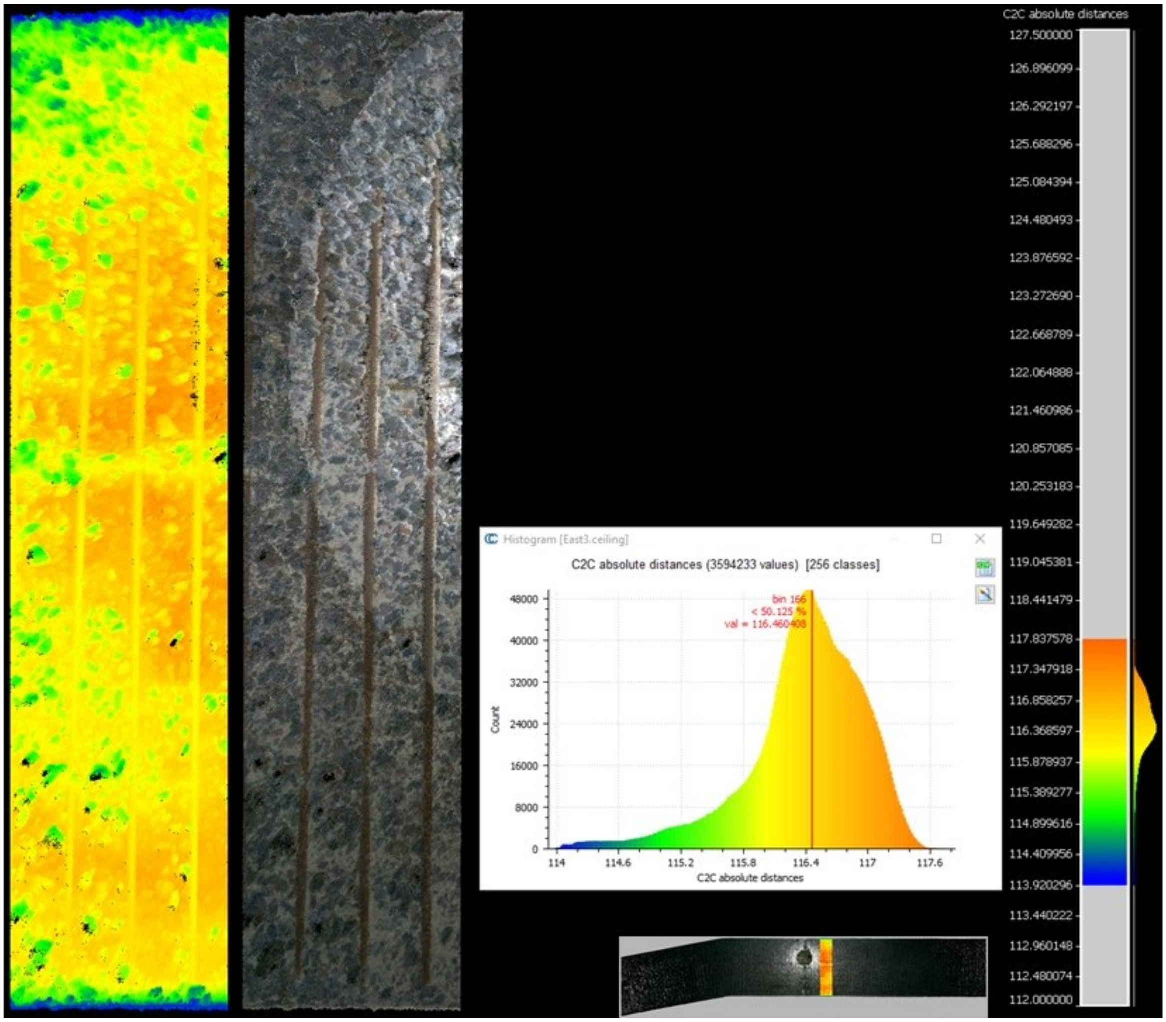


South

Figure E-3 Ceiling Contour Map of Segment E2 (2.34M points)

Segment E2 is located 1.54’ to 2.55’ on the East of the LiDAR scanner. The segment extends 1.92’ North and 7.51’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 111.88”. The mean and 95% erosion values are 2.50”, 3.14”. This segment has point density of 1738.09 points per square inch.

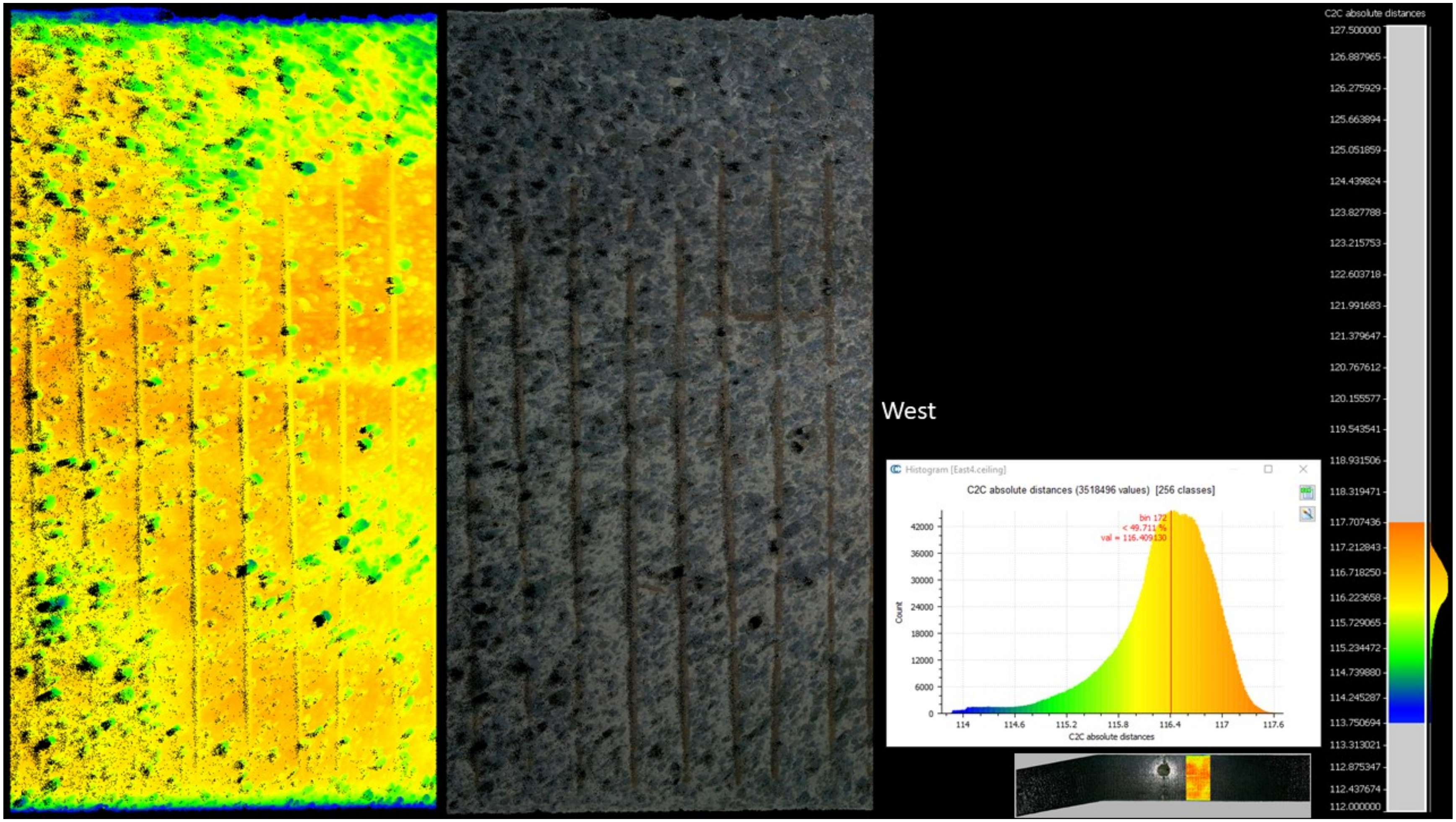
East



South

Figure E-4 Ceiling Contour Map of Segment E3 (3.59M points)

Segment E3 is located 2.55’ to 4.56’ on the East of the LiDAR scanner. The segment extends 1.91’ North and 7.54’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 111.43”. The mean and 95% erosion values are 2.46”, 3.16”. This segment has point density of 1341.26 points per square inch.



South

Figure E-5 Ceiling Contour Map of Segment E4 (3.52M points)

Segment E4 is located 4.56’ to 9.50’ on the East of the LiDAR scanner. The segment extends 1.89’ North and 7.57’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 112.26”. The mean and 95% erosion values are 2.41”, 3.07”. This segment has point density of 529.31 points per square inch.

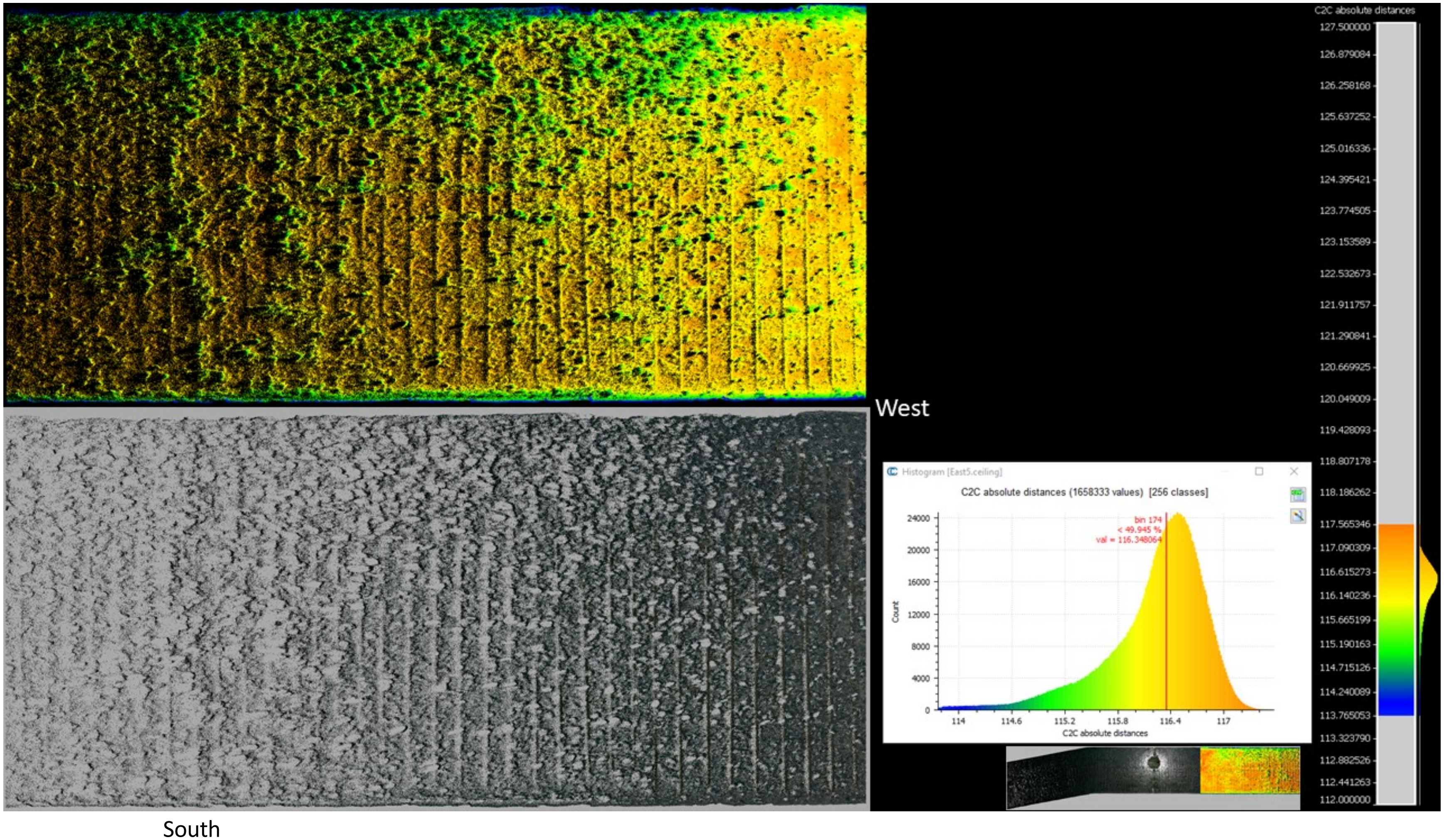
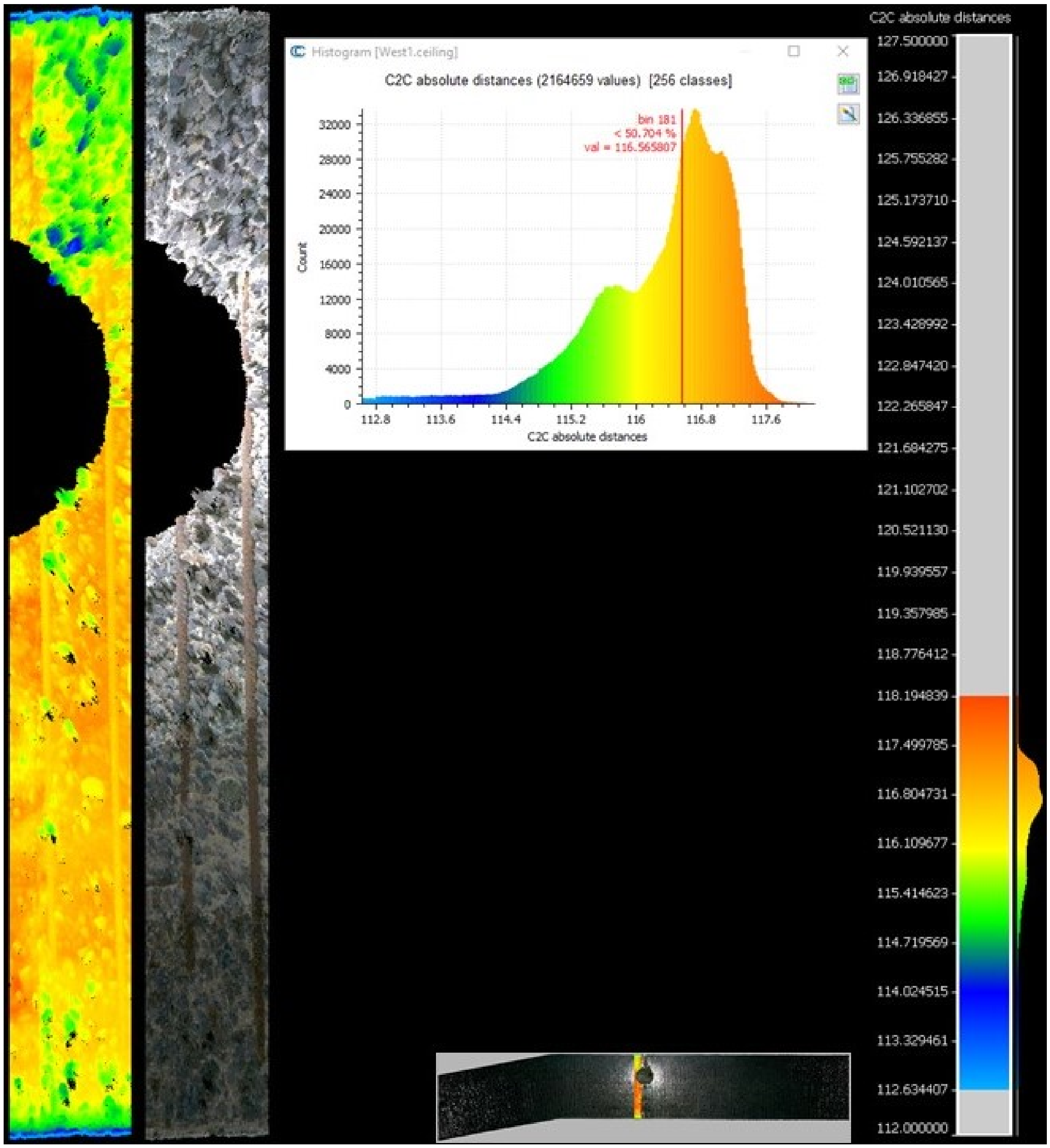


Figure E-6 Ceiling Contour Map of Segment E5 (1.64M points)

Segment E5 is located 9.50' to 29.85' on the East of the LiDAR scanner. The segment extends 1.87' North and 7.66' South of the Southern edge of the Northern most pitot tube. The segment has a width of 113.51". The mean and 95% erosion values are 2.35" and 2.92". This segment has point density of 59.34 points per square inch.

East

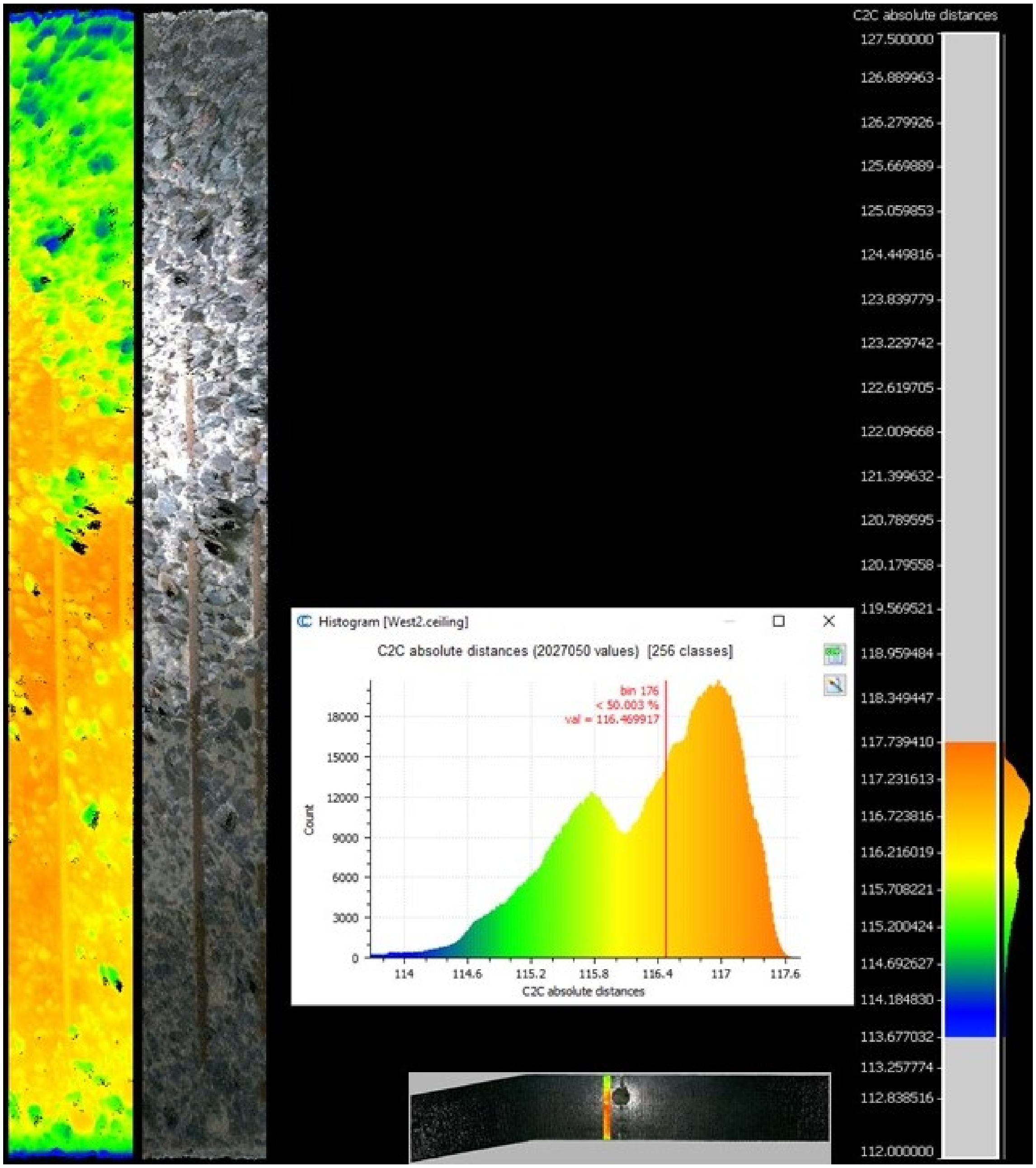


South

Figure E-7 Ceiling Contour Map of Segment W1 (2.16M points)

Segment W1 is located 0.48’ to 1.51’ West of the LiDAR scanner. The segment extends 1.90’ North and 7.54’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 112.66”. The mean and 95% erosion values are 2.55” and 3.28”. This segment has point density of 1931.72 points per square inch. The missing area in the contour map is a blind spot due to the device design of the BLK360.

East

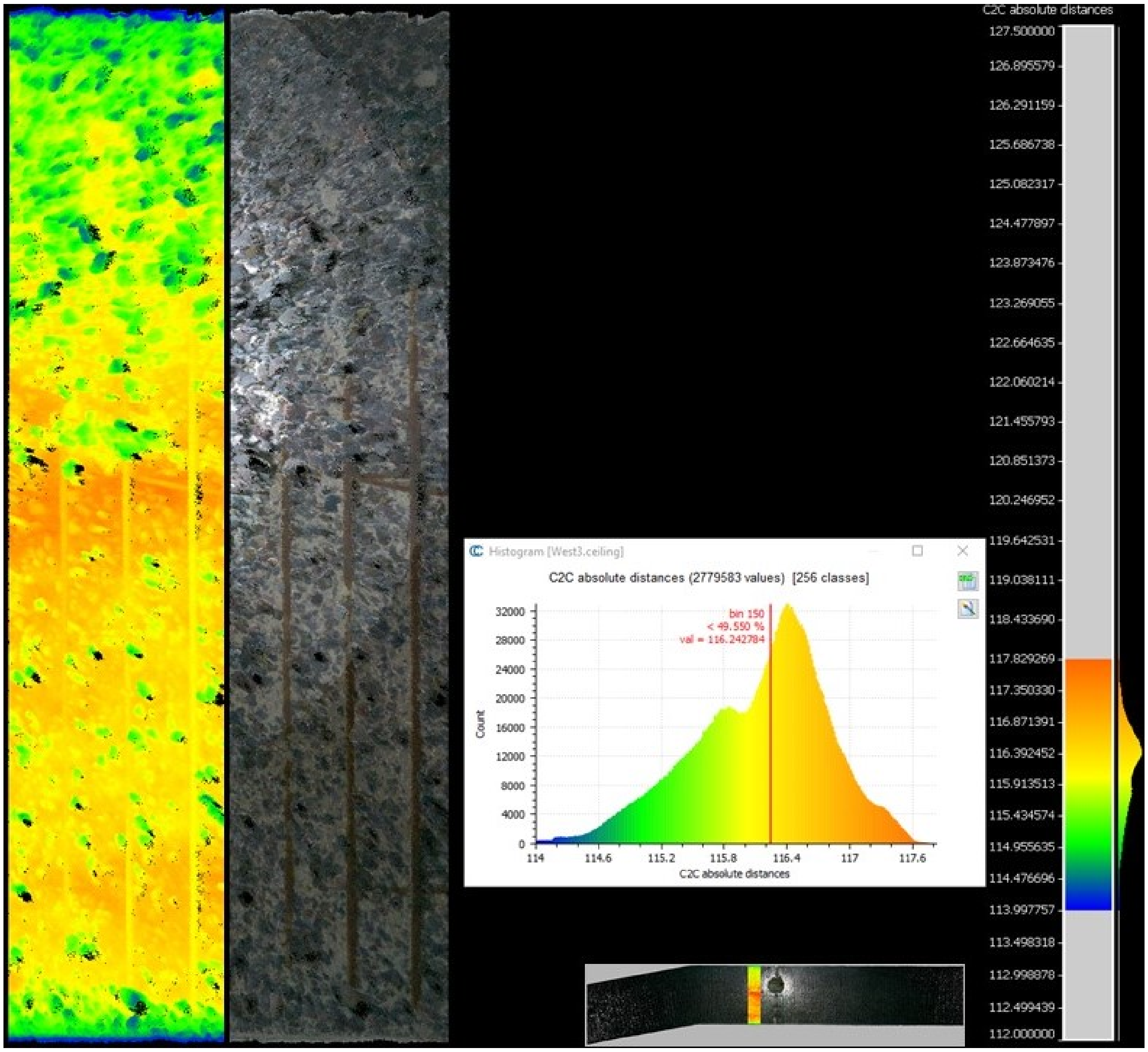


South

Figure E-8 Ceiling Contour Map of Segment W2 (2.03M points)

Segment W2 is located 1.50’ to 2.51’ West of the LiDAR scanner. The segment extends 1.89’ North and 7.50’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 111.71”. The mean and 95% erosion values are 2.47” and 3.30”. This segment has point density of 1515.00 points per square inch.

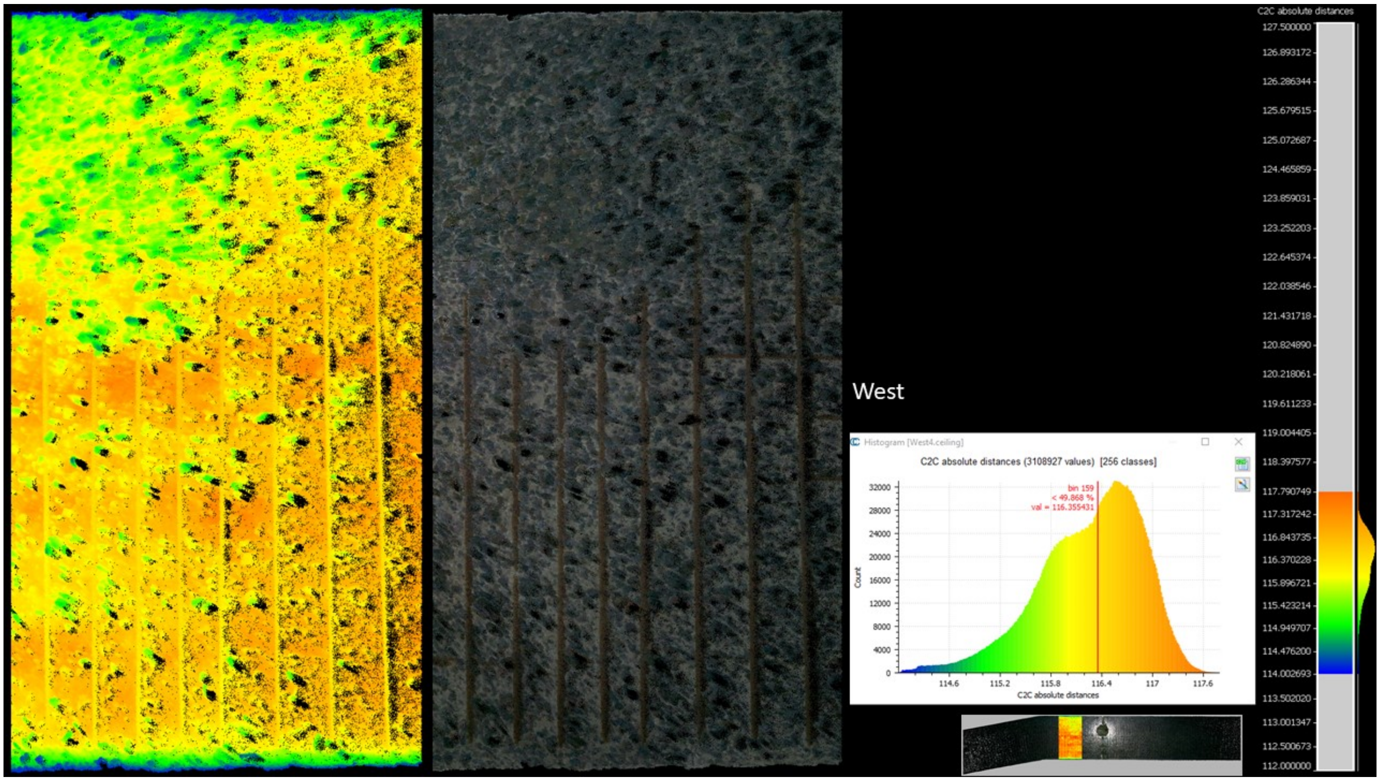
East



South

Figure E-9 Ceiling Contour Map of Segment W3 (2.78M points)

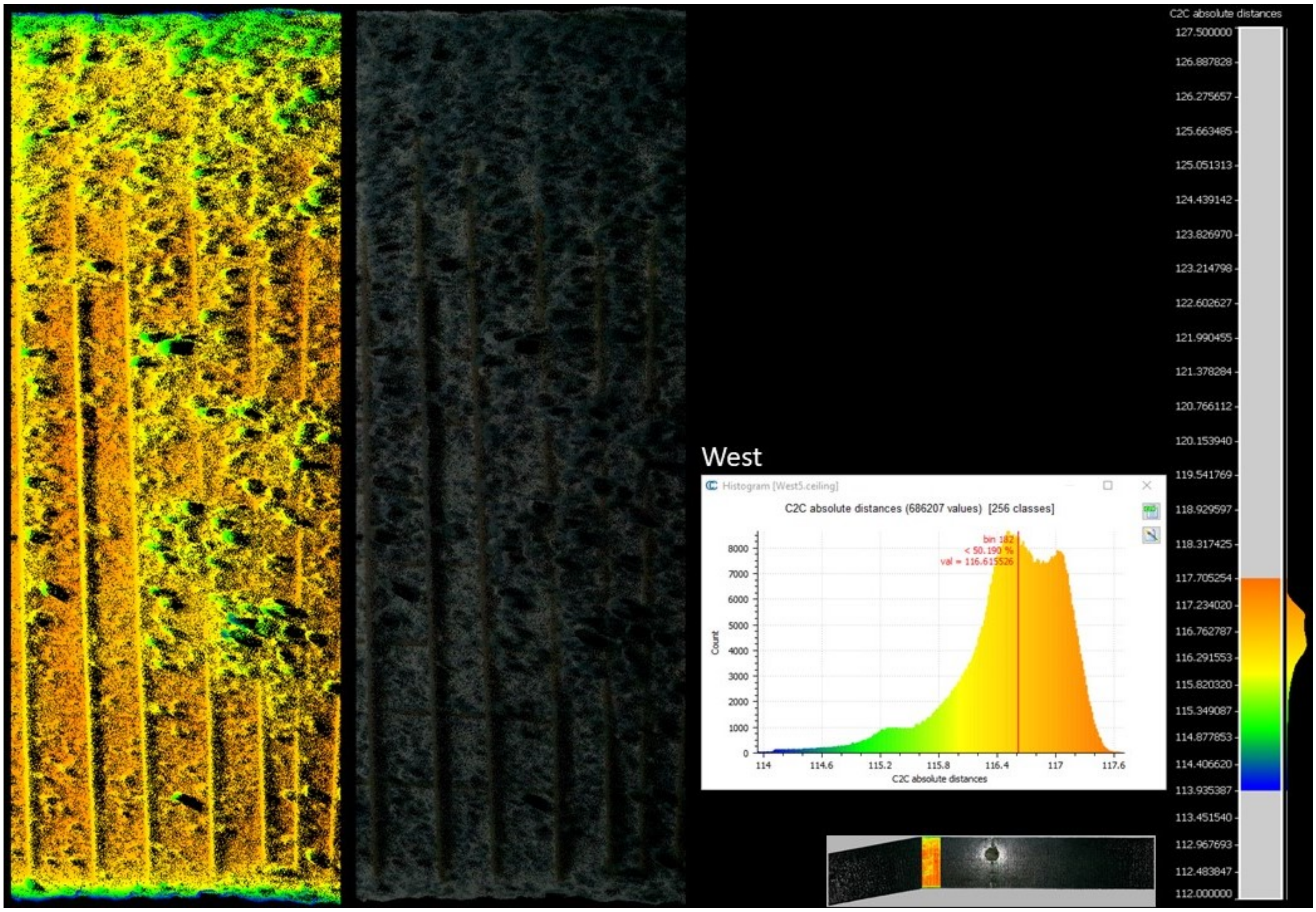
Segment W3 is located 2.50’ to 4.48’ West of the LiDAR scanner. The segment extends 1.91’ North and 7.52’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 111.92”. The mean and 95% erosion values are 2.25” and 3.10”. This segment has point density of 1050.33 points per square inch.



South

Figure E-10 Ceiling Contour Map of Segment W4 (3.11M points)

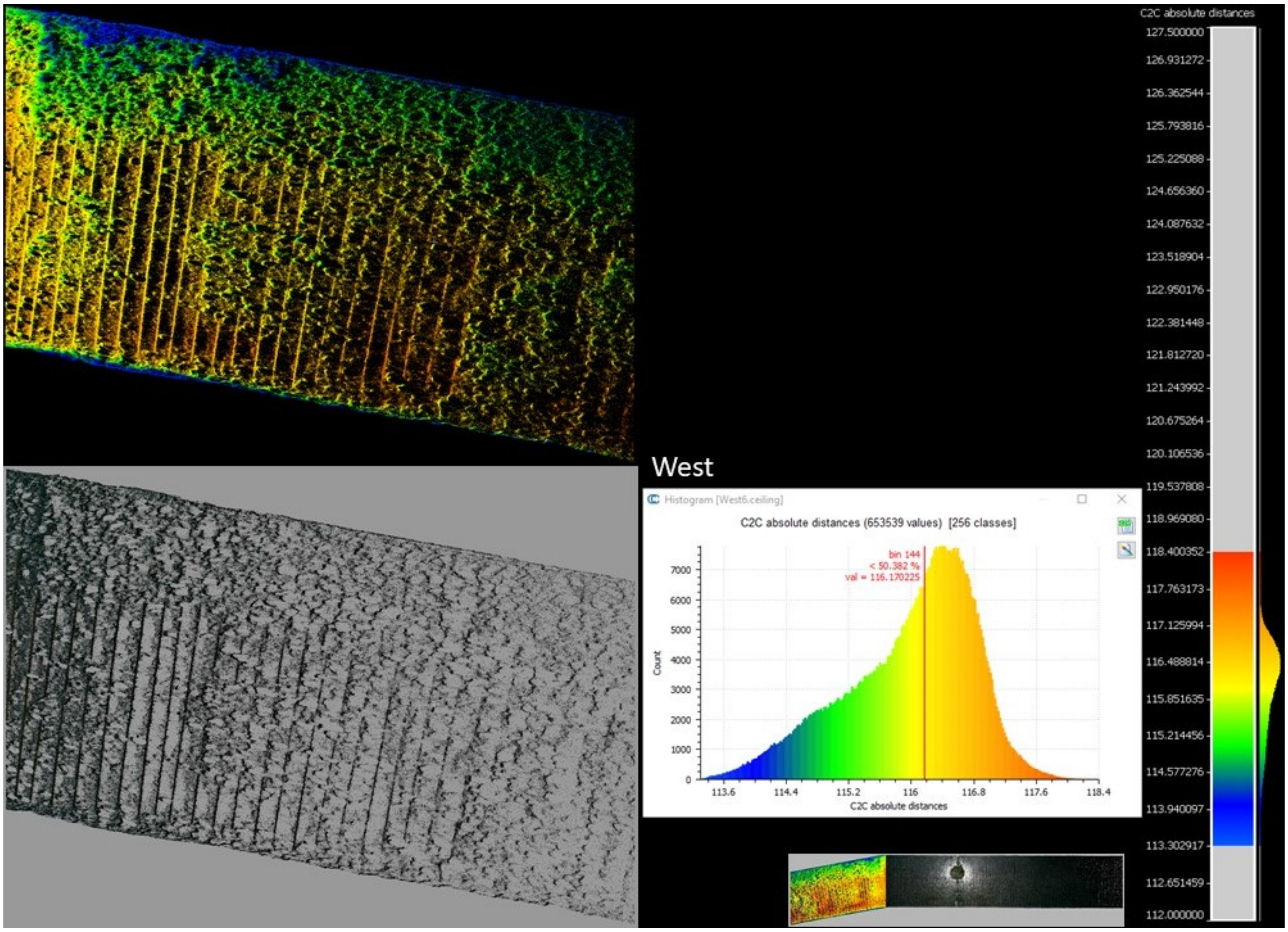
Segment W4 is located 4.46’ to 9.51’ West of the LiDAR scanner. The segment extends 1.94’ North and 7.51’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 112.154”. The mean and 95% erosion values are 2.36” and 3.11”. This segment has point density of 458.68 points per square inch.



South

Figure E-11 Ceiling Contour Map of Segment W5 (0.69M points)

Segment W5 is located 9.49’ to 12.93’ West of the LiDAR scanner. The segment extends 1.96’ North and 7.50’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 112.41”. The mean and 95% erosion values are 2.61” and 3.24”. This segment has point density of 148.45 points per square inch.



South

Figure E-12 Ceiling Contour Map of Segment W6 (0.65M points)

Segment W6 is located 12.91’ to 30.14’ West of the LiDAR scanner. The segment extends 1.94’ North and 10.61’ South of the Southern edge of the Northern most pitot tube. The segment has a width of 111.59”. The mean and 95% erosion values are 2.17” and 3.07”. This segment has point density of 27.81 points per square inch.

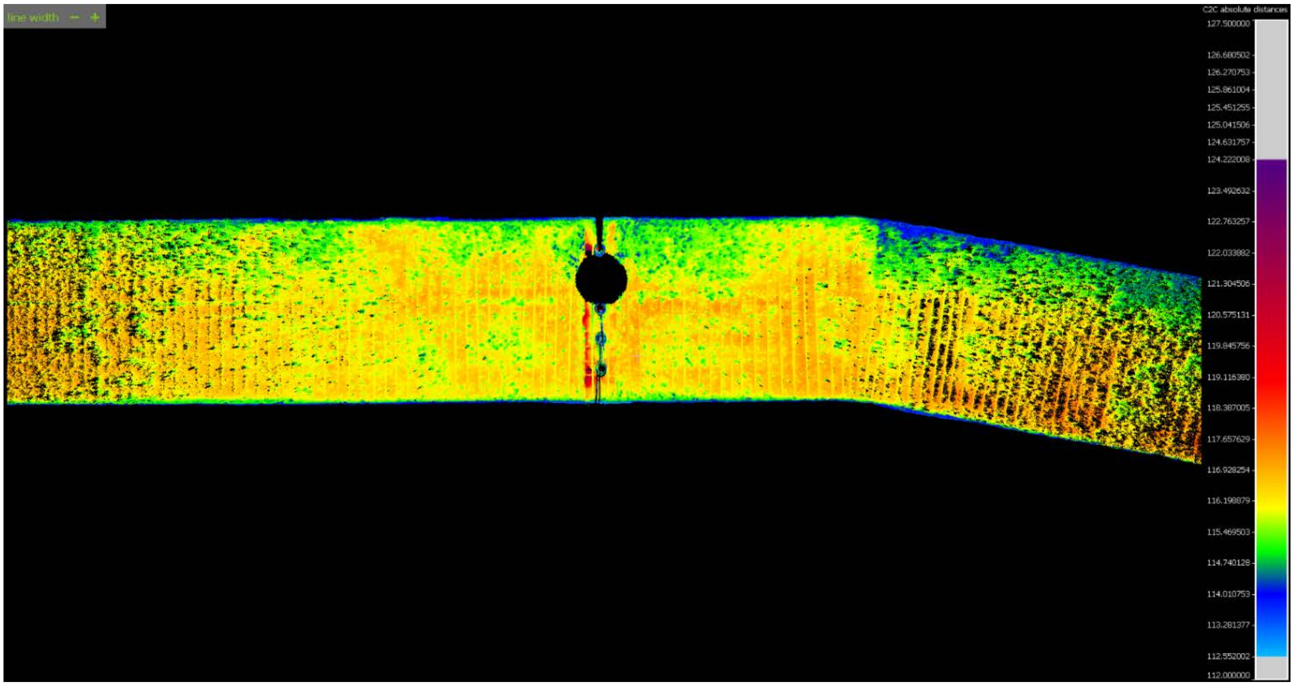
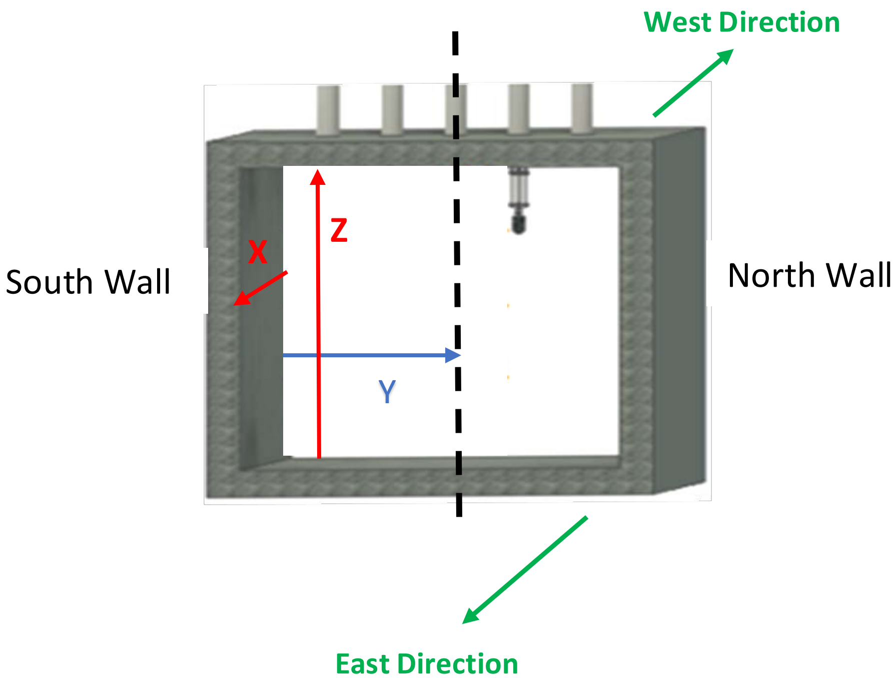


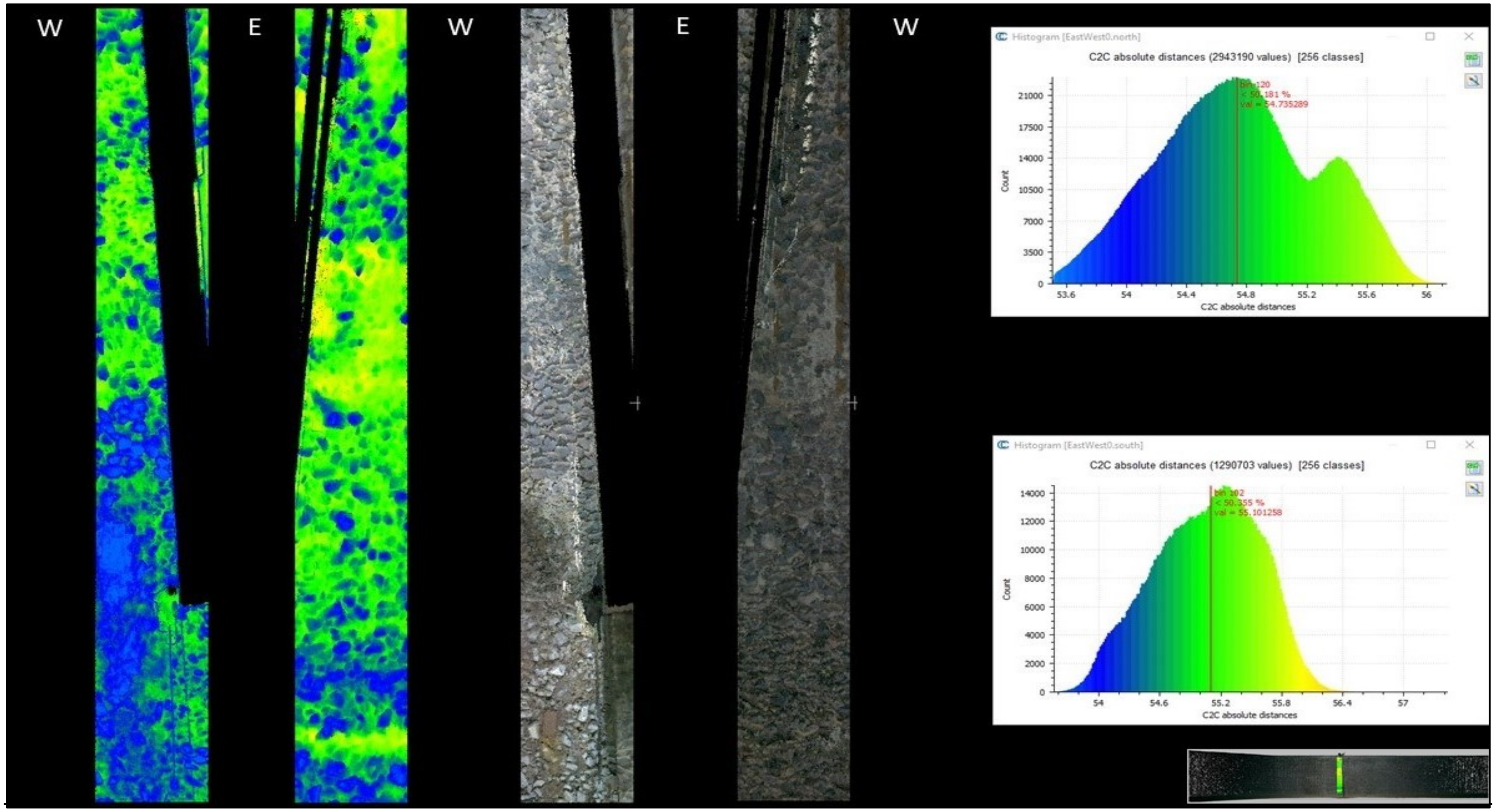
Figure E-13 Ceiling Contour Map with Distance Distribution within ± 10 Meter from BLK360 scanner

The above contour map displays 12 segments combined. This contour map shows an overall view along the tunnel where the data point cloud covered. Gaps in the maps are due to blind spots produced by the environment and LiDAR capabilities.

Attachment F Artificial Wall Plane to North and South Wall Comparison Method

Appendix F provides the contour maps, histograms curves and images for each of the 12 Segments. Contour maps, histogram curves and images are provided side by side for each group of data points.
A figure depicting the coordinates with the “X” and ‘Z” coordinates is noted below.

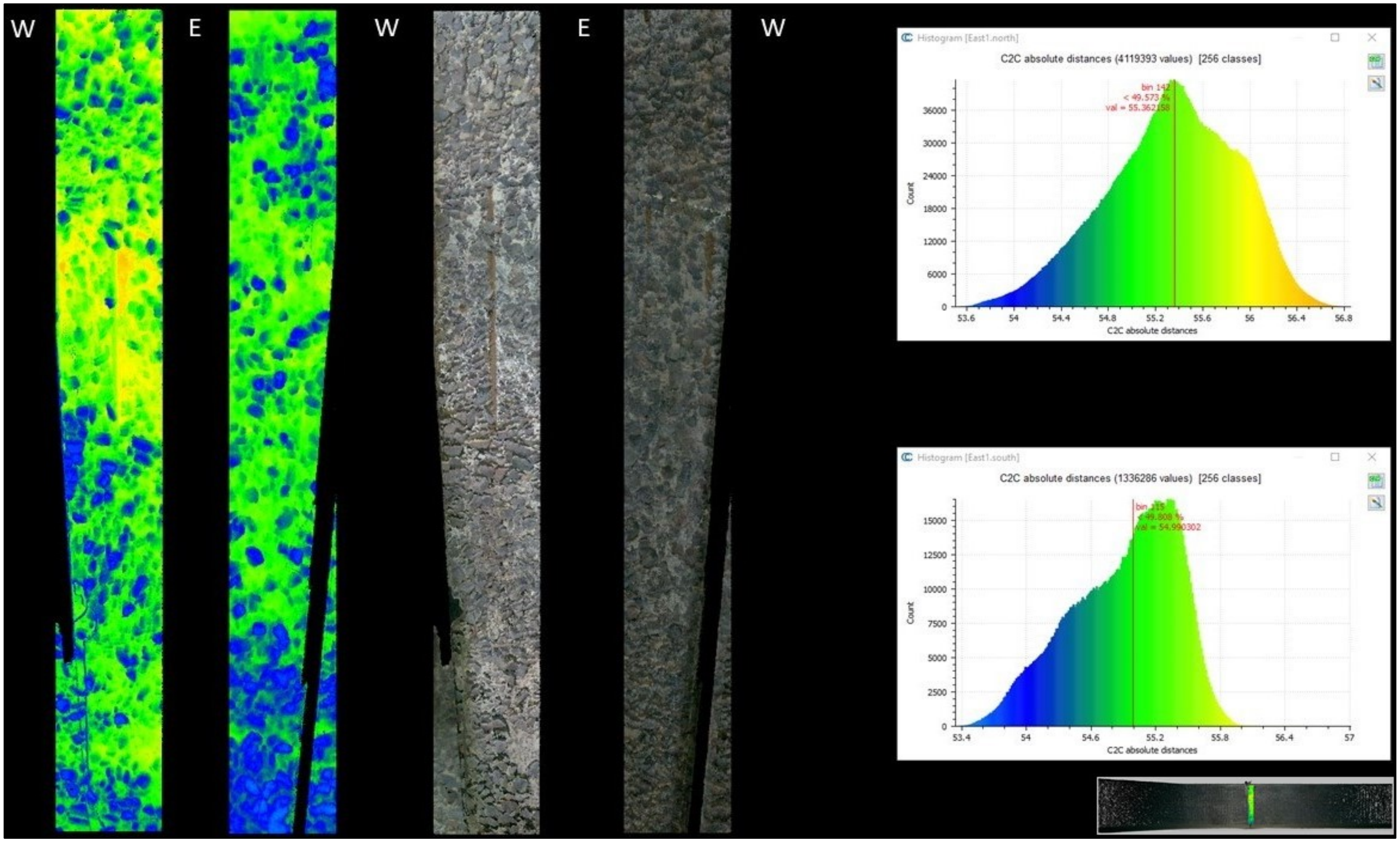




North South North South

Figure F-1 Contour Map of Segment EW0 (4.23M points)

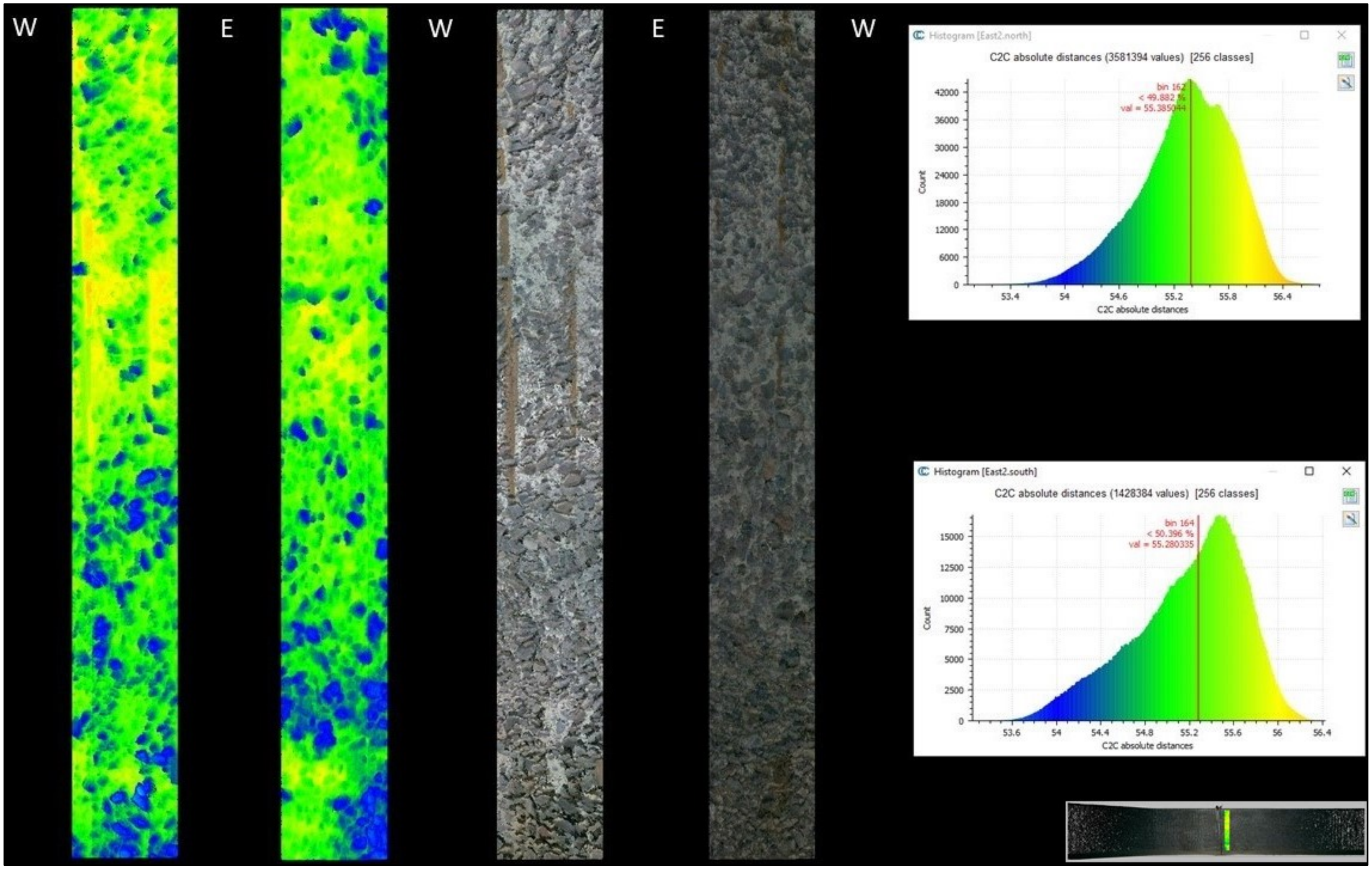
Segment EW0 is located parallel with the pitot tube deployment location, extending 0.48’ West and 0.53’ East. The segment has a length of 12.21”. The segment extends from 0.21’ to 8.27’ below the pitot tube pipe. The segment has a height of 96.65”. The missing areas in the contour map are blind spots due to a pipe holding a section of concrete (Coupon) on the North wall and abandoned in place instrument piping from other sensor deployments on the South wall hanging down in the tunnel. The red value bars are placed at the bin closest to 50% in the contour maps. The mean and 95% erosion values are North 0.73”, 1.61” and South 1.09”, 1.83”. Particulate and hanging objects are responsible for calculated distances less than 54”. This segment has [North, South] point density of [3393.55, 1367.73] points per square inch.



North South North South

Figure F-2 Distribution of Segment E1 (5.46M points)

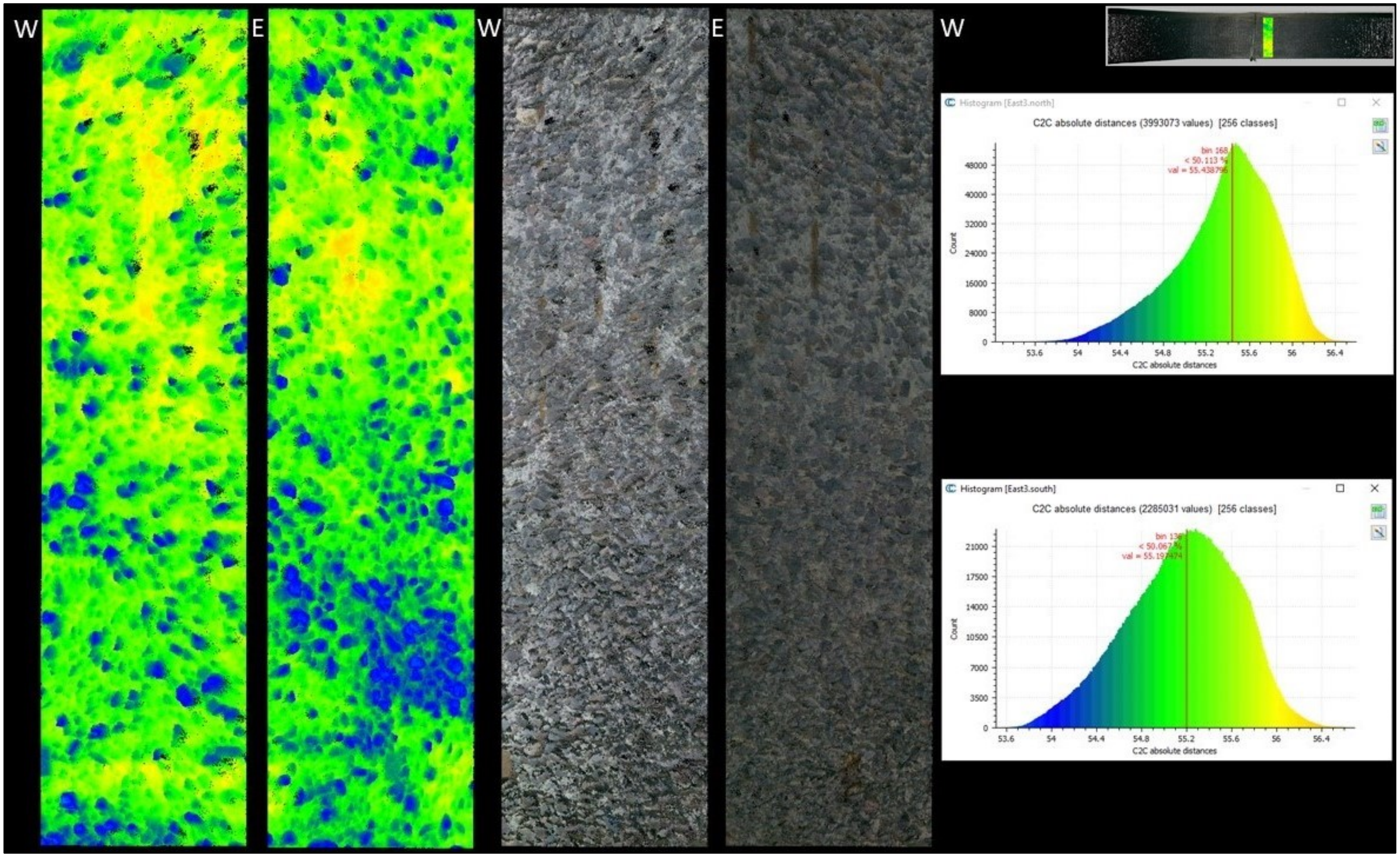
Segment E1 is located 0.52’ to 1.54’ on the East of the LiDAR scanner. The segment extends from 0.15’ to 8.30’ below the pitot tube pipe. The segment has a height of 97.80”. The missing areas in the contour map are blind spots due to a pipe holding a section of concrete (Coupon) on the North wall and abandoned in place instrument piping from other sensor deployments on the South wall hanging down in the tunnel. The mean and 95% erosion values are North 1.37”, 2.16” and South 1.00”, 1.58”. This segment has [North, South] point density of [3545.91, 1231.57] points per square inch.



North South North South

Figure F-3 Distribution of Segment E2 (5.01M points)

Segment E2 is located 1.54’ to 2.55’ on the East of the LiDAR scanner. The segment extends from 0.15’ to 8.30’ below the pitot tube pipe. The segment has a height of 97.83”. The mean and 95% erosion values are North 1.39”, 2.09” and South 1.27”, 1.86”. This segment has [North, South] point density of [3014.22, 1200.07] points per square inch.



North South North South

Figure F-4 Distribution of Segment E3 (6.28 M points)

Segment E3 is located 2.55’ to 4.56’ on the East of the LiDAR scanner. The segment extends 0.08’ to 8.28’ below the pitot tube pipe. The segment has a height of 98.64”. The mean and 95% erosion values are North 1.44”, 2.01” and South 1.20”, 1.89”. This segment has [North, South] point density of [1680.72, 961.84] points per square inch.

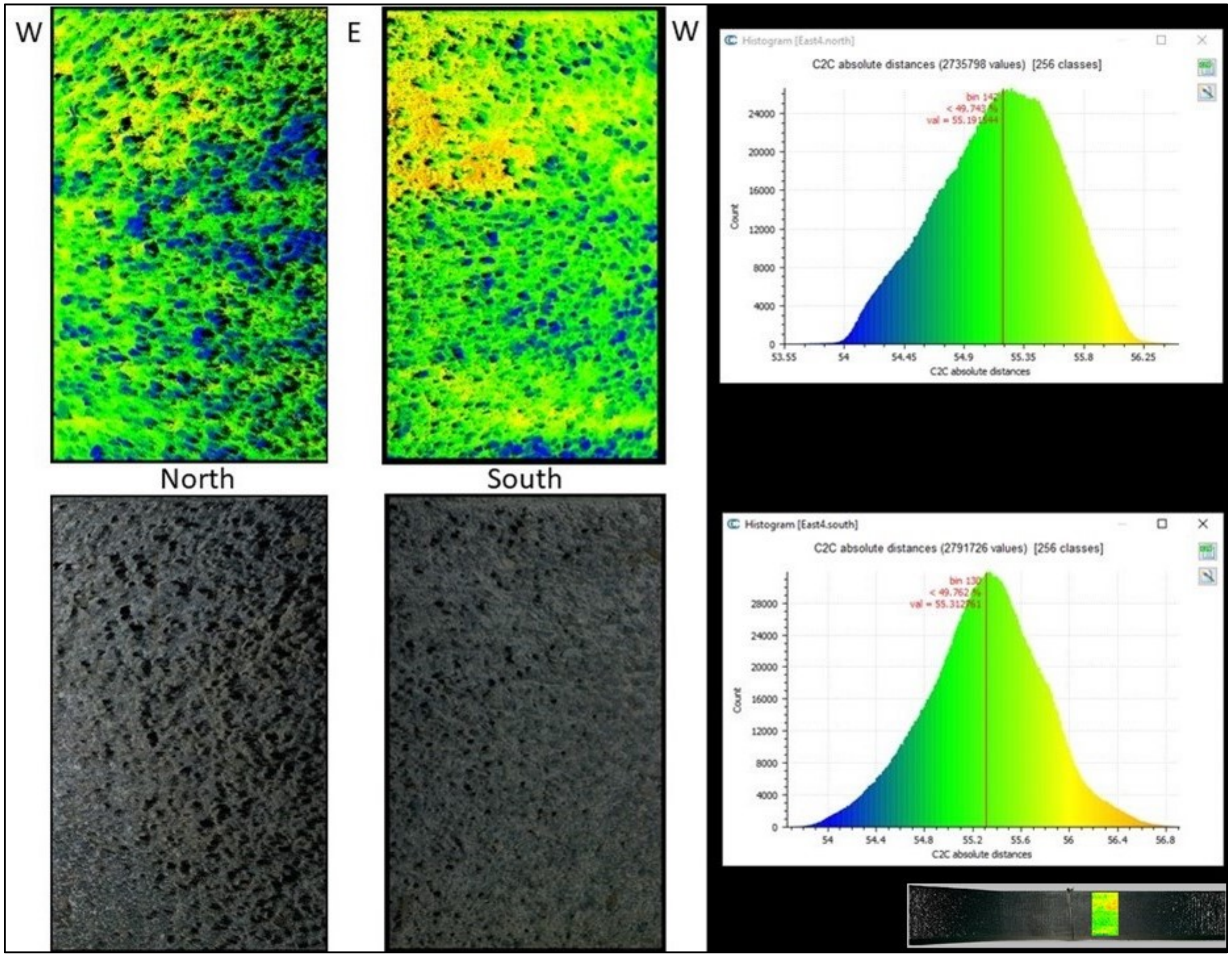


Figure F-5 Distribution of Segment E4 (5.53 M points)

Segment E4 is located 4.56’ to 9.50’ on the East of the LiDAR scanner. The segment extends from 0.09’ to 8.27’ below the pitot tube pipe. The segment has a height of 98.31”. The mean and 95% erosion values are North 1.20”, 1.87” and South 1.32”, 2.06”. This segment has [North, South] point density of [470.29, 478.81] points per square inch.

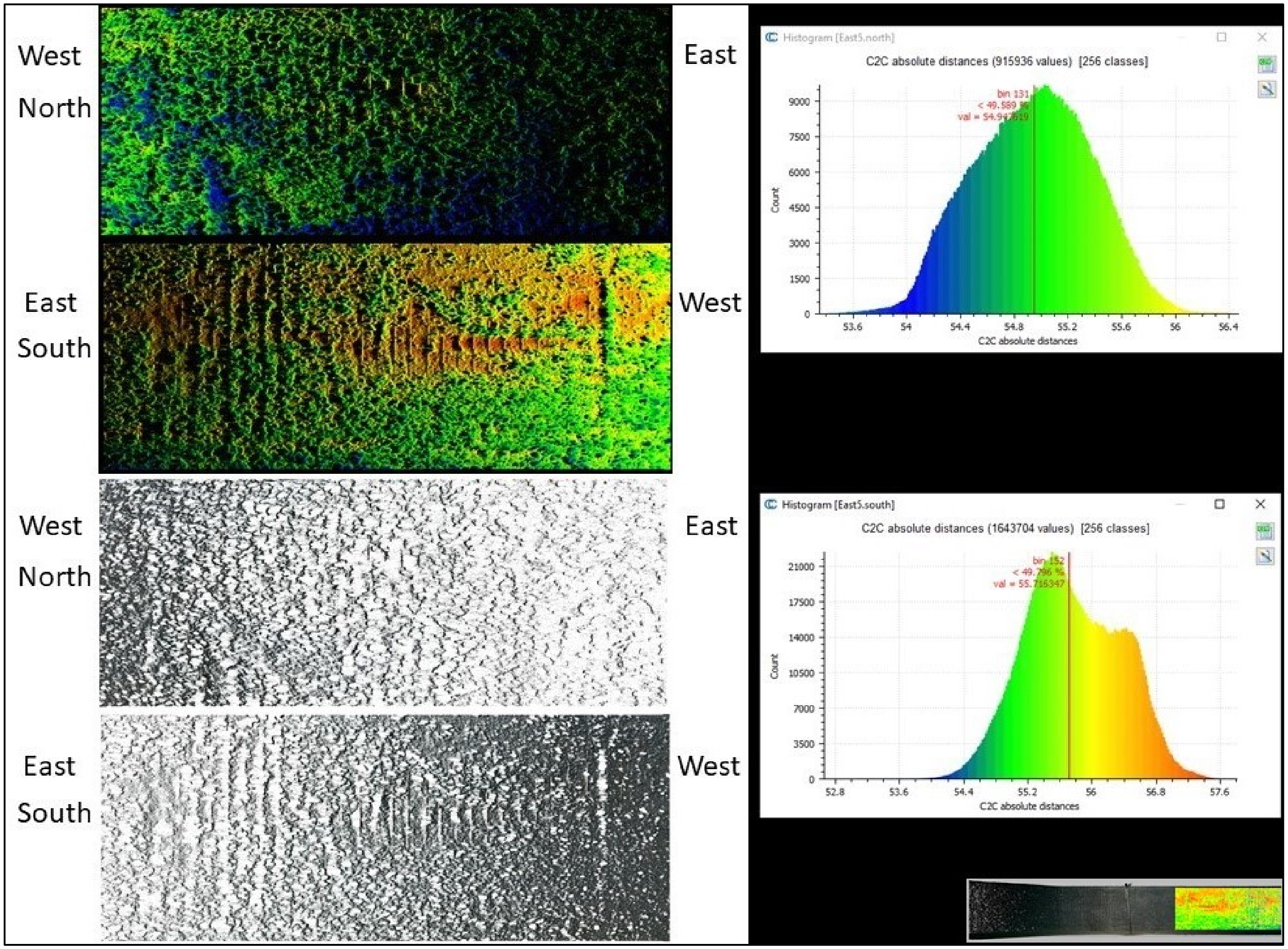
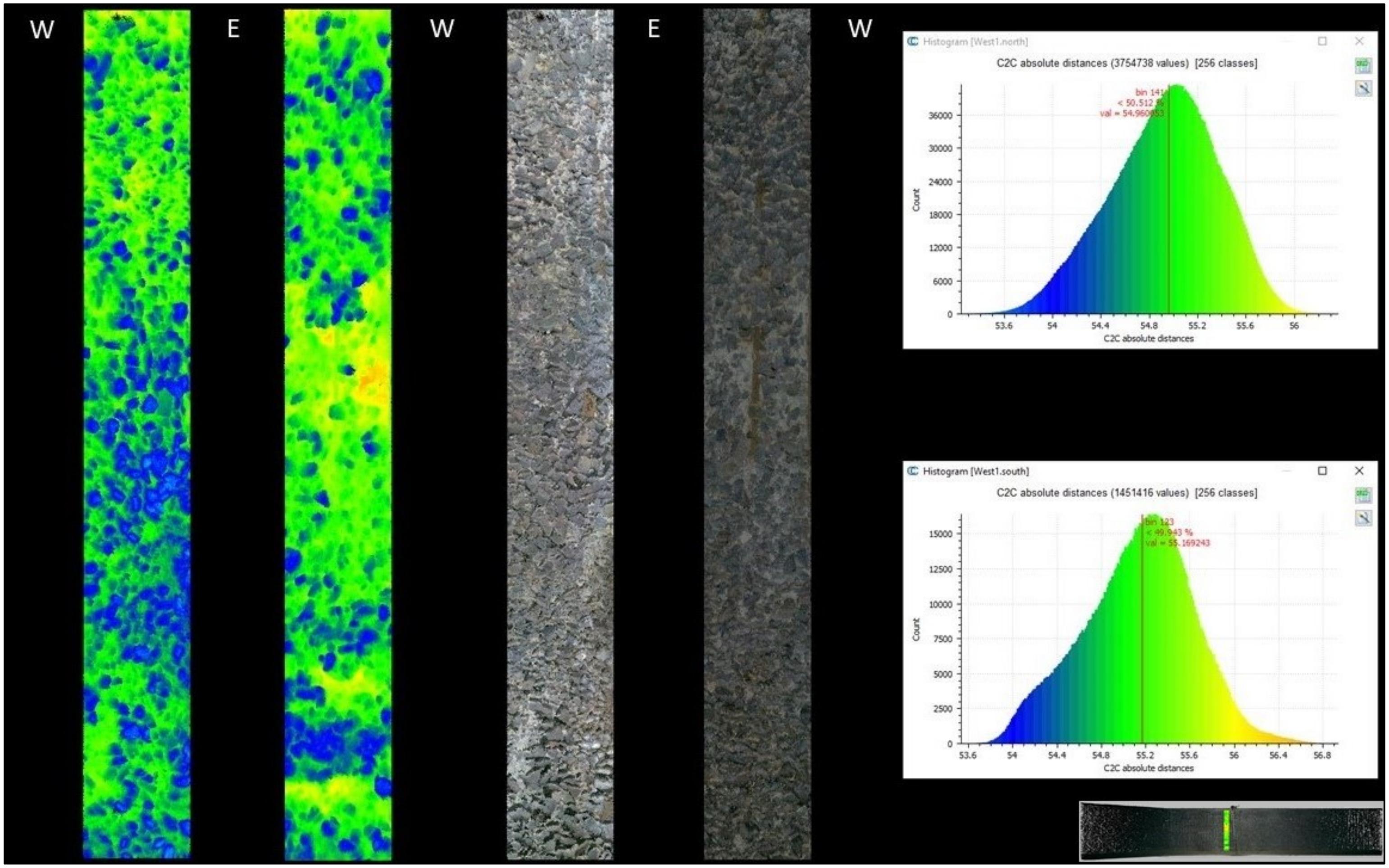


Figure F-6 Distribution of Segment E5 (2.56 M points)

Segment E5 is located 9.50’ to 29.85’ on the East of the LiDAR scanner. The segment extends from 0.09’ to 8.23’ below the pitot tube pipe. The segment has a height of 97.63”. The mean and 95% erosion values are North 0.95”, 1.63” and South 1.72”, 2.73”. This segment has [North, South] point density of [38.44, 68.96] points per square inch.



North South North South

Figure F-7 Contour Map of Segment W1 (5.21M points)

Segment W1 is located 0.48’ to 1.51’ West of the LiDAR scanner. The segment extends from 0.20’ to 8.30’ below the pitot tube pipe. The segment has a height of 97.29”. Rebar on the right side (South wall) shows lesser distance than the surrounding concrete. This indicates the surrounding concrete surface is lower than the exposed rebar. The mean and 95% erosion values are North 0.95”, 1.61” and South 1.17”, 1.90”. This segment has [North, South] point density of [3167.15, 1224.01] points per square inch.

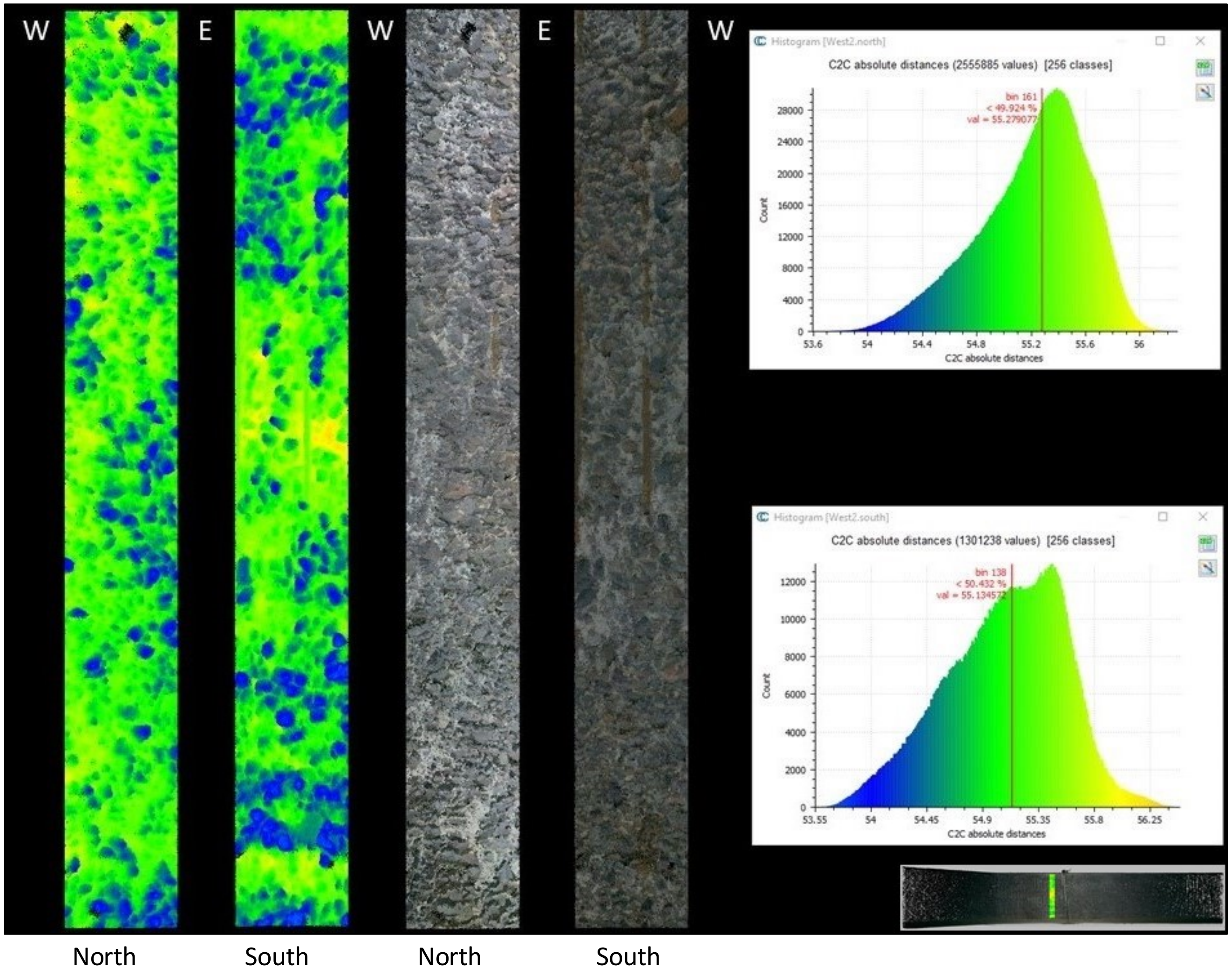
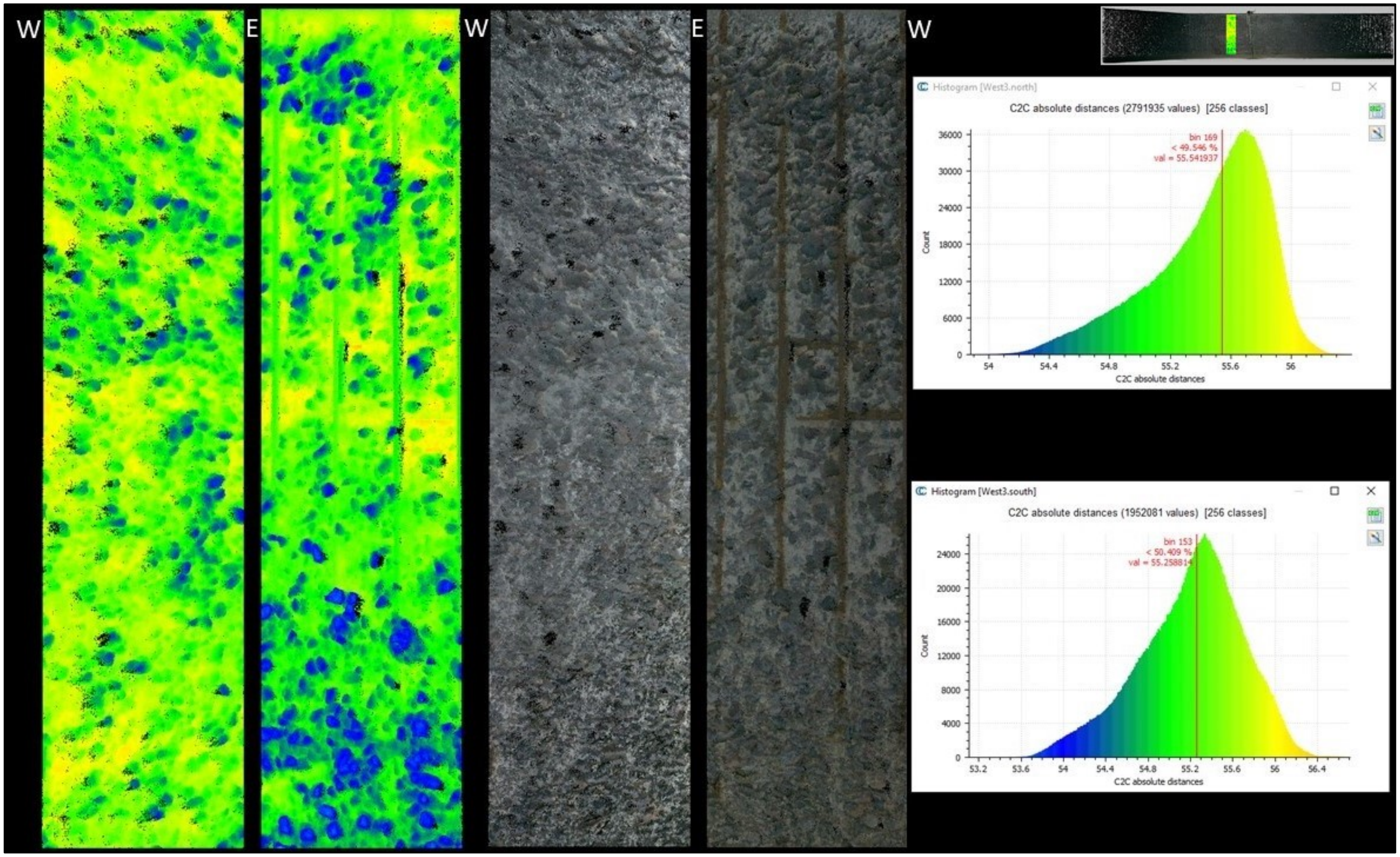


Figure F-8 Contour Map of Segment W2 (3.86M points)

Segment W2 is located 1.50’ to 2.51’ West of the LiDAR scanner. The segment extends from 0.11’ to 8.31’ below the pitot tube pipe. The segment has a height of 98.34”. The mean and 95% erosion values are North 1.28”, 1.77” and South 1.13”, 1.77”. This segment has [North, South] point density of [2153.29, 1096.40] points per square inch.



North South North South

Figure F-9 Contour Map of Segment W3 (4.74M points)

Segment W3 is located 2.50’ to 4.48’ West of the LiDAR scanner. The segment extends from 0.08’ to 8.32’ below the pitot tube pipe. The segment has a height of 98.85”. The mean and 95% erosion values are North 1.55”, 1.94” and South 1.25”, 1.94”. This segment has [North, South] point density of [1190.01, 831.95] points per square inch. The rebar on the_south wall shows green color, which indicate the yellow area in between green rebar loss concrete below the rebar surface. The contour map provides an overall description of the concrete loss on the wall.

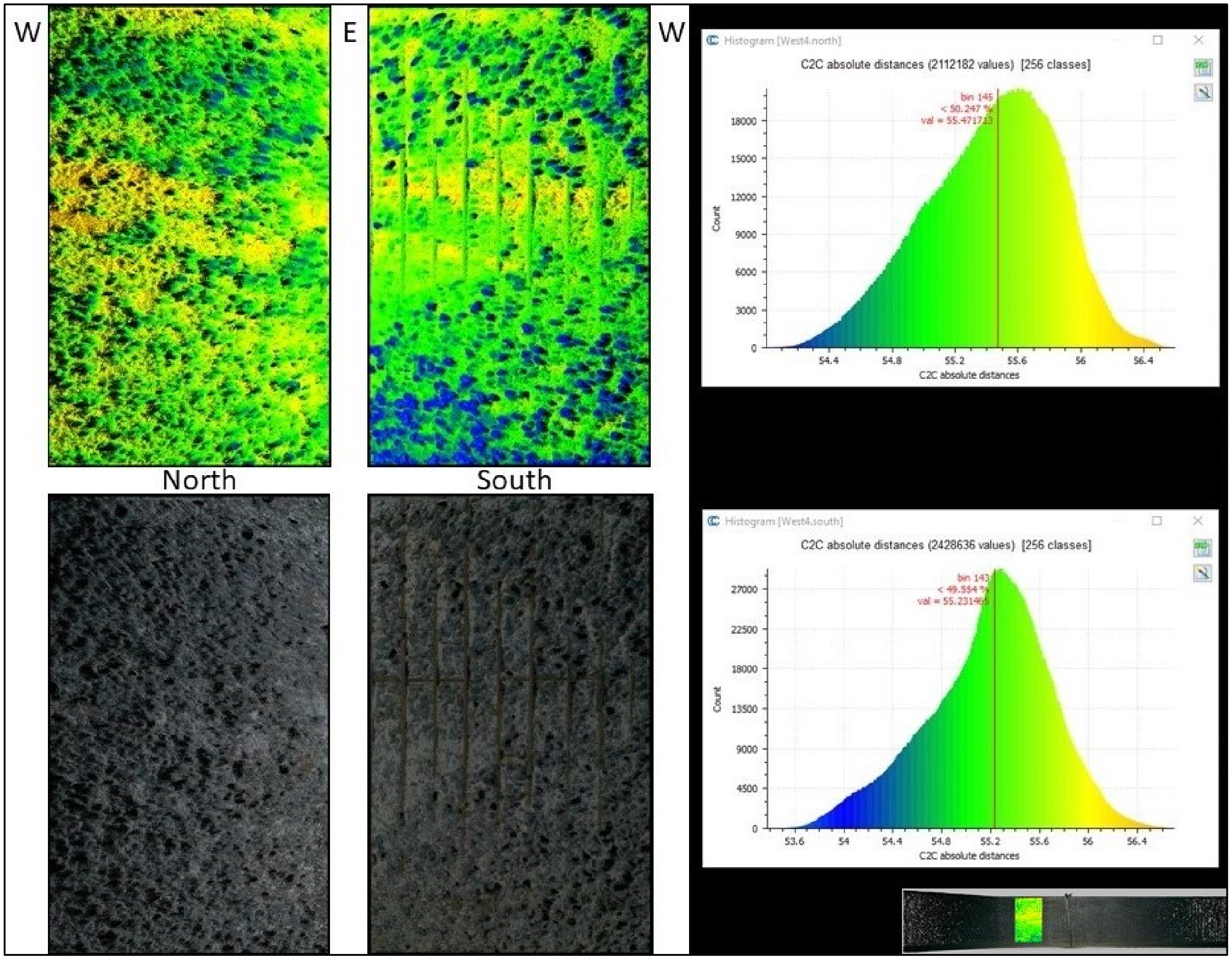


Figure F-10 Contour Map of Segment W4 (4.54M points)

Segment W4 is located 4.46’ to 9.51’ West of the LiDAR scanner. The segment extends from 0.08’ to 8.32’ below the pitot tube pipe. The segment has a height of 98.90”. The mean and 95% erosion values are North 1.46”, 2.03” and South 1.24”, 1.93”. This segment has [North, South] point density of [352.88, 405.73] points per square inch.

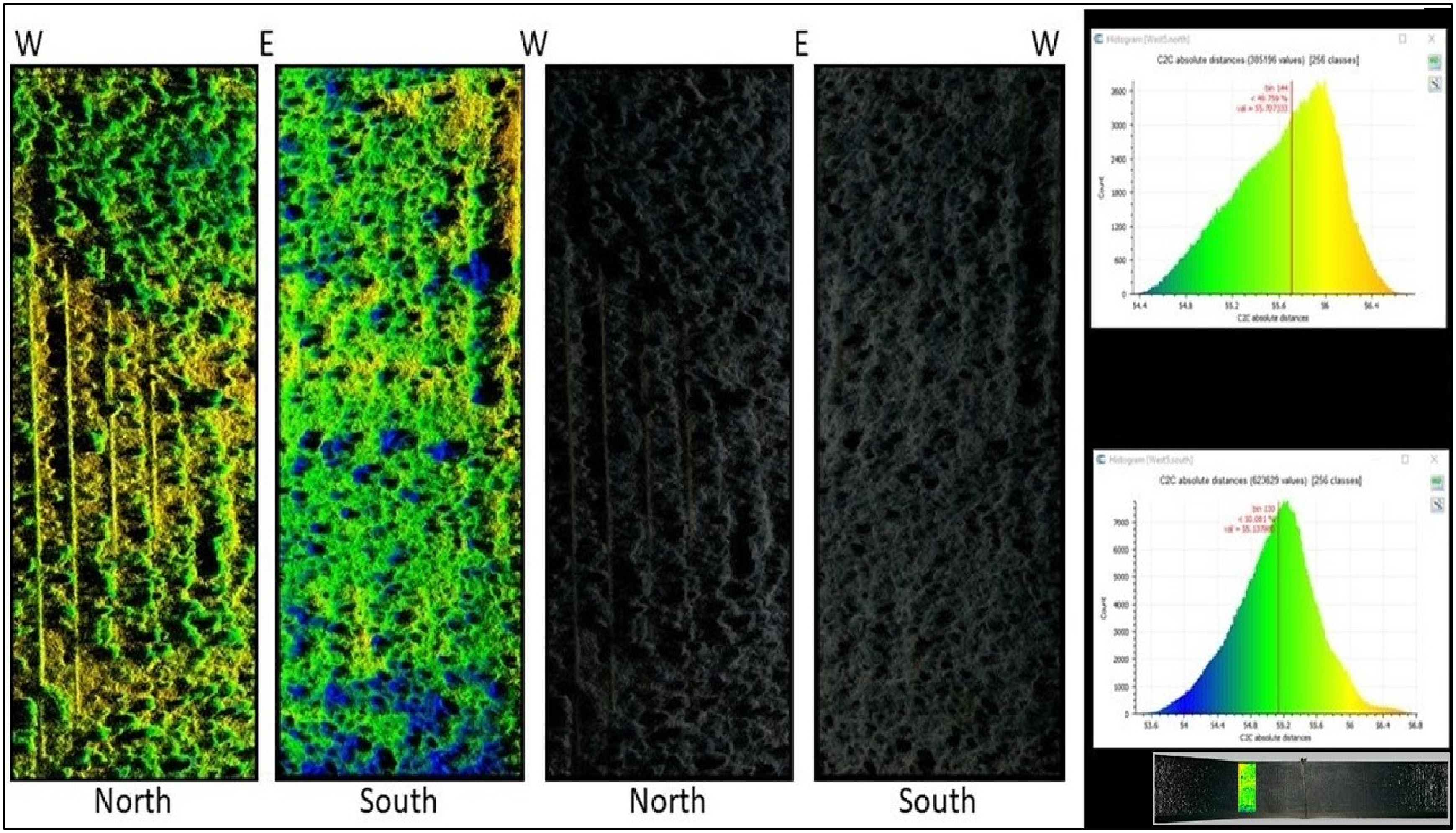


Figure F-11 Contour Map of Segment W5 (1.01M points)

Segment W5 is located 9.49’ to 12.93’ West of the LiDAR scanner. The segment extends from 0.09’ to 8.28’ below the pitot tube pipe. The segment has a height of 98.26”. The mean and 95% erosion values are North 1.71”, 2.26” and South 1.14”, 1.90”. This segment has [North, South] point density of [95.20, 154.00] points per square inch.

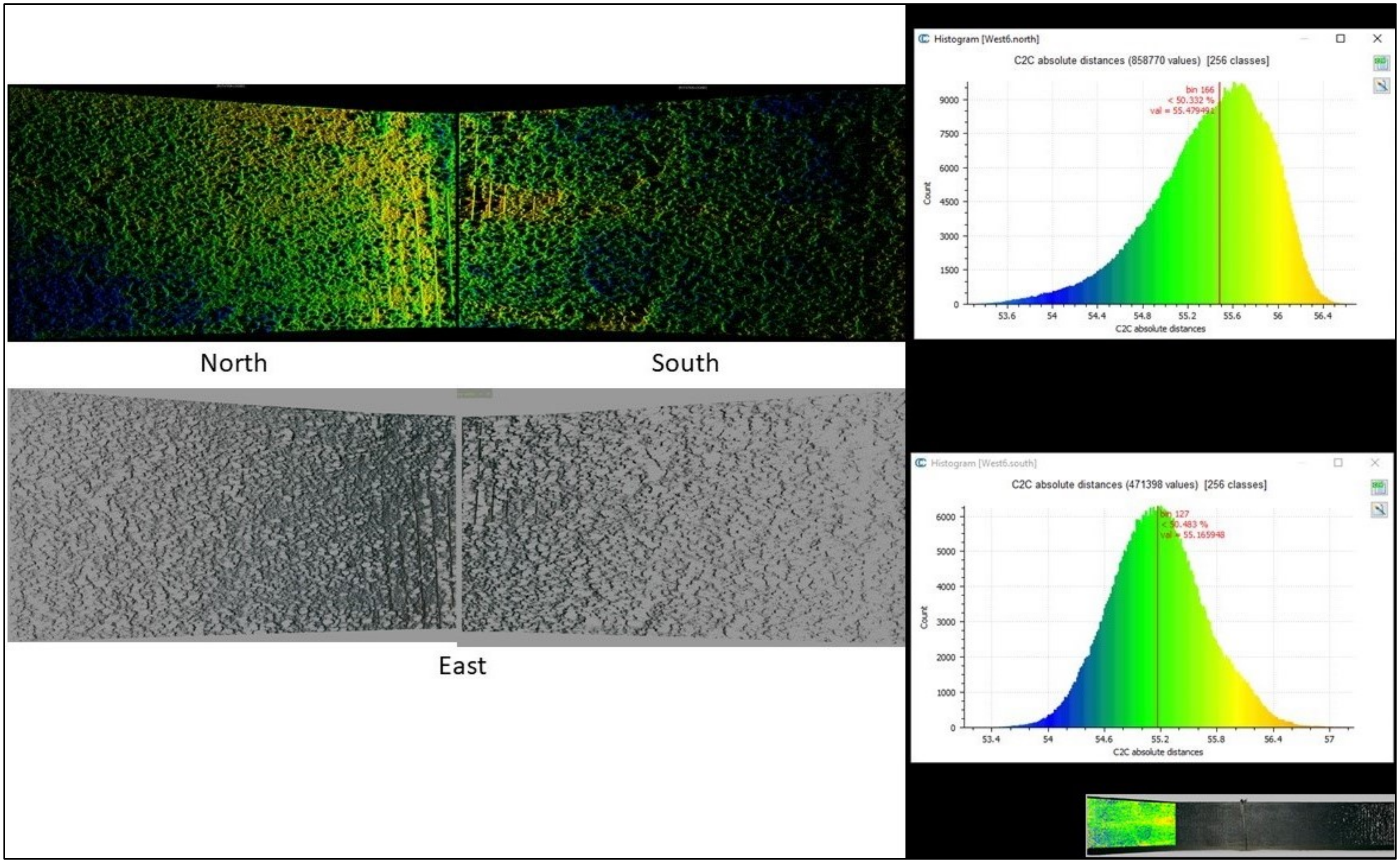


Figure F-12 Contour Map of Segment W6 (1.33M points)

Segment W6 is located 12.91’ to 30.14’ West of the LiDAR scanner. The segment extends from 1.00’ above to 8.74’ below the pitot tube pipe. The segment has a height of 98.64”. The left most 0.14’ of W6 is outside calibration range based on manufacturer specification. The mean and 95% erosion values are North 1.48”, 2.17” and South 1.16”, 2.04”. This segment has [North, South] point density of [37.98, 20.83] points per square inch.

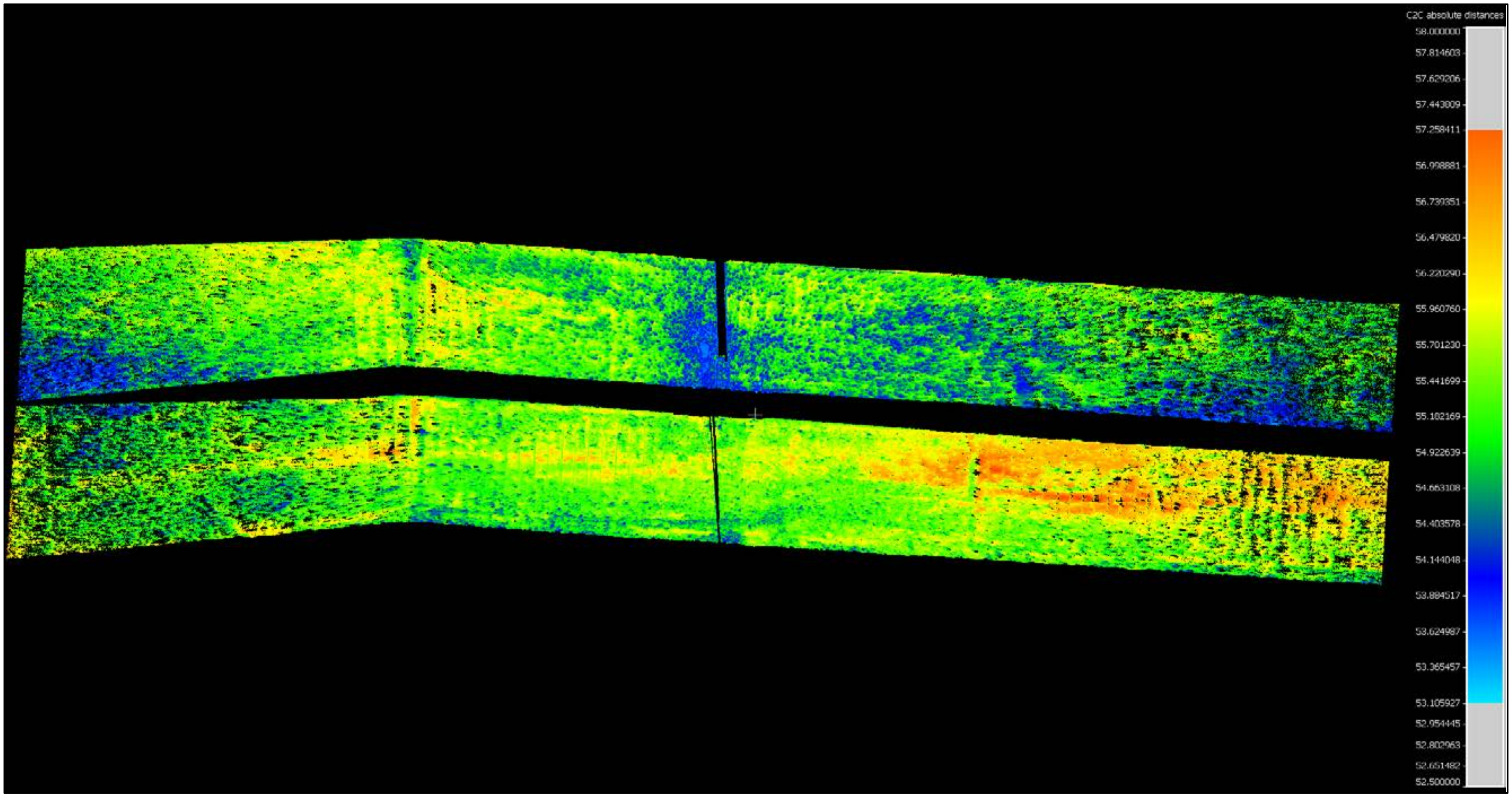


Figure F-13 Contour Map with Distance Distribution within ± 10 Meter from BLK360 scanner

The above contour map displays the 12 segments combined. This contour map shows an overall view along the tunnel where the data point cloud covered. Gaps in the maps are due to blind spots produced by the environment and LiDAR capabilities. Cloud to cloud (C2C) absolute distances are shown on the right with the same scalar field color scale as the contour maps. The C2C absolute distance bar is a visual aid to view the same data as the contour map. More distance values are displayed on the bar than the contour map including minimum and maximum calculated distance