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INTEGRATED REMOTE SENSING AND VISUALIZATION (IRSV) SYSTEM FOR TRANSPORTATION INFRASTRUCTURE OPERATIONS AND MANAGEMENT:

-PHASE TWO-

VOLUME 2

APPLICATIONS OF LiDAR TECHNOLOGY IN STRUCTURAL EVALUATION UNDER NORMAL TRAFFIC OPERATION AND POST BLAST LOADING

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This is the second of five volumes that provide a comprehensive description of the IRSV Phase Two project.

16. Abstract

This report focused on two potential applications of terrestrial LiDAR scans on highway bridges: 1) vehicle crossing effects measured by3-D, terrestrial LiDAR scans of highway bridges measuring clearance distance; and 2) bridge post-blast geometric assessments of ground-based or vehicle-mounted terrestrial LiDAR scans. Data collected create a 3-D point cloud, which was determined to be ideal for measuring before-and-after conditions on bridges and large culverts.

To determine the effects of ambient and seasonal temperature variation on clearance measurements, periodic monitoring was conducted using data from a four-lane bridge on Harris Boulevard near the UNC Charlotte campus. A simplistic but practical correlation analysis was performed, again illustrating that operational LiDAR scanning is a viable technique for bridge clearance measurements.

Terrestrial 3-D LiDAR scanners generate dense point cloud information that can be used to establish baseline geometric information for structures and to establish critical dimensional footprints for before and after-event comparisons. For close range blast effects, the pre-blast and post-blast scans of a bridge were made in order to establish the potential and measure the impact of construction blasting-induced effects, and in general, measure damages to bridges or large culverts. The Colony Road bridge in southeast Charlotte was monitored before and after a nearby construction blasting. Full-scale, three dimensional scans of the bridge conducted before and after blasting. Critical sections and geometries were compared to ensure that the bridges were safe for traffic.

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EXECUTIVE SUMMARY

This project reports studies on two potential applications of terrestrial LiDAR scans on highway bridges: 1) study of the outcomes of a study of the vehicle crossing effects on terrestrial LiDAR scan on highway bridges for under clearance measurements; 2) study of the bridge post-blast geometric assessments. Ground-based or vehicle-mount terrestrial LiDAR scanners, which recreate the bridge structure as 3D point cloud of thousands of position data points, have been found to be ideal for bridge clearance measurements. To determine the effects of ambient overhead vehicle crossing and seasonal temperature variation on clearance measurements, periodic monitoring of the Harris Road Bridge has been conducted. A simplistic but practical correlation analysis is performed which shows that operational LiDAR scanning is a viable technique for bridge clearance measurements.

Terrestrial 3D LiDAR scanners can generate dense point clouds of position information that can be used to establish baseline geometric information for structures and to establish critical dimensional footprints for before and after-event comparisons. For close range blast effects, the pre-blast and post-blast scans of a bridge are proposed to establish blasting induced effects and damage information. The Colony Road bridge was monitored for a nearby construction blasting. Full-scale three dimensional scans of the bridge have been conducted before and after blasting, critical sections and geometries are then compared to ensure the safety of the bridge.

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1.1 INTRODUCTION

Scanning LiDAR (Light Detection And Ranging) is a laser technology used to collect vast amounts of geometric data. In a typical five to ten minute scan, the scanning LiDAR unit can collect millions of data points that include the XYZ position of each scan point. As a result, structures can be represented as a large point cloud of physical position data.

LiDAR technology is similar to traditional radar technology. A LiDAR unit is made of a light transmitter, a light sensor, and a processing unit. The LiDAR unit emits light, the light returns to the light sensor after reflecting on a surface, and the signal is then compared to a reference beam for range distance computation.(Liu 2010)

Fuchs et al. (Fuchs, Washer et al. 2004; Fuchs, Washer et al. 2004) described several applications of high resolution, LiDAR measurements on bridges, notably for displacement measurements during bridge static load tests. With the introduction of advanced land-based LiDAR scanning systems, new opportunities in structural evaluations are presented. Several applications have already been identified including: static deflection measurements of loaded structures (Pieraccini, Parrini et al. 2007; Liu 2010), bridge clearance measurements (Lefevre, Shipley et al. 2000), structural damage detection (Kayen, Pack et al. 2006; Bian, Bai et al. 2011), and for new construction monitoring (Chen 2010), etc.

The result of a LiDAR scan is a large dataset of millions of position measurements, called "point clouds". A bridge evaluation program, LiBE (LiDAR based Bridge Evaluation), has been developed to evaluate highway bridges to find damage, road clearance, and deflection. (Liu 2010; Bian, Bai et al. 2011) Bridge damage can be assessed by determining the plane of the structural surface and finding irregular points relative to that surface. The irregular points would represent the damage the structure has sustained. After determining the irregular points, the damage can be characterized by shape and volume using a two-parameter (absolute position difference and local slopes) evaluation technique.(Liu 2010) Road clearance can be calculated by finding the least relative distance between the bridge deck and the road.

Advances in land-based (terrestrial) LiDAR systems have opened potential avenues for new applications including bridge clearance measurements: By scanning the underside of a bridge and comparing the position data of the roadbed to the position data of the bridge superstructure, the under clearance of a bridge can be determined.(Chen, Hauser et al. 2009; Liu 2010) To automate the process, Liu (2010) recommended a match-and-search technique to determine the shortest distance between any two matching positions on the underside of a bridge deck and the roadbed, which is taken as the minimum vertical under clearance.(Liu, Chen et al. 2010) There have also been reports of using vehicle-mounted scanning systems for bridge clearance measurements: when traveling at traffic speed, this technique can significantly reduce the time for bridge inspection.(Kim, North Carolina. Dept. of Transportation et al. 2009)

The clearance measurements under the bridge have only been established by using LiDAR scans. Two major methods are available for determining distance from the transmitted laser energy: The first method is the time-of-flight method where a pulse of light is transmitted to the object surface and the transceiver records the length of time that the laser light travels before and after returning; the second method is called the phase-shift analysis where light of varying wavelengths gradually becoming out of sync and the measurement of the phase deviation is used to determine the distance of travel. The scanning LiDAR system used in current study is a phase-shift system: the scanning system transmits the laser, which reflects off of a vertically spinning mirror while the base of the LiDAR unit spins horizontally.(FARO Technologies 2009)

The LiDAR system used in this study is capable of recording 120,000 data points per second. The infrared light reflects off a distant surface and returns to the LiDAR unit where the phase shift is analyzed. The distance between amplitudes of the three wavelengths that return to the infrared sensor are then used to determine the distance the light traveled. The LiDAR unit will use the new distance data combined with the position of the mirror and LiDAR unit to determine the new position data point.(Sabine 1986)

The key advantage of using LiDAR for structural assessment is that the structure is recreated in fine detail by recording millions of geometrical data points. Large complex structures can be recreated as three dimensional models that can be viewed from any angle and distance. LiDAR technology is capable of analyzing complex shapes and contours.(Teza, Galgaro et al. 2009) LiDAR scanners have been used in cases of excavation of important cultural sites: Guarnieri et al. (2005) scanned and established the digital archive of the complex surface of the walls of Montagnane, a small ancient city, in Italy.(Guarnieri, Pirotti et al. 2005) They further use the point clouds to generate finite element models of the actual structures.

The LiDAR scan also aids in the visual inspection process by keeping a permanent record of the structure during inspection. With a three dimensional LiDAR computer model, organizations can sidestep the visual acuity and reliability issues of inspectors presented in a Federal Highway Administration survey.(Rolander, Phares et al. 2001) The records provided by the LiDAR technology also allow for a structural review years later with direct report evidences: It allows for an improved quality assurance process by having unbiased evidence from which several individuals can evaluate. An office review of inspection reports can now include a direct review of the bridge structure without costly trips to the field. LiDAR data can allow for further inspection uniformity as a greater number of engineers can be made available to review the data.

Another advantage of using LiDAR scans is that the 3D point clouds of the structure can save permanent records for future retrieval. This allows the engineer to review the structure directly without needing to return to the site or sorting through pages of bridge pictures. Even more critical is that the 3D point cloud is an exact physical measurement of the structure, hence, comparing before and after event scans can reveal actual bridge movements. Occasional issues may arise that are not noticeable to the engineer until a later site walkthrough, however, with a 3D model record, the engineer can have a more complete review of the structure with quantifiable deformations.

In addition, LiDAR technology allows for temporal structural review: An engineer can see the actual condition of the structure over several years of bridge inspection. Damage that is exacerbated over time can be evaluated and the rate of degradation can be determined (Liu 2010). Additional research has developed methods for using LiDAR to detect changes in the surroundings, such as in construction areas to record changes in excavation or structures.(Girardeau-Montaut and Roux 2006)

Also, a series of scans from different positions can be connected into one global coordinate system such that a full 3D model can be generated for a large structure. The 3D model can then be used to determine subtle condition changes from unexpected loading or impacts beyond original structural design – providing invaluable information to bridge engineers about the history of the bridge.(FARO 2009)

LiDAR data processing is significantly simpler than photography image processing. Since LiDAR output is 3D position data, it can be saved in text format and can be preserved longer than image data, hence, it is the preferred tool of analysis for future applications. This flexibility in analysis makes LiDAR an extremely useful tool for analyzing structures.

1.2 LITERATURE REVIEW

The first part of this project is an analysis of a typical simple span steel girder bridge. LiDAR technology is used in this case to determine the effectiveness of measuring vibrations and vertical clearance. Vibrations may occur as vehicles cause a disturbance when they pass over an expansion joint or a rough section of the road surface. (Manning and National Research Council, Transportation Research 1981). While the velocity of the vehicle does affect the vibration of the bridge, weight is the most crucial factor. The vibrations may lead to noticeable deflection that could be recorded by the use of LiDAR units.

As bridges age, their behavior can deviate from structural analysis results (Ritter 2003). This can be due to the concrete getting stronger with age or exposure to the environment. Bridge behavior may also change due to diaphragm connections relaxing or the pin connections may behave differently according to their condition or repeated loadings (Stiller 2003). This project will record the temperature at several points along the structure to evaluate environmental influence. Additionally, this project will record the number and type of vehicle that passes over the bridge during the scanning process.

As part of this project the Colony Road bridge will be examined for any damage or cracking to determine if the nearby blasting had any effect on the structure. The LiDAR unit was used in this case to review the original condition of the structure and to compare that to the post-blast condition. Local blasting regulations limit the peak particle velocity to 2.54 cm/sec as listed in Table 9.(Conner, University of North Carolina at Charlotte. Dept. of et al. 2007)

Blasting regulations, in most states, are designed with respect to wooden frame residences or to minimize complaints.(Revey 2006) This in turn leads to very conservative blasting designs for reinforced concrete structures and understandably leads to complicated and therefore more expensive blasting designs. Large detonations may be designed with dozens of drilled holes on delays so that the ground vibration will meet the limits set by their locale's regulations. However, in this case study the blast was very close to the bridge structure at 11.1 meters so it may have some noticeable effect upon the structure. The LiDAR unit will be used to assess the condition of the bridge structure itself.

During the construction of nuclear facilities for the Tennessee Valley Authority, Oriard and Coulson completed a study in which they found approximate safe levels of blasting for large concrete structures.(Oriard and Coulson 1980) The determination for the peak particle velocity allowed was found based on the age of the concrete and the distance from the blasting. The values of allowable peak particle velocity ranged from 10.2 cm/sec to 50.8 cm/sec for concrete less than 4 hours old and concrete older than 10 days, respectively. This result is many times the allowed limit provided in state regulations and if taken into consideration would allow for simpler designs. Simpler designs in turn would have a lower cost to implement in the field.

No studies have been found that establishes the effect of traffic above the bridge on LiDAR scanning results. Hence, as part of the development of this new LiDAR application, this study will explore the above bridge traffic effects on the minimum vertical under clearance for a specific bridge under normal operational conditions. The intent of this study is to determine the application of LiDAR scan for two conflicting issues: 1) Can scanning LiDAR be reliably used for "static" clearance measurements under operational traffic conditions? and 2) Will LiDAR data convey "overloading" information from traffic above? Because bridges are constantly under traffic loading resulting in likely bridge movements, which depending on the susceptibility of the bridge to vibration problems, the displacements may temporarily influence on LiDAR measurements. Assuming the two issues are inversely related and assuming that the following is true: If the standard deviations of LiDAR measurements under the operational conditions are less than the tolerance of laser measurements, then scanning LiDAR is good for bridge clearance measurements. Then a correlation analysis can be performed based on the following hypothetical conditions:

$$\begin{cases} \begin{array}{l} \quad\quad\quad (1)\sigma_{clearance\ measurement} < LiDAR\ tolerance \\ if \quad and\ (2) no\ significant + or - correlation\ to\ temperature \\ \quad and\ (3) if\ no\ significant + or - correlation\ to\ traffic\ effect \end{array} \xrightarrow{yields} LiDAR\ technique\ valid \\ if\ none\ of\ the\ above\ are\ true \xrightarrow{yields} LiDAR\ technique\ either\ conditionally\ valid\ or\ not\ valid \end{cases}$$
(1)

where $\sigma_{\text{clearance measurements}}$ is the standard deviation of the LiDAR scans. The correlations to temperature and traffic effects will be determined by calculating the correlation coefficients, *Correl(X, Y)*, established statistically from measurements performed in this study:

$$Correl(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (2)$$

where X and Y refers to any likely events.

The goal of the study is to validate the above simplistic hypothesis. Bridge vibration under traffic is a complex issue that requires an a priori knowledge of the natural vibration modes of the bridge (bridge span, bridge weight, bridge stiffness, bridge type) and the ambient traffic characteristics (amount of cars, car types, vehicle velocities and weights).(Biggs, Suer et al. 1959; Aramraks, Gaunt et al. 1977; Gaunt and Sutton 1981; Manning and National Research Council . Transportation Research 1981; Ritter 2003) Hence, in this study, the problem will be simplified and addressed by conducting systematic scans on a typical highway bridge that has no significant vibration problem.

The variables considered in the study include: 1) temperature effect (summer and winter) and 2) traffic flow (volume and trucking). If the hypothesis is shown to be true, then scanning LiDAR can detect clearance of the bridge because it is not susceptible to bridge vibration. On the other hand, if the hypothesis is tested and shown to be untrue, then LiDAR scan is susceptible to vibration, then it should probably only apply during low traffic hours and the application for bridge clearance may be limited or constrained under certain operational conditions.

To date there has been very limited studies of actual blast effects to bridge structures for construction purposes. Most studies were focused on monitoring the vibration impacts. For example, Lindsey (Lindsey 1989) and Jayasuriya (Jayasuriya, Ohio et al. 1989) instrumented the three-span, steel girder, US Rt. 52 bridge in Ironton, OH as part, of a study to validate the published guidelines for construction blast control by the Ohio Department of Transportation. They found that the recommended scaled distance factor by the Office of Surface Mining to be larger than actual measured values.

1.3 DESCRIPTION OF CASE STUDIES IN CHARLOTTE

1.3.1 Harris Boulevard Bridges

Harris is a four-lane, separated median set of bridges that are independent of each other and therefore carry traffic in a single direction. The bridge inventory numbers for these bridges are 590512 and 590511. Both bridges 590512 and 590511 were built in 1987. Bridge 590511 carries west bound traffic while 590512 carries east bound traffic. The average daily traffic for each bridge is 26,000 vehicles. The truck percentage of average daily traffic is twelve percent. The 590511 and 590512 bridges are built on route NC 29 and cross over NC 49. The bridges are located at longitude 80° 44’ 36.1” and latitude 35° 17’ 44.8”. For this study only bridge 590511 was assessed for minimum vertical under clearance. Figure 3 shows the physical position and area surrounding bridges 590511 and 590412 from Google Map®.(Google 2010)

Figure 1 Overhead view of bridges 590512 and 590511 (Google Map®, 2009)

The superstructure of bridge 590511 is reinforced concrete deck on steel I beams. The spans and supports were cast-in-place. The substructure consists of reinforced concrete caps on steel piles. The bridge is a simple, composite structure with four spans that have lengths of 9.4 m (31'), 23.0 m (75'6"), 23.0 m (75'6"), and 10.4 m (34'0"). Only the two 7.8 m (25'6") spans of bridge 590511 were scanned for minimum under clearance. Figure 4 shows the superstructure and substructure of bridge 590511.

Figure 2 Substructure and superstructure of bridge 590511
– the concrete deck is lined with corrugated steel forms.

The North Carolina Department of Transportation has rated most criteria for bridges 590512 and 590511 as ‘good’.(NCDOT 2006) Abutments, slopes, and steel guarders were given a ‘good’ rating for eight out of nine possible points each. The response to live load criteria was given another ‘good’ rating. The most noted flaws in the bridge are longitudinal cracks in the concrete decking, but bridges 590512 and 590511 are still rated as ‘good’ with seven out of a possible nine points. The concrete guardrails sustained some vertical cracking, but again were rated at seven out of a possible nine points. The overall substructure and superstructure of the bridge was given eight out of nine possible points. Overall the bridge is in very good condition and is expected to last another forty years based on the 2006 inspection. The design load for bridges 590512 and 590511 is a standard truck HS20. The bridge structures exceed the minimum requirements for vertical under clearance specified by AASHTO.(AASHTO 2002)

1.3.2 Colony Road Culvert

This study explores the process of structural evaluation using LiDAR technology for possible detection of change of conditions for bridges after large loading events such as blast waves, hurricanes or earthquakes. Bridge structures may experience permanent deformations or cosmetic damages from large external loadings. To ensure safety of a structure, event blast monitoring and post-event inspections are needed and often performed especially for blasting. However, it is frequently difficult to get exact geometric, structural and surficial data of a structure since, other than site surveying; there is currently no technique that images a structure. It should be mentioned that LiDAR has been used commercially for surface and underground mining monitoring, tunneling blast volume quantification and shot hole placement documentation and remote safety assurance.(Lato, Diederichs et al. 2010) However, there has been no documentation of post-blast monitoring of structures.

In this study, a bridge under close-range blasting impact is studied using LiDAR scan before and after the blast. The bridge studied is the Colony Road bridge in Charlotte, North Carolina. A bed rock blasting is scheduled near the Colony Road bridge for underground pipeline construction. Figure 1 shows the Google Map ® (Google 2010) location of the bridge relative to the blast site. The bridge is located close to a residential area and is a major access road to a local high school. There was concern that shock damage may occur to the bridge due to the close proximity to the blasting site.

The blasting scheduled is for a nearby construction project that was connecting a new pipeline under Colony Road. The blasting occurred on April 5th, 2010 about 11.1 meters east of the bridge along the centerline of the road. Blasting was required to clear away a large set of rocks so that pipeline could be installed beneath the road. Figure 1 shows the area around the Colony Road Bridge including the blasting area and the position of the LiDAR scanner to record the culvert tunnel. Figure 2 shows the overall geometry of the Colony Road Bridge.

For the LiDAR scanning sessions on December 4th, 2009 the maximum car traffic occurred at 8:04 AM, while the maximum truck traffic arrived at 8:42 AM. On May 28th, 2010 the maximum car traffic occurred at 8:15 AM. During the same LiDAR scanning session the maximum of four trucks occurred at 8:15 AM, 9:00 AM, 11:19 AM, and 11:26 AM. The minimum car count that happened on December 4th, 2009 occurred at 10:21 AM. The minimum truck count, on the same day, was recorded at 10:37 AM and 1:03 PM. On May 28th, 2010 the minimum car count was recorded at 12:31 PM. The minimum truck count during that scanning session happened at 9:15 AM, 11:32 AM, and 11:46A.

Figure 3 Position of LiDAR scanner and blasting areas relative to bridge site (modified from (Google 2010)).

Figure 4 Dimensions of culvert tunnel.

1.4 METHODOLOGY FOR HARRIS BOULEVARD CASE STUDY

1.4.1 Bridge Monitoring

The first series of LiDAR scans were taken on December 4th, 2009 (winter condition) and a second series was recorded on May 28th, 2010 (summer condition). The two scanning sessions recorded the state of the bridge in very different temperature conditions. Figures 7 and 8 show the measured temperature variation throughout part of a day at bottom of the bridge (concrete deck and steel girder). The thermal measurements are performed using a FLIR infrared thermal camera at mid span of each girder and span between girders for each scan. The individual scans were spaced apart from early morning to early afternoon to record a variety of traffic loadings.

All scans of bridge 590511 were administered under normal traffic conditions: there is no intentional traffic control during the testing. Scanning took place from early morning to mid-afternoon to include a variety of traffic conditions. The LiDAR scanning unit was placed in the center median below the bridge supports to capture both major spans. Figure 5 shows the placement of the LiDAR unit beneath bridge 590511.

The LiDAR scanning unit recorded data for five to ten minutes during each scan. During each scan a traffic count was conducted. Two people watch oncoming traffic on the bridge to record how many cars and trucks cross over using a JAMAR board counter. For this study cars were considered to be two axle vehicles and trucks were three axles or more.

Figure 5 Placement of LiDAR unit under bridge 590511.

1.4.2 Data Collection

LiDAR scan data sets were used to determine the minimum vertical underclearance of bridge 590511. For each single span position data from the bottom of the superstructure of the bridge was outputted to a XYZ file. The XYZ files are text files that include position data in the classic X, Y, and Z coordinate systems. A matching position dataset was outputted that described the geometric characteristics of the roadbed beneath the bridge. Figure 6 shows a typical reflectivity picture from the scan record of bridge 590511. The LiDAR unit measures the amount of light that returns to the unit and determines the reflectivity of the surface based on that measurement. The LiDAR scan data was processed by using a LiDAR-Based Bridge Evaluation (LiBE) algorithm.(Liu, Chen et al. 2010) The program evaluates position data of the two compared datasets, one set for the roadbed and one set for the bridge superstructure.

Figure 6 Typical reflectivity picture from LiDAR scan of bridge 590511. Easternmost span is on the left, westernmost is on the right.

1.4.3 Data Analysis

The temperature variations throughout each test period are presented in Figures 7 and 8. Table 1 contains the recorded temperature data for both spans on December 4th, 2009 in Fahrenheit. Table 2 contains temperature data from both spans on May 28th, 2010 in Fahrenheit. Also shown in the tables are the median temperatures, temperature variations, from both days.

On review of the temperature data, it was found that the greatest relative difference between the winter and summer data was among the minimum temperatures of the east span. A range of 37.5 and 37.9 degrees Fahrenheit was recorded for the minimum temperatures of girders and concrete spans, respectively. The greatest difference in temperature is in the girders of both the east and west spans of 48.4 and 48.2 degrees Fahrenheit, respectively. The largest temperature differences were between the minimum winter temperatures and the maximum summer temperature.

The second set of recorded data points are car and truck counts for bridge 590511 during the test periods which are shown in Figures 9, 10, 11, and 12. For this study a car is defined as a vehicle with two axles. A truck is defined as a vehicle with three or more axles. Traffic counts were recorded using a JAMAR board and were taken for the length (five to ten minutes) of each LiDAR scan. The vehicle crossing is critical since loading caused by vehicles moving across the bridge may cause a deflection that is detected by the LiDAR point cloud data. By collecting data on the vehicles crossing the bridge spans during LiDAR scanning sessions this study can evaluate possible relationships between bridge deflection and live traffic loading. Table 3 and

Table 4 contain data of truck and car loads on bridge 590511 during winter and summer scanning sessions, respectively.

A total of sixteen scans were taken on December 4th, 2009 and twenty-two scans were taken on May 28th, 2010. Table 5 and Table 6 contain a summary of the vertical under clearance data recovered from the LiDAR datasets in terms of meters.

The scanning sessions on December 4th, 2009 returned a collection of underclearance values with standard deviations for the east and west spans of 0.03 m (1.2") each. The May 28th, 2010 underclearance values were more varied for east spans at 0.07 m (2.8") and for the west spans at 0.06 m (2.4").

Minimum values are the lowest value for underclearance returned from all LiDAR scans for that day. Maximum values also represent minimum vertical underclearance, but are the largest returned value for that day. The minimum value returned for underclearance was consistent for the east span in both the winter and summer scanning sessions. The east span minimum underclearance values were compared against a physical measurement of 5.1 m (16'9") taken by the side of the road to the bottom of the girder.

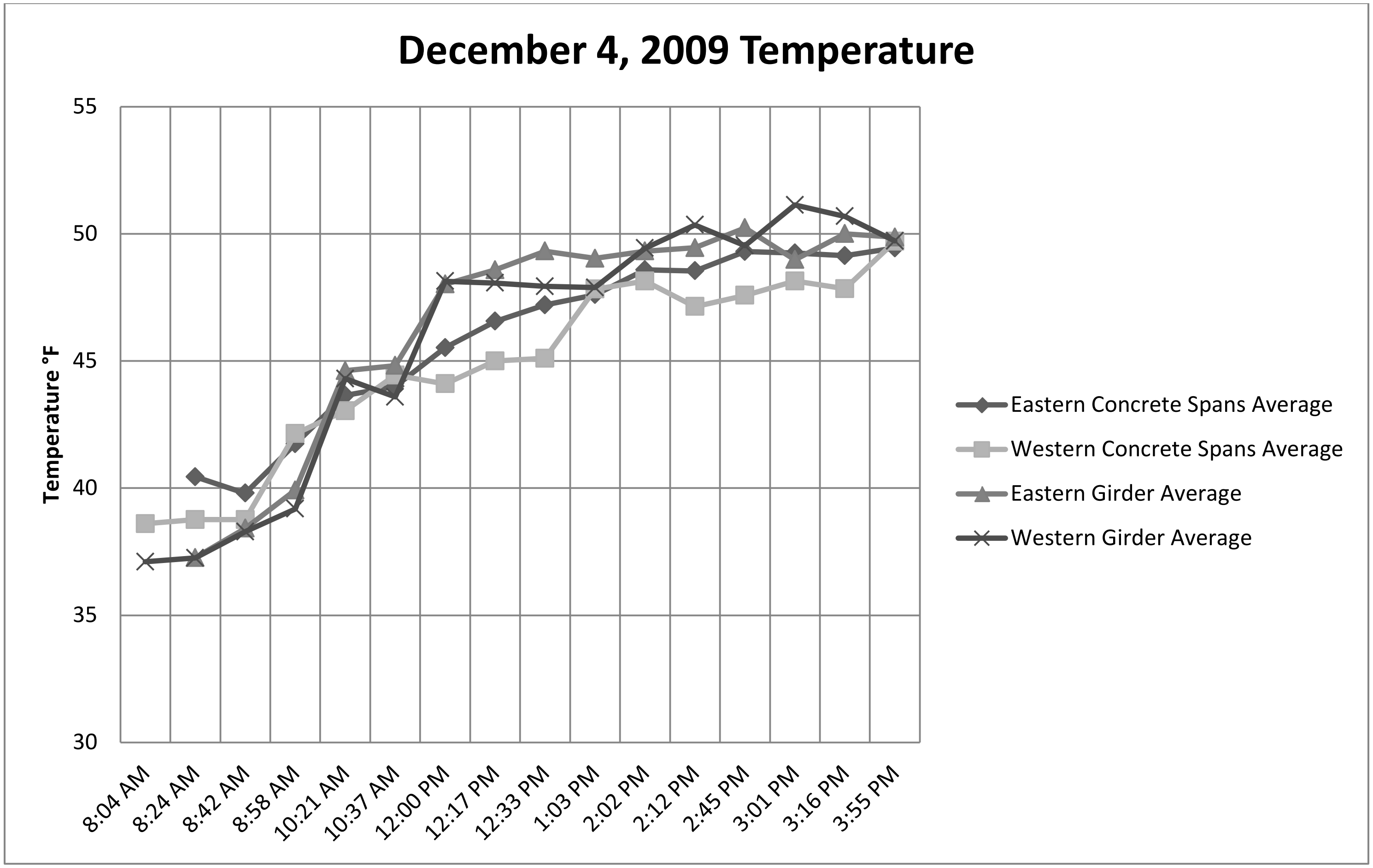


Figure 7 Temperature Variation During the Winter Scan (December 4th, 2009)

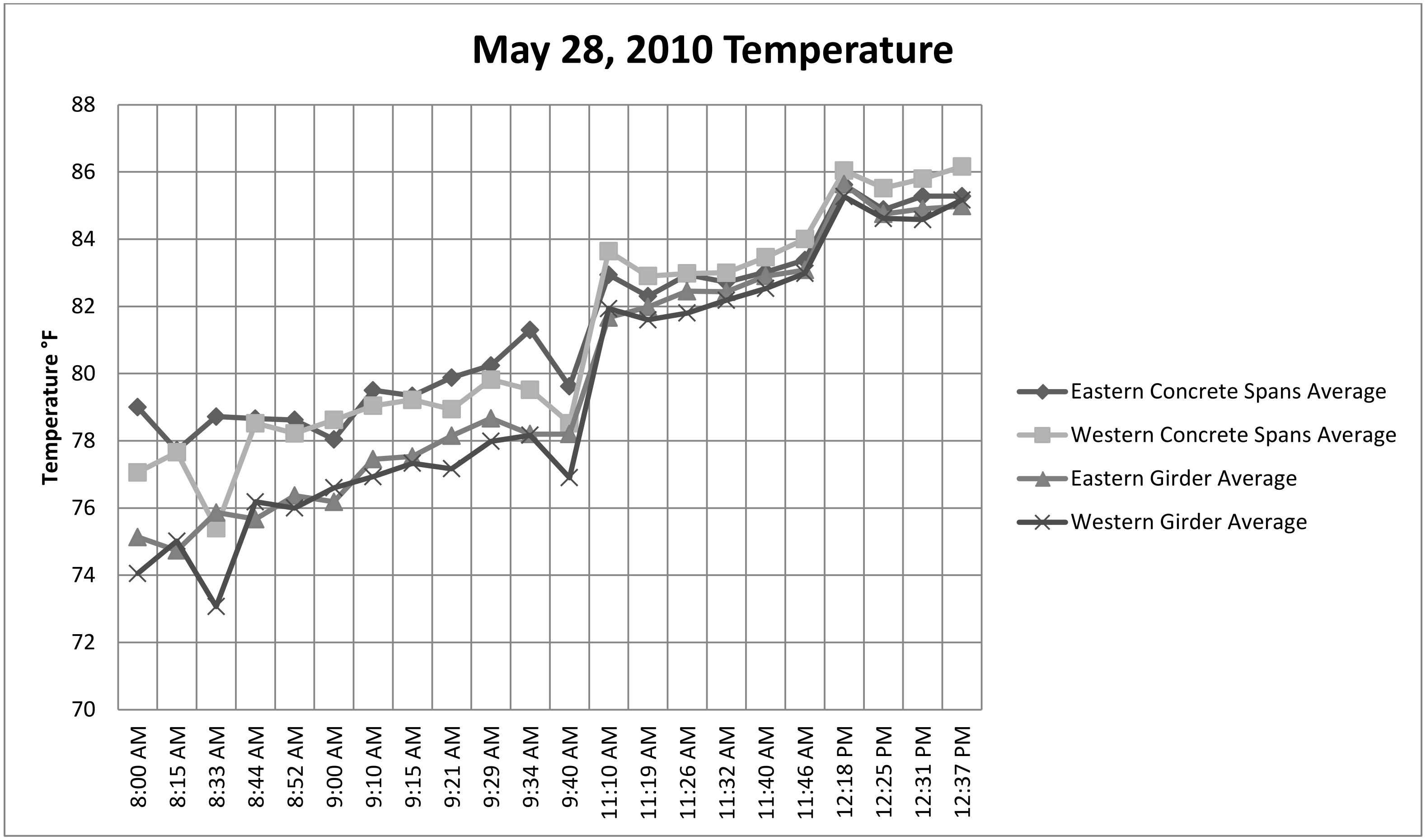


Figure 8 Temperature Variation During the Summer Scan (May 28th, 2010)

Table 1: Temperature data, in Fahrenheit, of east and west spans on December 4th, 2009.

December 4th, 2009	Minimum Temperature	Maximum Temperature	Average Temperature During Scans	Std. Dev.	COV
West Span					
Girders	37.1	51.1	45.8	5.0	11.1
Spans	38.6	49.7	44.8	3.4	7.8
East Span					
Girders	37.3	50.2	46.5	4.5	9.7
Spans	39.8	49.4	46.0	3.3	7.1

Table 2: Temperature data, in Fahrenheit, of east and west spans on May 28th, 2010.

May 28th, 2010	Minimum Temperature	Maximum Temperature	Average Temperature During Scans	Std. Dev.	COV
West Span					
Girders	73.1	85.3	79.5	3.6	4.5
Spans	75.4	86.2	81.1	3.2	3.9
East Span					
Girders	74.7	85.6	79.9	3.4	4.2
Spans	77.7	85.6	81.3	2.5	3.1

Table 3 Traffic count data of bridge 590511 during LiDAR scanning sessions.

December 4th, 2009	Minimum	Maximum	Average	Std. Dev.	Coefficient of Variance
Cars	157	367	226.8	100.6	39.9
Trucks	0	9	3.8	3.0	75.0

Table 4 Traffic count data of bridge 590511 during LiDAR scanning sessions.

May 28th, 2010	Minimum	Maximum	Average	Std. Dev.	Coefficient of Variance
Cars	102	177	135.6	22.0	16.2
Trucks	1	4	2.6	1.0	38.4

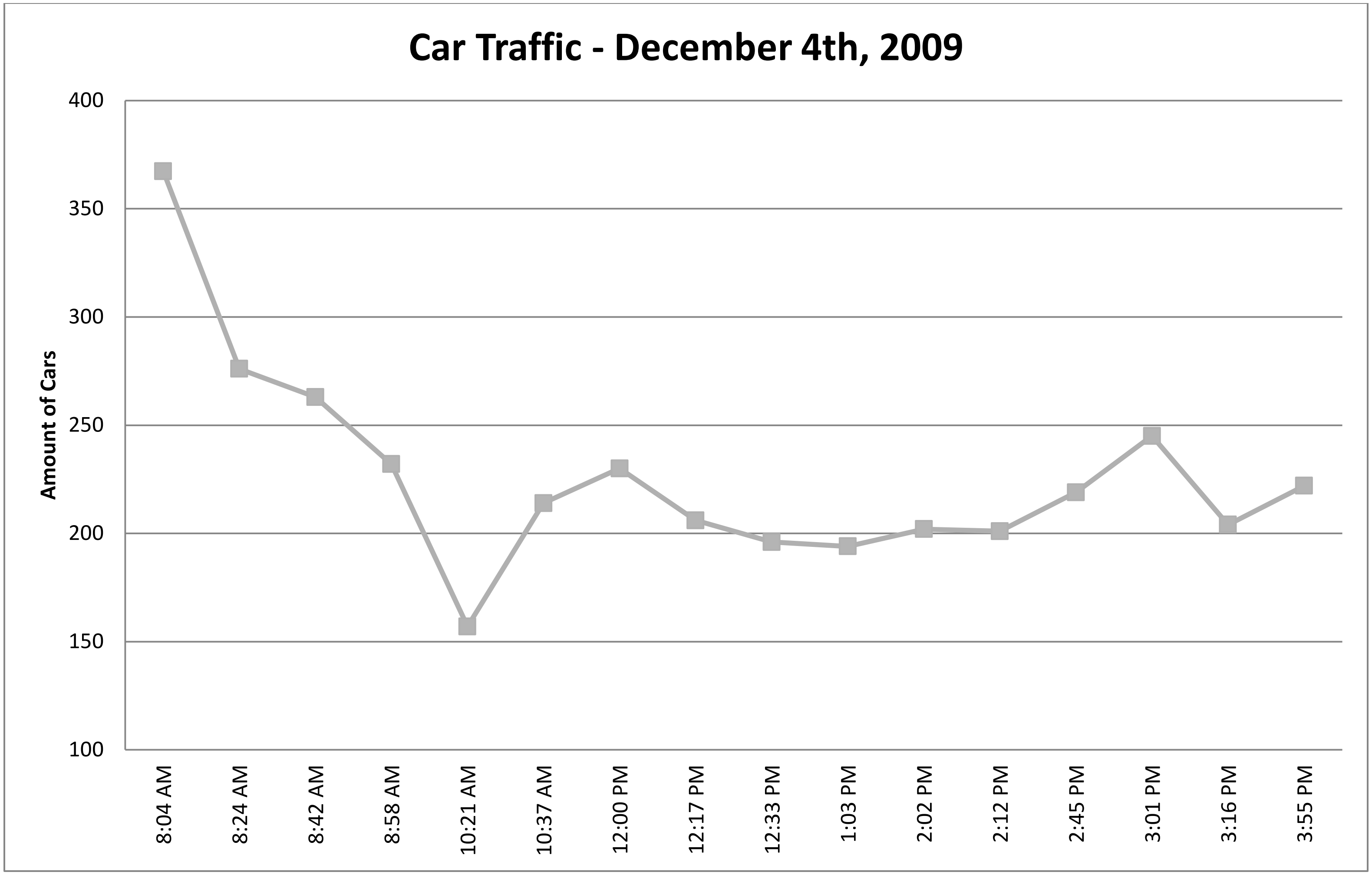


Figure 9 Recorded car traffic during LiDAR recording sessions on December 4th, 2010.

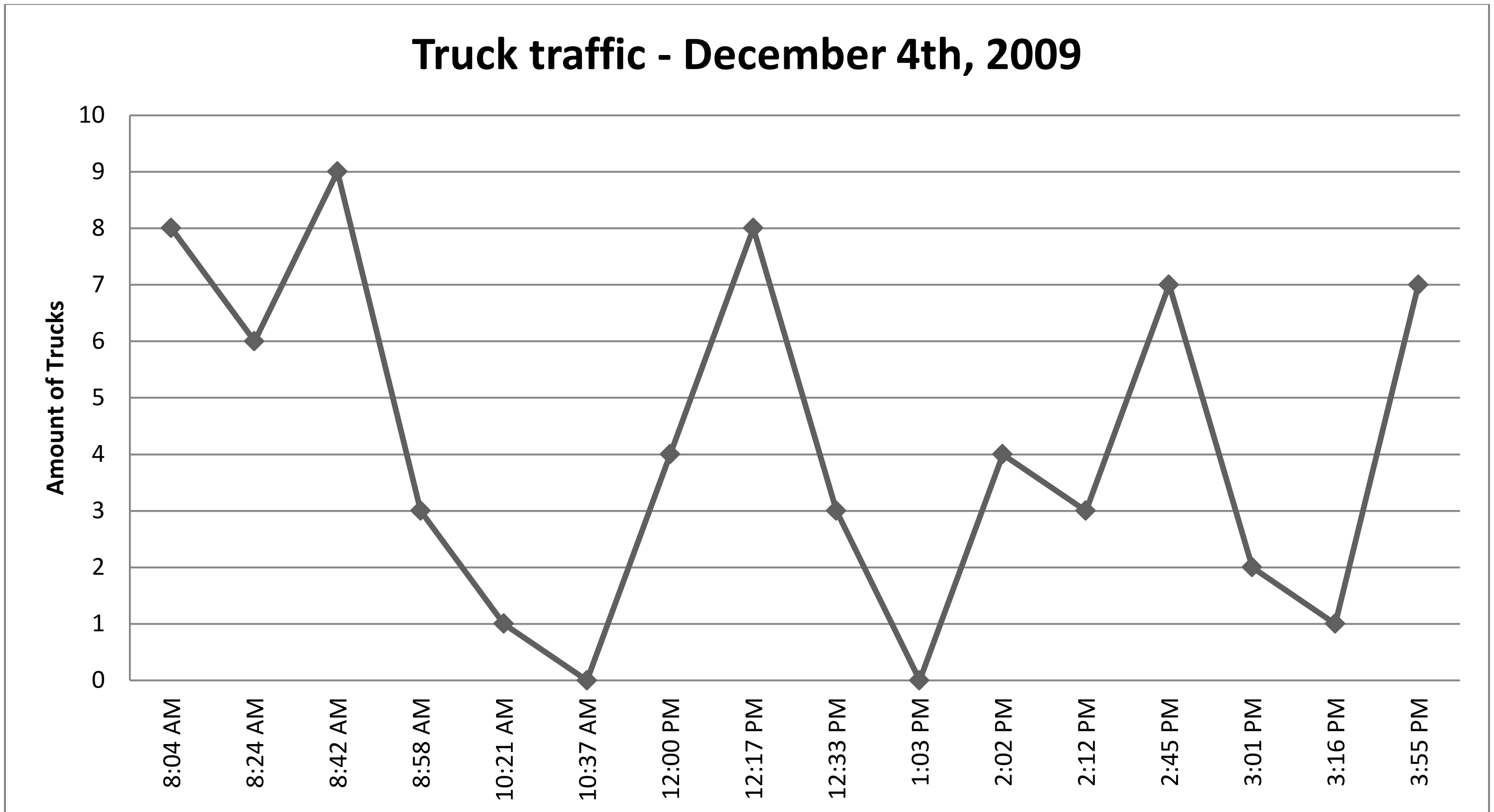


Figure 10 Recorded truck traffic during LiDAR recording sessions on December 4th, 2010.

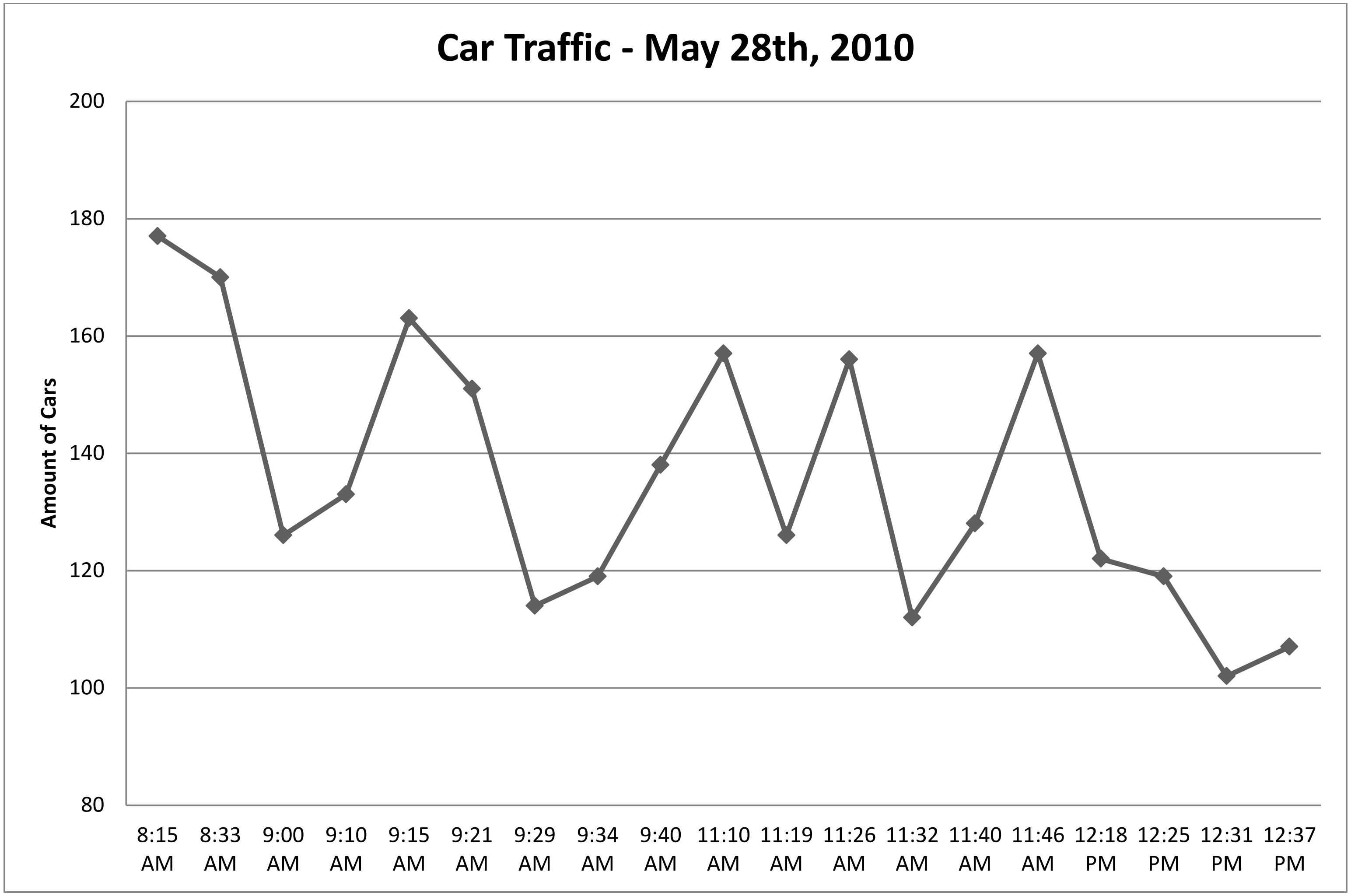


Figure 11 Recorded car traffic during LiDAR recording sessions on May 28th, 2010.

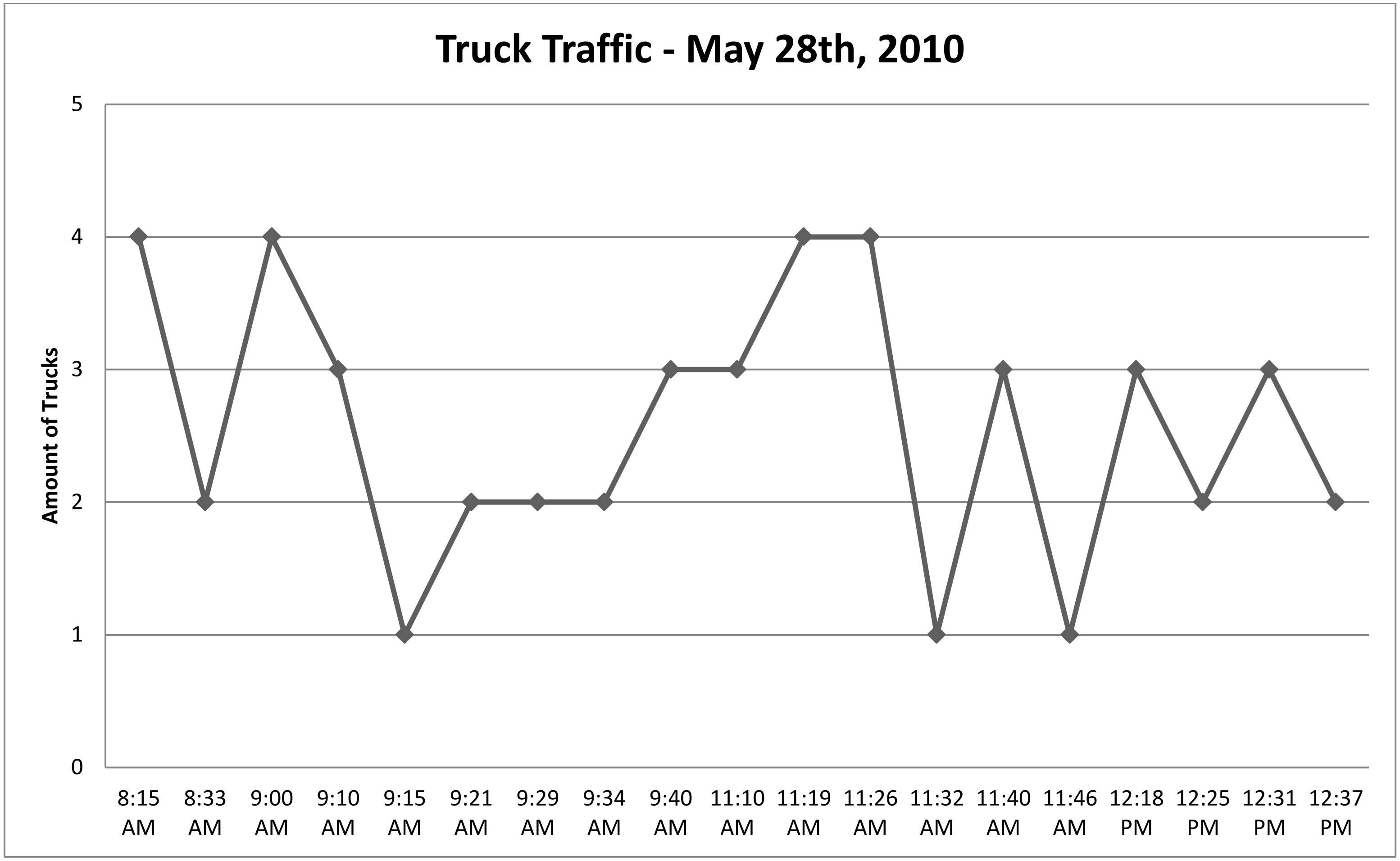


Figure 12 Recorded truck traffic during LiDAR recording sessions on May 28th, 2010.

Table 5 Minimum vertical under-clearance of the west span of bridge 590511.

West Span Clearance	5/28/2010	12/4/2009
Average	5.19 m (17’0”)	5.17 m (16’11”)
Median	5.19 m (17’0”)	5.18 m (16’12”)
Std. Dev. (σ)	0.07 m (2.8”)	0.03 m (1.2”)
Coefficient of Variance (COV)	1.18 %	0.53 %

Table 6 Minimum vertical under-clearance of the east span of bridge 590511.

East Span Clearance	5/28/2010	12/4/2009
Average	5.16 m (16’11”)	5.10 m (16’9”)
Median	5.16 m (16’11”)	5.10 m (16’9”)
Std. Dev. (σ)	0.06 m (2.4”)	0.03 m (1.2”)
Coefficient of Variance (COV)	1.13 %	0.63 %

1.4.4 Before and After Analysis

Bridge clearance is a critical issue considering the long term bridge displacements that may reduce the overall underclearance of a bridge including: elastic shortening due to pre-stressing or post-tensioning, creep, shrinkage, relaxation, temperature expansion, and movements due to live loads.(Shiu, Russell et al. 1986) For short term effects, it is also possible that varying temperature ranges may cause the boundary conditions of the bridge spans to act more closely to fixed end conditions rather than as a simple span (elastic shortening). This effect is determined in this study by considering only if the deviation of the LiDAR clearance measurements actually exceeds the tolerance of the system. The road surfaces were between 6 m (19’8”) and 11 m (36’1”) away from the LiDAR scanner.

From manufacturer’s information, it is known that the LiDAR scanning equipment has a measurement uncertainty of points of ±3 mm (±0.12”).(FARO Technologies 2009) When considering measurements between two physical points, this measurement uncertainty can be as large as ±6 mm (±0.24”). Thus, the winter measurements are considered well within the normal accuracy (±3 mm) of the LiDAR equipment; whereas, the summer measurements are within the limits of the uncertainty at ±6 mm (±0.24”). The sunny summer day may have increased amounts of ambient light that may interfere with measurements.

The day of the winter measurement was cloudy and allowed for a better measuring environment by limiting the amount of ambient light. This difference could be due to a higher number of vehicles being recorded into the LiDAR dataset in the summer than in the winter. After compiling temperature, traffic count, and vertical underclearance data, the relationships between these values may be explored. Table 7 and Table 8 contain the lists of correlations to clearance to the other variables measured during this study. The correlations are computed using equation (2). A positive correlation is usually indicated by a value close to 1. Negative values usually represent inverse correlations.(Dowdy and Wearden 1983) Using the hypothesis established for the correlation analysis in equation (1), it is shown in Table 8 that the strongest correlation between any results is between the amount of car passing and the underclearance measurements (-0.890) for the West Span measured during December 4th, 2009. None of the other correlations show any values higher than 0.5. This indicates that the LiDAR measurements are not significantly sensitive to traffic or temperature deviation for the Harris Boulevard Bridge.

Table 7 List of correlations for the east span of bridge 590511.

East Span Correlation - 05/28/2010	**Correlation to Clearance**	**East Span Correlation - 12/04/2009**	**Correlation to Clearance**
Cars	-0.007	*Cars*	-0.179
Trucks	-0.229	*Trucks*	-0.328
Span Average Temperature	-0.206	*Span Average Temperature*	0.391
Beam Average Temperature	-0.252	*Beam Average Temperature*	0.317

Table 8 List of correlations for the west span of bridge 590511.

West Span Correlation - 05/28/2010	**Correlation to Clearance**	**West Span Correlation - 12/04/2009**	**Correlation to Clearance**
Cars	-0.250	*Cars*	-0.890
Trucks	-0.303	*Trucks*	-0.245
Span Average Temperature	-0.056	*Span Average Temperature*	0.466
Beam Average Temperature	-0.046	*Beam Average Temperature*	0.472

The correlation values for temperature measurements for both east and west spans during the winter LiDAR scanning session may suggest that there is a positive, albeit weak, relationship between temperature of the structure and the vertical under-clearance. During the May 28th, 2010 scanning session the relationship between clearance and structural temperature was very weak.

This result would fall into line with the bridge span end boundary conditions acting as if they were fixed end connections rather than simple spans. As the temperature increases the ends of the bridge spans may press against the supports to more closely resemble a fixed connection. In the case of cars and trucks there is a possibility of an inverse relationship with respect to clearance. The amount of cars has a negative relationship with clearance in every testing session and is weakest for the east span case. During the December 4th, 2009 testing correlations to temperature and clearance increase in each case from the May 28th, 2010 pair indicating that temperature effects may be influential to LiDAR measurements.

To determine the significance of the correlations this thesis will conduct a two-tailed test. If the hypothesis is true then it is not likely that there is a correlation between recorded values and clearance.(Petruccelli, Nandram et al. 1999) The following hypothesis with a significance of α=0.05:

H_0: ρ=0
H_a: $\rho \neq 0$

The t* will be calculated based upon Equation (3):

$$t^* = (r - \rho_0)\sqrt{\frac{(n-2)}{(1-r^2)(1-\rho_0^2)}} \qquad (3)$$

With 16 samples for the December 4th, 200 9 session and 22 samples for the May 28th, 2010 session the t* and probability values are arrived at in Table 9 and Table 10.

Table 9 Calculated values of t* and probability for east span.

	12/4/2009		**5/28/2010**	
East Span: Two-Tailed Test	**t***	**P-value (%)**	**t***	**P-value (%)**
Cars	-0.681	> 20	-0.031	> 20
Trucks	-1.299	> 20	-1.052	> 20
Span Average Temperature	1.590	14.2	-0.941	> 20
Beam Average Temperature	1.251	> 20	-1.165	> 20

Table 10 Calculated values of t* and probability for west span.

	12/4/2009		**5/28/2010**	
West Span: Two-Tailed Test	**t***	**P-value (%)**	**t***	**P-value (%)**
Cars	-7.303	< 0.01	-1.155	> 20
Trucks	-0.946	> 20	-1.422	17.6
Span Average Temperature	1.971	7.2	-0.251	> 20
Beam Average Temperature	2.003	6.8	-0.206	> 20

Upon review of the p-values, most cases cannot reject the hypothesis that there is no population correlation between any measured value and clearance, as the calculated p-value is greater than the significance factor. In one case of cars on December 4, 2009 for the west span there is a value that meets the significance threshold. This p-value for the western span was determined to be an anomaly as this value did not hold for the eastern span. Additionally, it is unlikely that any given combination of cars would deflect the bridge significantly more than trucks. Therefore it is believed that if there was continued testing then this value would normalize to a value more consistent with the eastern span during the same time period.

Based on criterion established in Equation (1), the hypothesis that traffic conditions and temperature effects may play on LiDAR measurements is shown to be negative, meaning that in real world situations, LiDAR can be applied as an underclearance measurement technique under most situations. This conclusion is significant, since LiDAR measurements offer several advantages over conventional surveying techniques in that its usage is without interrupting traffic and offers much shorter set up time, which would lead to more cost effective and accurate data for DOTs while causing less hassle for drivers.

1.4.5 Conclusions

A simple correlation analysis is performed on the effects that may influence terrestrial LiDAR underclearance measurements on the Harris Boulevard Bridge. Upon review of the data and the results of the analysis, there seems to be no evidence of direct influence due to structural temperature or vehicle crossings over the bridge. Variations in vertical underclearance measurements were also within the sensitivity range of the LiDAR scanner. One instance with the western span in the winter with respect to cars was most likely a random variation. The difference in the averages of vertical clearance between the summer and winter measurements may be due to differences in boundary conditions. The conclusion of this study is that vehicles and temperature, in this case, had little effect on vertical underclearance measured by LiDAR. Further this study finds that LiDAR scanners can be used to create accurate models of structures even while the structure is open to live traffic. This can be a very valuable advantage to the LiDAR technology as traffic disturbance is kept to a minimum.

1.5 CASE STUDY OF THE COLONY ROAD CULVERT

1.5.1 Bridge Characteristics

The Colony Road Bridge is a concrete culvert with a two-lane road above. The abutments of the culvert are backfilled with earth, which is retained by large trees, shrubs, and large granite gravel to protect the embankments and foundation from erosion. At both openings of the culvert are wing walls that angled out from the culvert. The culvert crosses Briars Creek which is a slow moving creek about ten meters wide. Figure 12 outlines the basic geometry of the culvert, which has a width of 10.380 m and a height of 5.670 m. The LiDAR has a resolution of 0.003 m.(FARO 2009)

1.5.2 Blasting Event Characteristics

Most blast vibration typically regulated by regulatory agencies by a ground vibration velocity limit near the target structure, even though such regulations are likely to be over simplistic.(Schneider 2001) Connor (2007) lists several ground vibration limits from different state jurisdictions. A list of recent ground vibration limit regulations is shown in Table 11. Current regulations in North Carolina set at a limit of 2.54 cm/sec for ground vibration.
(Conner, University of North Carolina at Charlotte. Dept. of et al. 2007)

For the Colony Road Bridge, there were several concerns with respect to the construction blasting project. A layer of rock had to be removed in order to lay a new sanitary pipe, but the construction area is nearby to the reinforced concrete culvert, a school, and family homes. With the close proximity to several important structures there was concern for excessive ground vibrations. The structure of most concern was the concrete culvert as the blasting would occur only 11.1 meters away from the structure, which is less than the allowable distance of a blasting from the city.(National Drilling & Blasting 2010) Under the Zoning Ordinance, the City of Charlotte (Charlotte 2011) requires that excessive ground vibrations detectable at property lines should not create a nuisance to any person of ordinary sensitivities on another property and any blast should have a distance to residential or institutional structures of not less than 152.4 m.(Oscar Renda 2010)

A single rock blasting was conducted on April 5th of 2010. The blasting occurred at 11.1 meters along the center line of the road way. Figure 1 shows the location of the blasting site and the location of the concrete culvert. The blast plan called for 3.67 kg of high explosives including: 2x16 dynamite and 2 1/2x16 unimax blasting agent. The drill pattern was 1.54 x 1.83 meters with 20 to 30 holes drilled. The diameters of bore holes were approximately .0889 m with a depth of .762 meters. The blasting was done to remove a 3.96 meter layer of rock below 5.18 meters of earth so that a new 1.52 meter diameter sanitary sewer could be constructed.(Oscar Renda 2010)

Table 11 Ground Vibration Limits from Different Jurisdictions (Connor, 2007)

Jurisdiction	Ground Vibration Limits		Jurisdiction	Ground Vibration Limits
Alabama	19.1 – 50.8 mm/s		New Jersey	19.1 – 50.8 mm/s
Arizona	None		New Mexico	19.1 – 31.8 mm/s
Phoenix	25.4 mm/s		New York	No regulations
Arkansas	25.4 mm/s		Amherst	19.1 – 50.8 mm/s
Florida	12.7 mm/s		Clarence	19.1 – 50.8 mm/s
Georgia	50.8 mm/s		**North Carolina**	**25.4 mm/s**
Idaho	No regulations		North Dakota	25.4 mm/s
Lewiston	12.7 mm/s		Ohio	50.8 mm/s
Illinois	19.1 – 31.8 mm/s		Oklahoma	25.4 – 50.8 mm/s
Indiana	19.1 – 31.8 mm/s		Oregon	N/A
Iowa	19.1 – 31.8 mm/s		Gladstone	19.1 – 50.8 mm/s
Kentucky	50.8 mm/s		Pennsylvania	50.8 mm/s
Louisiana	19.1 – 31.8 mm/s		Rhode Island	12.7 mm/s
Maine	50.8 mm/s		South Carolina	25.4 mm/s
Maryland	19.1 – 31.8 mm/s		Tennessee	50.8 mm/s
Massachusetts	19.1 – 50.8 mm/s		Texas	19.1 – 31.8 mm/s
Minnesota	25.4 mm/s		Austin	43.2 mm/s
Missouri	No regulations		Utah	19.1 – 31.8 mm/s
Kansas City	19.1 – 31.8 mm/s		Virginia	19.1 – 31.8 mm/s
Montana	19.1 – 31.8 mm/s		West Virginia	19.1 – 31.8 mm/s
Nevada	No regulations		Charleston	50.8 mm/s
Clark County	12.7 mm/s		Wyoming	19.1 – 31.8 mm/s
New Hampshire	50.8 mm/s			

Typically, charge weight, Q, and vibration velocity, Vp, are expressed by an empirical, square root or cube root relationship to the distance to the structure, R.(Dowding 1985):

$$V_P = K\left(\frac{\sqrt{Q}}{R}\right)^{\alpha}$$
(4)

Where coefficients, such as K and α have to be experimentally determined.

Comparing blast vibration velocity and charge relations, Liang et al. (Liang, An et al. 2011) concluded that both square and cubic roots can produce good results and is a function of the site geology. Most states and municipalities do not adopt the scientific basis of Equation (4) - in some cases, much simplistic correlations may be adopted for blast control. For example, the state of Washington adopted a distance-to-charge and allowable maximum particle velocity correlation (Table 12). Considering the hard quartzite rock (K assumed as 222.4 and α assumed to be 1.7088) in Charlotte and a square root scaling, with the given distance of 11.1 meters and

3.67 kg charge weight, it is found that peak particle velocity at the bridge should be 11.05 mm/sec.

Several records were taken of the ground vibration during the blasting and are listed in Table 13. Figure 13 displays the locations of the sensors from Table 13. In the cases of nearby street intersections and the school buildings vibrations were well within the limits set for ground vibration. However, the geophones placed on the Colony Road bridge detected vibrations up to 3.708 cm/sec.(Oscar Renda 2010) Although this recommended value for ground vibration is with consideration to residential structures it may cause issues at this magnitude and distance from the culvert structure.

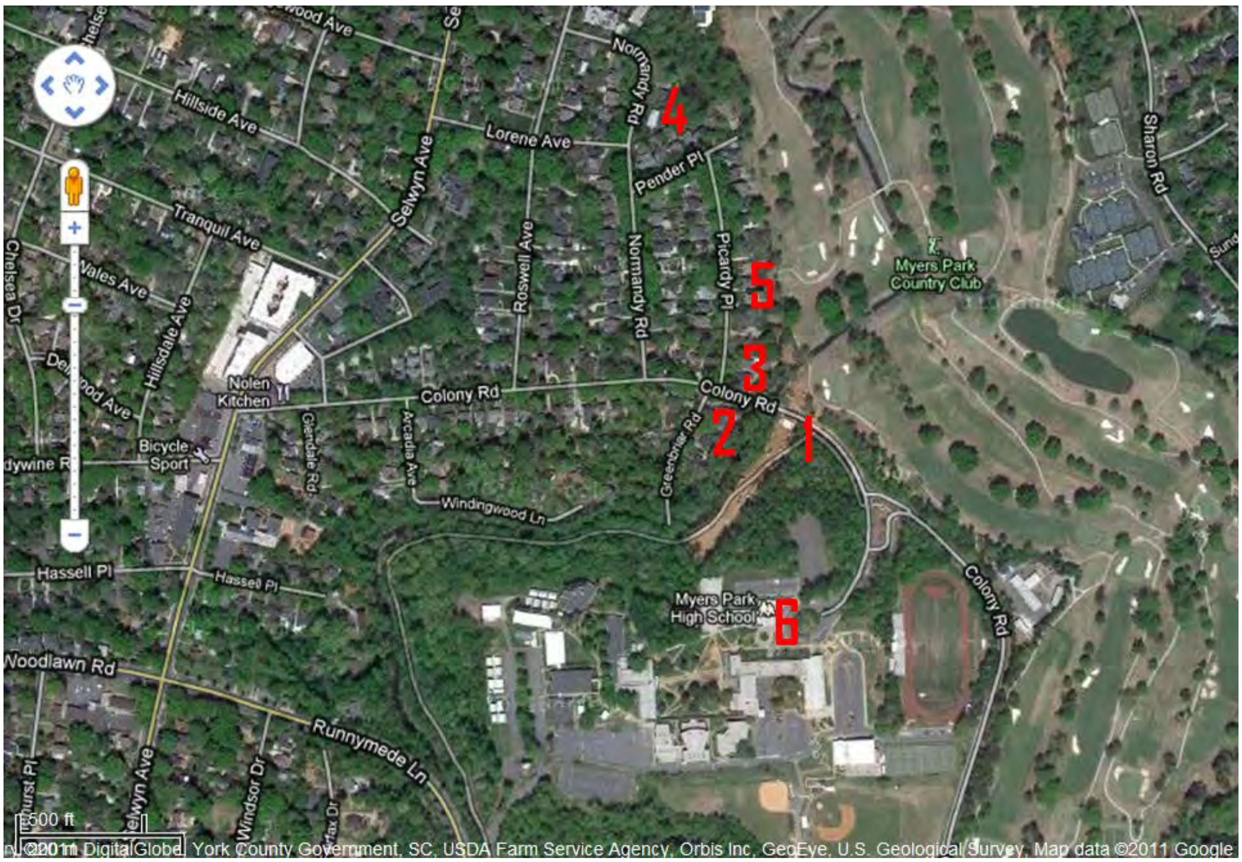


Figure 13 (Google 2010) Google Maps[3] image of Colony Road Area with Vibration Sensor Locations Marked in Red Numbers.
(1. Colony Road Culvert, 2. Colony Road Residential A, 3. Colony Road Residential B, 4. Residence on Normandy, 5. Residence on Picardy, and 6. Meyers Park High School)

Table 12 Blast Limit Legislated by the State of Washington (2011)

Distance from Blasting Location	**Maximum Allowable Peak Particle Velocity (measured in all three axes)**
0 to 91.4 m	31.75 mm/sec

91.5 m to 1524 m	25.4 mm/sec
1525 m and beyond	19 mm/sec

Table 13 List of PPV at test stations around blast site.

Location	Radial (cm/s)	Transverse (cm/s)	Vertical (cm/s)
Colony Road Culvert	1.74	2.18	3.04
Residence on Colony Road A	0.83	0.75	0.98
Residence on Colony Road B	0.65	0.95	0.71
Residence on Normandy	0.06	0.08	0.08
Residence on Picardy	1.19	0.50	0.95
Local High School	0.41	0.27	0.34

Blasting codes are typically designed for residential homes in order to prevent cosmetic damage, such as cracks in drywall or plaster.(Revey 2006) In this study we are concerned with a large reinforced concrete culvert where residential vibration limits may not be appropriate. To approximate a more appropriate ground vibration limit this study will compare previous studies and current blasting regulations. Studies done during the construction of nuclear facilities for the Tennessee Valley Authority have shown acceptable vibration limits, for large masses of concrete, of 10.2 cm/sec to 50.8 cm/sec depending upon concrete age and distance to blasting.(Oriard and Coulson 1980) Based upon these previous studies and current regulations in the field a more appropriate vibration limit may be approximated.

1.5.3 Methodologies

1.5.3.1 LiDAR Scanning Process

A set of LiDAR scans from before blasting was taken and compared to a set of scans after the blasting event. Figure 14 contains a black and white rendering (Top image) of the reflectivity image of the Colony Road culvert before the blasting and an image of a 3D point cloud of the pre-blast scan (Bottom image). Figure 14 was created by the LiDAR scan, which recorded the reflectivity of the returned at each recorded point. A higher reflectivity corresponds to a white pixel, while a lower reflectivity may be grey or black. A second scan was conducted on May 5th, 2010. Figure 15 contains both the black and white reflectivity image (Top image) and the respective 3D point cloud (Bottom image) of the post-blast Colony Bridge. Visual inspection conducted during the second scan did not reveal any major flaws or problems found on the bridge structure. Since both sets of scan results entailed millions of position measurements, it is possible to compare the position data from both scans to find the differences.

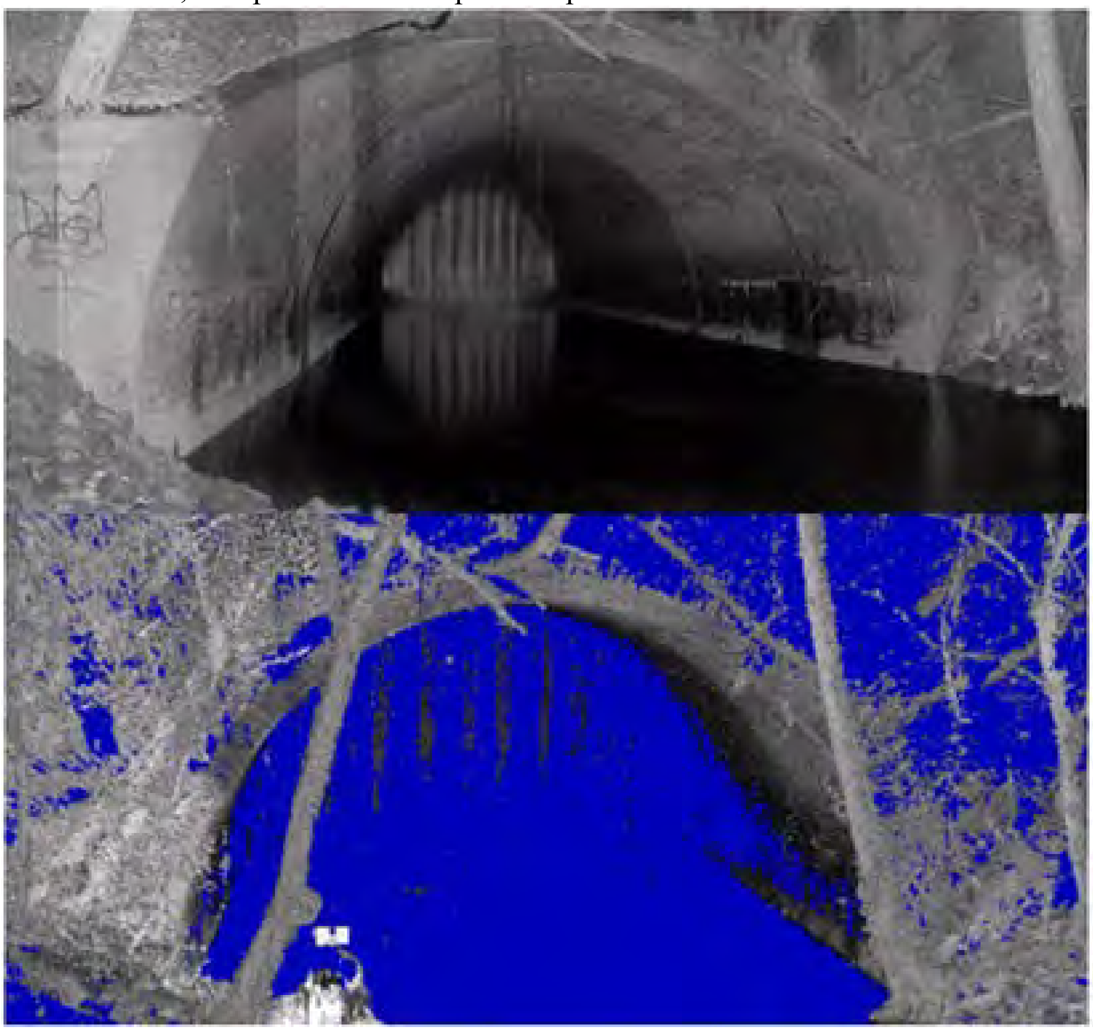


Figure 14 Pre-blasting scan of culvert interior (top: reflectivity bottom: point cloud).

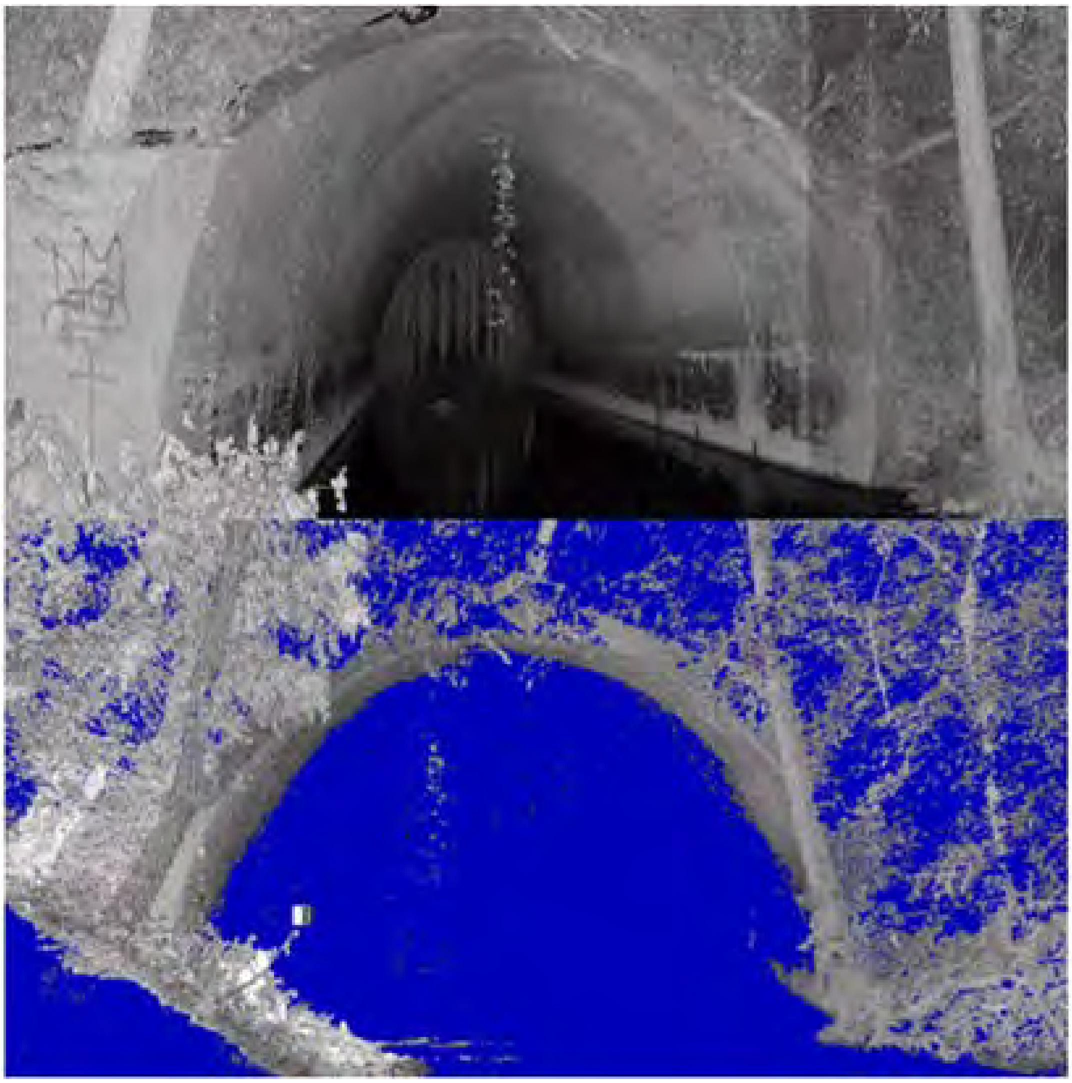


Figure 15 Post-blasting scan of culvert interior (top: reflectivity bottom: point cloud).

1.5.3.2 Damage Evaluation

Three computer programs were used in this study to record, synthasize, and evaluate the point cloud data: 1) FARO Record® (FARO 2009), which was used to control the LiDAR scanner and to record the point data; 2) FARO Scene® (FARO 2009), which was used to synthesize the point cloud data; and 3) Geomagic Studio 11® (Geomagic 2009), which performs the "reverse engineering" and polymesh creation. The overarching process consisted of taking scans of the bridge using the LiDAR unit, aligning the models, and comparing the pre-blast scans to the post-blast scans in Geomagic Studio 11®. Figure 16 outlines the general process of analyzing the Colony Road culvert data.

The first step consists using the LiDAR unit to scan the surrounding area and recreate the 3-D point clouds. The X, Y, and Z values of the points are relative to the position of the scanner. The position of the scanner would be the origin for each scan. To connect the scans together, a set of reference points is required that are common between the scans. For this study a set of spheres of .0725 meters in diameter were used as reference points. The reference spheres were placed around the bridge structure where they were along the line-of-sight of multiple scanning locations. The reference spheres would allow the scans to be connected together into one global coordinate system.

Several scans were conducted to record the original condition of the bridge which would be used as a comparison to the post-blast condition. The blasting was originally scheduled for late January, but had to be rescheduled for April. Several scans of the structure were subsequently taken after the blasting which was three months later. The plants around the bridge have since grown much higher and obscured much of the bridge, preventing the team from using the same sphere positions as in January. In addition, many of the rods that were set had gone missing or were damaged preventing an automatic alignment of pre-blast and post-blast scans through FARO Scene®. Hence, the following results are manually assembled and compared.

1.5.3.3 Point Cloud Alignment

The point cloud data was first aligned using FARO Scene®. One of the manipulation functions within FARO Scene® is the 'coordinate transformation.' Coordinate transformation may cause shift of all the data points in the X, Y, or Z directions by a specified distance. Coordinate transformation may also result in rotation of data points around the X, Y, and Z axes. By using the coordinate transformation functions, the post-blast set of scans were made to align closely with the coordinate system of the pre-blast scans. Figure 17 shows the original alignment of the bridges (bottom image) and the final result of the FARO Scene alignment (top image).

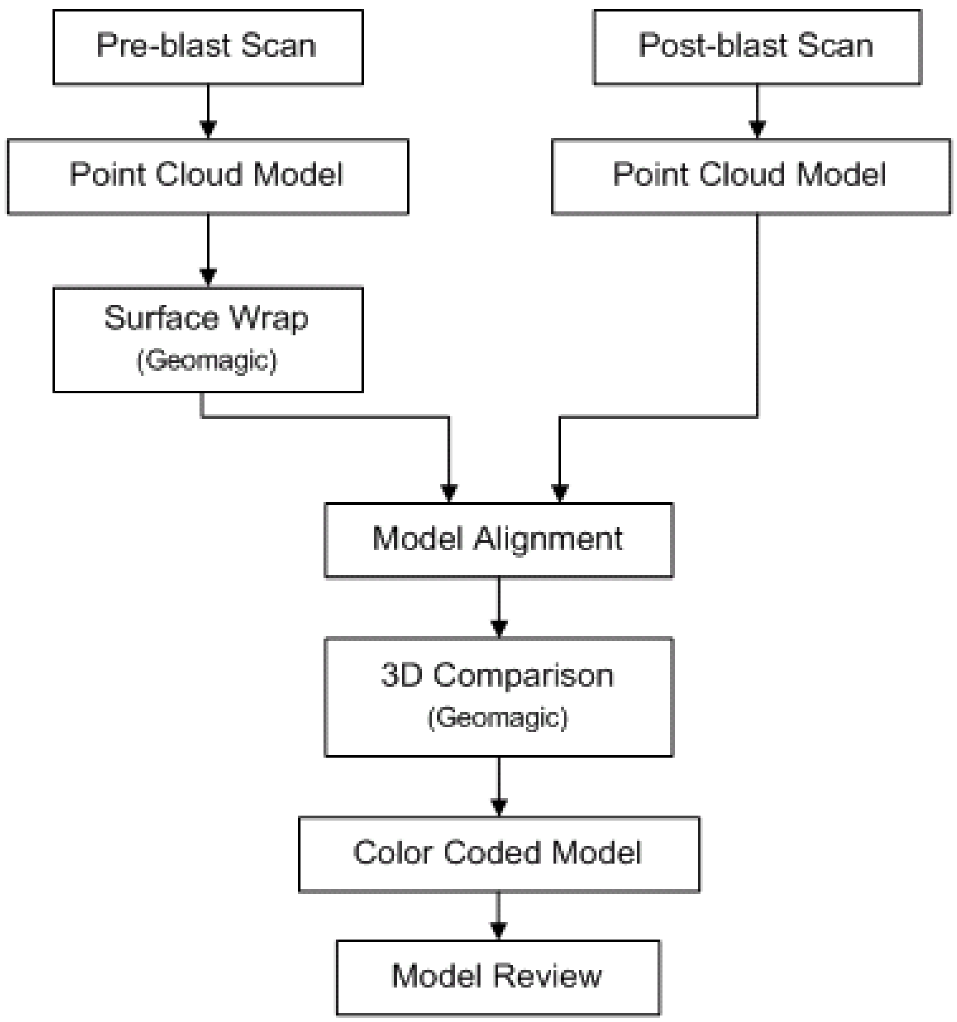
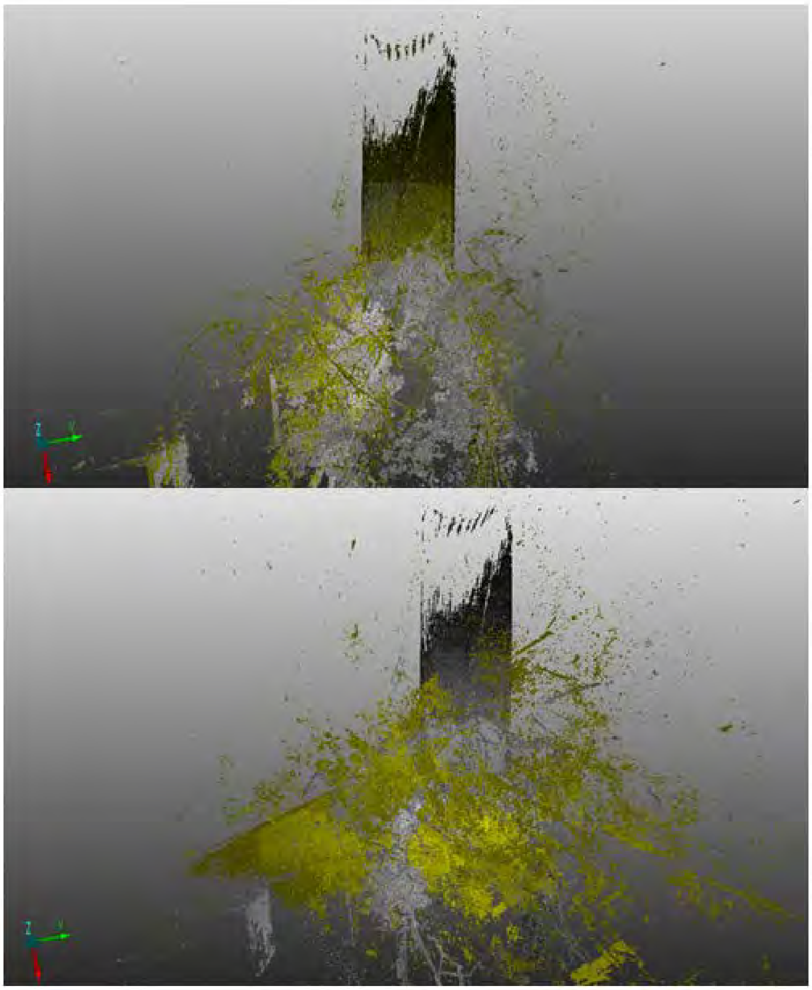


Figure 16 LiDAR data collection and comparison process.



Post-alignment

Pre-alignment

Figure 17 FARO Scene alignment of culvert tunnel scans (Top: post-alignment; Bottom: pre-alignment).

Once all the scans were manually aligned into the same coordinate system, the point cloud data sets were then used in Geomagic Studio 11® for anomaly quantification. The point cloud data were reduced to only the points describing the concrete culvert and the areas of the interior of the tunnel, which both scans were recorded. With the pre-blast data of the tunnel structure, a “surface wrap” was created. The “surface wrap” takes the point data and creates a three dimensional shape function made of triangles. The “surface wrap” represents the curvatures of the culvert and is used as a reference for comparison to the post-blast data set.

The pre-blast surface wrap was then compared to the post-blast point cloud using the 3D features in Geomagic Studio 11®. This process examines each point within the point cloud and finds the shortest distance to the surface wrap. Geomagic then outputs a 3D color map of displacement with the pre-blast bridge as a reference. This means damage to the bridge or movement in the post-blast scan would show as a positive or negative displacement relative to the same area on the pre-blast scan.

1.5.4 SUMMARY OF ANALYSIS

With the relatively light charge load, despite the close range of the blast to the culvert, the measured peak particle velocity at the culvert is higher than theoretical calculation. After reviewing the results of the terrestrial LiDAR scans, it was found that there were no significant changes to the structure of the bridge. Most measurements were well within the ±3.0 mm accuracy for a range distance of 25 m or less from the LiDAR scan (Liu 2010). Figure 18 shows the comparison of the LiDAR scans of the Colony Bridge tunnel pre-blasting and post-blasting.

Although small areas of the comparison result may show positive or negative displacements, this is expected as individual points may fall outside of the expected accuracy deviation. However, there is no general trend in the data to suggest that the structure has been moved or has been damaged by the blasting.

In order to ensure safety and structural stability, there is a need for techniques that can rapidly establish the pre-blast structural conditions, which can compare to the post-blast condition, in order to assess permanent effects resulted from the blasting. This paper with the recommended terrestrial 3D LiDAR technology demonstrated the technology maturity for such applications as post-blast impact study.

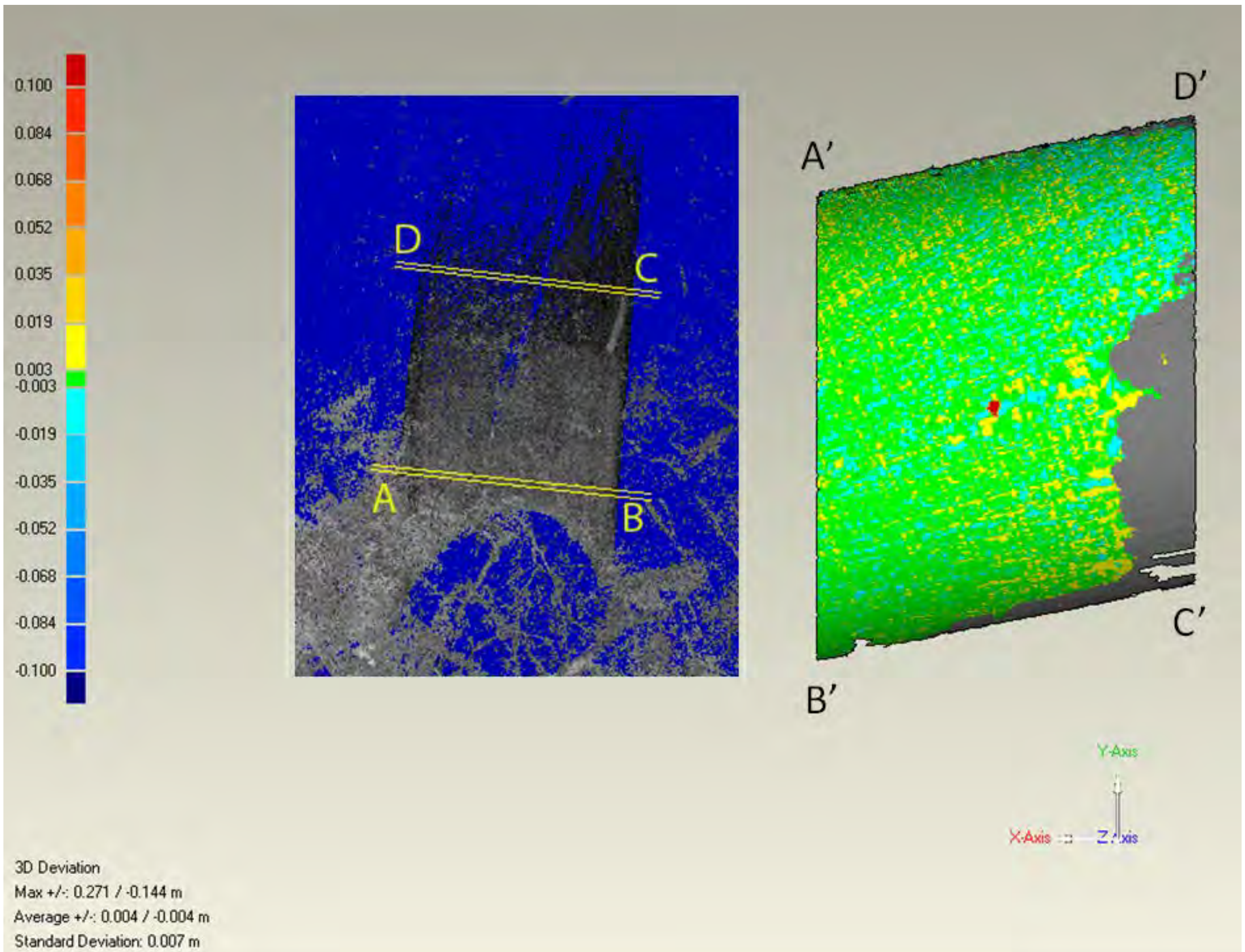


Figure 18 Three dimensional comparison of bridge culvert pre-blasting and post-blasting.

1.6 CONCLUSIONS

LiDAR has the potential to be used in many different applications, but there are several practical concerns when using this technology in the field. Several of these issues were explored during the course of the project and methods for overcoming those issues.

The first issue of using a ground unit LiDAR is determining where to position the scanner. In the case of the Harris Boulevard Bridge the focus was on determining the potential of LiDAR to be used as tool to measure minimum vertical underclearance or bridge behavior. The most important areas of study were the underside of the superstructure and the roadbed located beneath that bridge span. Because of the structure of the bridge and of live traffic during scanning it was not possible to capture one entire span and its end conditions from any given position.

After considering several different positions for the scanner it was decided to place the LiDAR unit in the center median. This position obscured the end conditions of the spans in the center of the bridge structure, but allowed for both spans of the bridge and roadbeds to be recorded in each scan. The decision of where to locate the LiDAR unit effectively allowed the researchers to record two separate data sets during each scan. Taking into account proper placement of LiDAR and what is in view of the LiDAR unit can save significant amounts of time. In any given project there may not be a single easily accessible position to record everything of interest, but careful consideration can allow for the best use of time and effort when using LiDAR technology. Another option that was not used in this project is to scan from multiple positions and create a common coordinate system for all scans to use. There are multiple software packages, including FARO Scene, that can transform coordinate systems to match a given reference.(FARO 2009)

A second issue considered during LiDAR scanning was the location of light sources. The FARO LiDAR unit in use for this project uses several wavelengths of infrared to determine distance by phase shift analysis.(FARO Technologies 2009) If there is a source of infrared that is shining into the LiDAR sensor then there will be very little data recovered from the scan. Figure 19 shows a scan where the LiDAR unit was not shaded from the sun and a similar scan shaded. This issue can be avoided by placing the LiDAR unit in a shaded area, blocking the infrared source, or restricting the scanner from scanning in the direction of the source. Another method is to avoid times where the sun will be in the background near the structure of interest. By taking these issues into consideration the effect of infrared sources can be minimized and the chances can be maximized for a high quality scan.

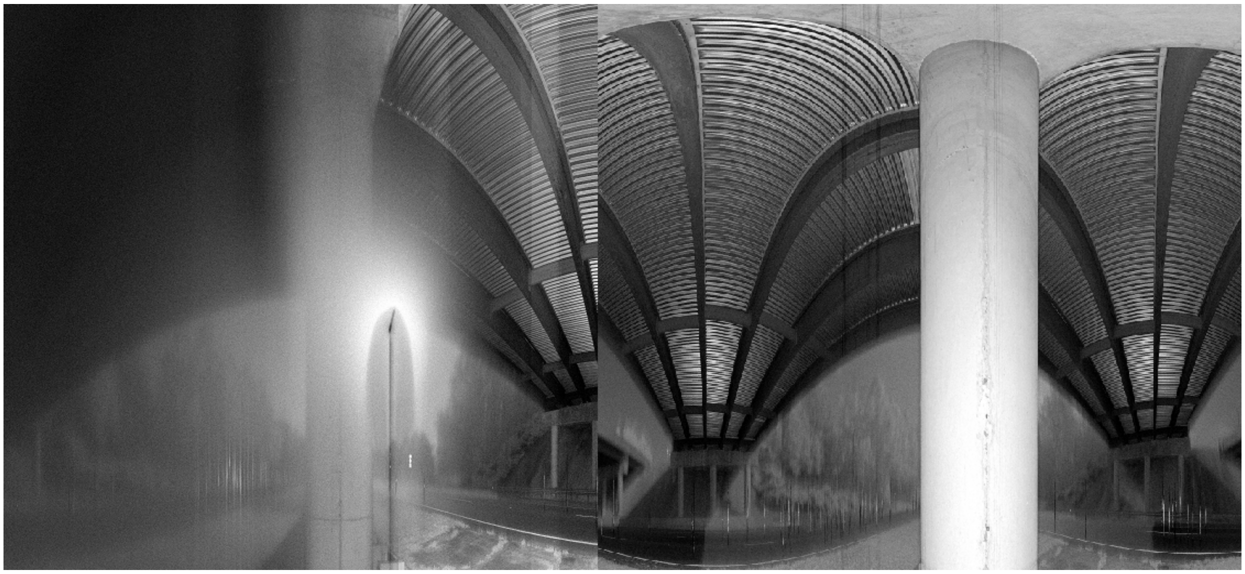


Figure 19 Effects of sunlight on LiDAR scans. The image on the left is a scan in bright sunlight and the image on the right is in the shade of the column.

Another issue that was dealt with in this project was the live traffic conditions of the lower roadbed. Taller vehicles like trucks or SUV's may be partially scanned as they drive by. This tended to be a minor issue because FARO Scene allows for ease of removal of these position points from the outputted XYZ files.(FARO 2009) If traffic were to go to a standstill this may prevent the LiDAR unit from scanning the bridge and roadbed due to vehicles blocking line-of-sight to critical scan areas. This condition can be avoided by allowing traffic to pass, choosing another location to place the scanner, or temporarily blocking traffic. LiDAR scans take very little time and including a full set-up and take down can take less than a half-hour. Furthermore, advances in LiBE software now allow for automatic removal of data points associated with vehicles or other objects.

The last major issue that was considered during this project was the material properties of the structure. Materials that reflect higher amounts of infrared will have a much higher number of recorded position data points than a material that absorbs that spectrum. The bridge girders and concrete spans reflected infrared very well, but the asphalt of the roadbed tended to absorb or not reflect back to the LiDAR unit. There are options to deal with this issue such as the LiDAR unit could be moved closer to the asphalt or the resolution of the scan can be increased to pick up more data points. For this project it was found that the LiDAR unit picked up enough points for analysis from the roadbed and that the unit didn't need to be moved.

The Colony Road culvert did not significantly move as a result of the close-range construction blasting and that no evidence of blast damage was found. The majority of the pre-blast and post-blast scans of the Colony Road Bridge were well within the accuracy of LiDAR measurement (±3.0 mm). Additionally, this result is enforced after a second site visit and inspection found the bridge suffered no visual damage due to blasting. Based on the data and results, this study validated the use of LiDAR as a method of examining structures, which can be a very robust tool for structural evaluation of complex structures.

1.7 RECOMMENDATIONS FOR FURTHER STUDY

At the start of this project there were many questions about how LiDAR could be utilized in practical field applications. One of these questions was if a combination of normal daily bridge traffic, environmental affects, and bridge characteristics could allow detection of bridge movement or for reliable use in underclearance measurements. In another case this project pushed the boundaries of LiDAR applications in structural evaluation after a blasting event. The area of structural evaluation is always advancing and new areas of study should be investigated in order to find other useful applications of LiDAR technology.

For future study, new LiDAR applications should be investigated to make use of the large point cloud data sets such as determining stress, strain, or large crack size distributions. LiDAR may also be used to determine the changes in a cliff face that is particularly susceptible to rock slides. Analysis of the changes could yield information on how the cliff face may behavior in the future. Another application to study would be to use LiDAR to analyze surfaces for how water will flow. By detecting how water may flow it could be possible to detect future erosion patterns or to determine the effectiveness of runoff designs on roads or structures.
Future research should also be done into analyzing the behavior of unique structures, such as structures with complex surfaces. New methods will be needed to describe surfaces that do not follow flat planes or simple curved surfaces.

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APPENDIX A. LIST OF ACRONYMS AND DEFINITIONS

AADT – Average Annual Daily Traffic
AASHTO - American Association of State Highway Transportation Officials
ACE – Army Corps of Engineers
ACI - American Concrete Institute
ADT – Average Daily Traffic
AISAA - Aerial Image Shape-file Automation and Analysis
AMBIS – Assisted Management Bridge Information System
AMPIS – Automated Management of Pavement Inspection System
ASCE – American Society of Civil Engineers
ASTM – American Society of Testing and Materials

BHI – Bridge Health Index
BHM – Bridge Health Monitoring
BMS - Bridge Management System (more accurately called a process)
BSCI – Bridge Surface Condition Index

CBA – Cost Benefit Analysis
CBR – Cost Benefit Ratio
CDOT – City of Charlotte Department of Transportation
CFID - Cognitive Fused Imaging of Damages

COTS – Commercial off the shelf Software
CR – Condition Rating
CRS – Commercial Remote Sensing
CRS-SI – Commercial Remote Sensing and Spatial Information
CTPS – Center for Transportation Policy Studies at UNCC
CoRe – Commonly Recognized Structural Elements

DBIR - Dual-Band Infrared Thermography
DEM – Digital Elevation Model
DI - Digital Imaging
DLF - Dynamic Load Factor

FEA – Finite Element Analysis
FEM - Finite Element Method
FHWA – Federal Highway Administration

GenOM – Generic Object Model
GIS – Geographical Information System
GPR – Ground Penetrating Radar
GPS - Geographical Positioning Satellite
GSM – Global System for Mobile communications
GVW – Gross Vehicle Weight (loaded total weight)

HBRRP – Highway Bridge Replacement and Rehabilitation Program
HPS – High Performance Steel
HTF – Highway Trust Fund

IDE – Integrated Development Environment
IF - Image Fusion
ImageCat – a private sector partner in the IRSV Project
IRSV – Integrated Remote Sensing and Visualization
IRV – Integrated Remote Views (for Infrastructure Monitoring)
ISTEA – Intermodal Surface Transportation Efficiency Act

LCCA – Life Cycle Cost Analysis
LiBE – LiDAR Bridge Evaluation
LaDAR – Laser Detection And Ranging
LiDAR – Light Distancing And Ranging
LOS – Level of Service

MR&R – Maintenance, Repair and Rehabilitation
MSVE – Microsoft Virtual Earth

NBI – National Bridge Inventory
NBIP – National Bridge Inventory Program
NBIS – National Bridge Inspection Standards
NCDOT – North Carolina Department of Transportation
NCRS-T - National Consortium for Remote Sensing in Transportation
NCSBEDC – North Carolina Small Business and Economic Development Center
NDE - Non-Destructive Evaluation
NDI – Non-Destructive Inspection
NDT – Non-Destructive Testing
NEVC – Nondestructive Evaluation Validation Center
NHS – National Highway System
NIST – National Institute for Standards and Technology
NPV – Net Present Value
NSTIFC – National Surface Transportation Infrastructure Financing Commission
OAM – Office of Asset Management, FHWA
Ontology - Synonym meaning Knowledge Modeling

PC – Prestressed Concrete
PCView – Parallel Coordinate View
PDI – Pavement Distress Index
PDO – Problem Domain Ontology
PMS – Pavement Management System
Point Cloud – A display of 3-D surface points in a laser scanned image

PONTIS – A “Bridgeware” software suite of programs developed through AASHTO that is used by many states as part of their Bridge Management System
RC – Reinforced Concrete
RITA – Research and Innovative Technology Administration

SAR – Synthetic Aperture Radar
SBRP – Special Bridge Replacement Program
SD/FO – Structurally Deficient and/or Functionally Obsolete
SDOF - Single-Degree-Of-Freedom
SFAP - Small Format Aerial Photography
SHM - Structural Health Monitoring
SI – Spatial Information
SIS – Software and Information Systems Department at UNC Charlotte
SMO – Semantic Matching Operation
SOA – Service Oriented Architecture
SPIE – an acronym identified as the International Society for Optics and Photonics
SPView – Scatter Plot View
SQL - Standard Query Language
STIP – State Transportation Improvement Program

TRB – Transportation Research Board, a part of the NAS/NAE
UNCC – University of North Carolina at Charlotte
USDOT – United States Department of Transportation
VBA - VBA program
VIS – Visualization
VisCenter – Charlotte Visualization Center at UNCC

APPENDIX B. NATIONAL DRILLING & BLASTING

Figure B. 1 National Drilling & Blasting --- Blasting Plan

National Drilling & Blasting

Blasting Plan

Compiled for Oscar Renda Contracting: Briar Creek

Date of Proposed Blast: Mid January 2010
Proposed Time: Unknown
Shot #1

HOLE & DRILL PATTERN

Drill Pattern: 5'x 6'
Number of Holes: 20 – 30
Location: Colony Road
Inclination: Vertical
Diameter of Bore Hole: 3.5 inches
Depth of Bore Hole: 30' Approx.

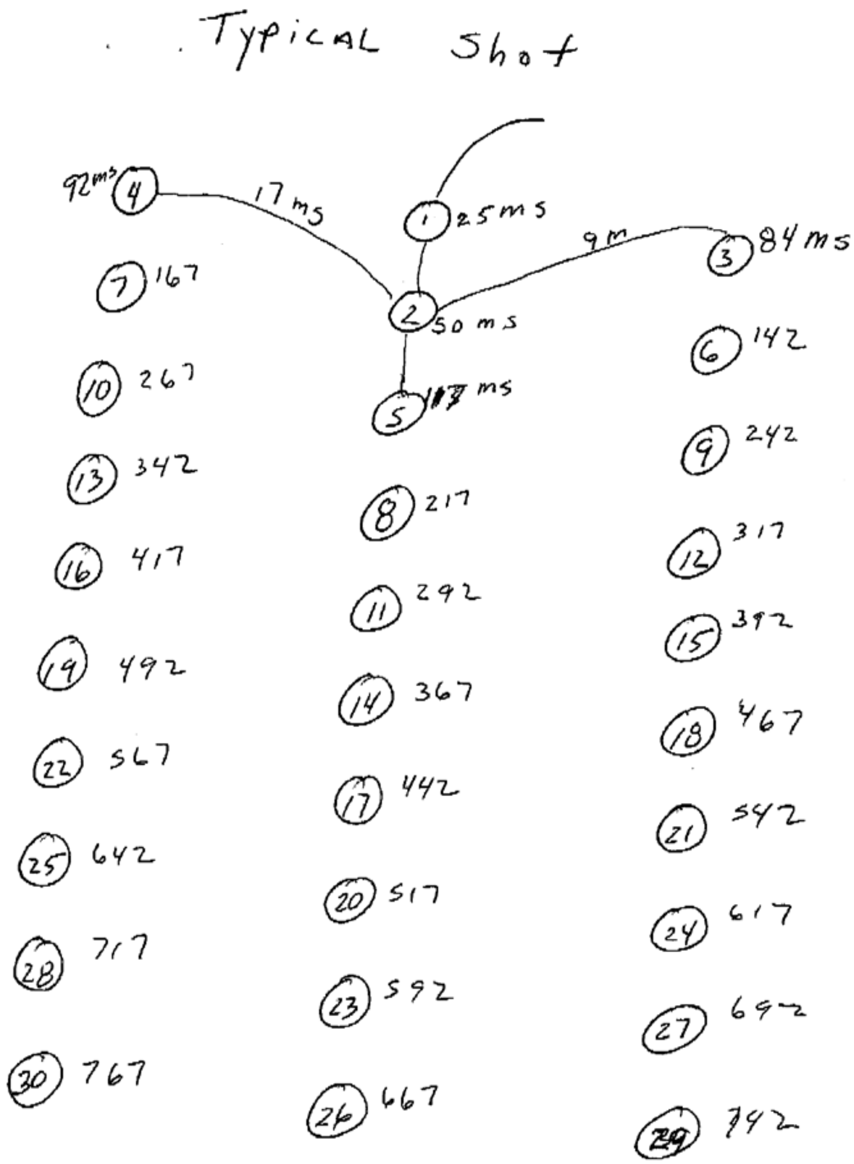
EXPLOSIVE INFORMATION

Total Amount of Explosives: 825 Pounds
Type of Explosives: 2x16 Dynamite – 60% Dyno-Nobel – 2.2 lbs per Stick
2 ½ x16 Unimax Blasting Agent – 3.3 lbs per Stick

Distribution of Explosives per Hole: 27.5 lbs per Hole
Powder Factor: 2.47 lbs per Yard
Time Delays: 9, 17, & 25 ms
Max Pounds per Delay: 27.5 Pounds
Sequence of Firing: In order starting with Hole #1 through #30

Depth of Overburden: +/- 12'
Length of Stemming: 17 – 18'

Figure B. 2 Typical Shot



APPENDIX C. SEISMOGRAPHY DATA

Figure C. 1 Seismograph – Report 1

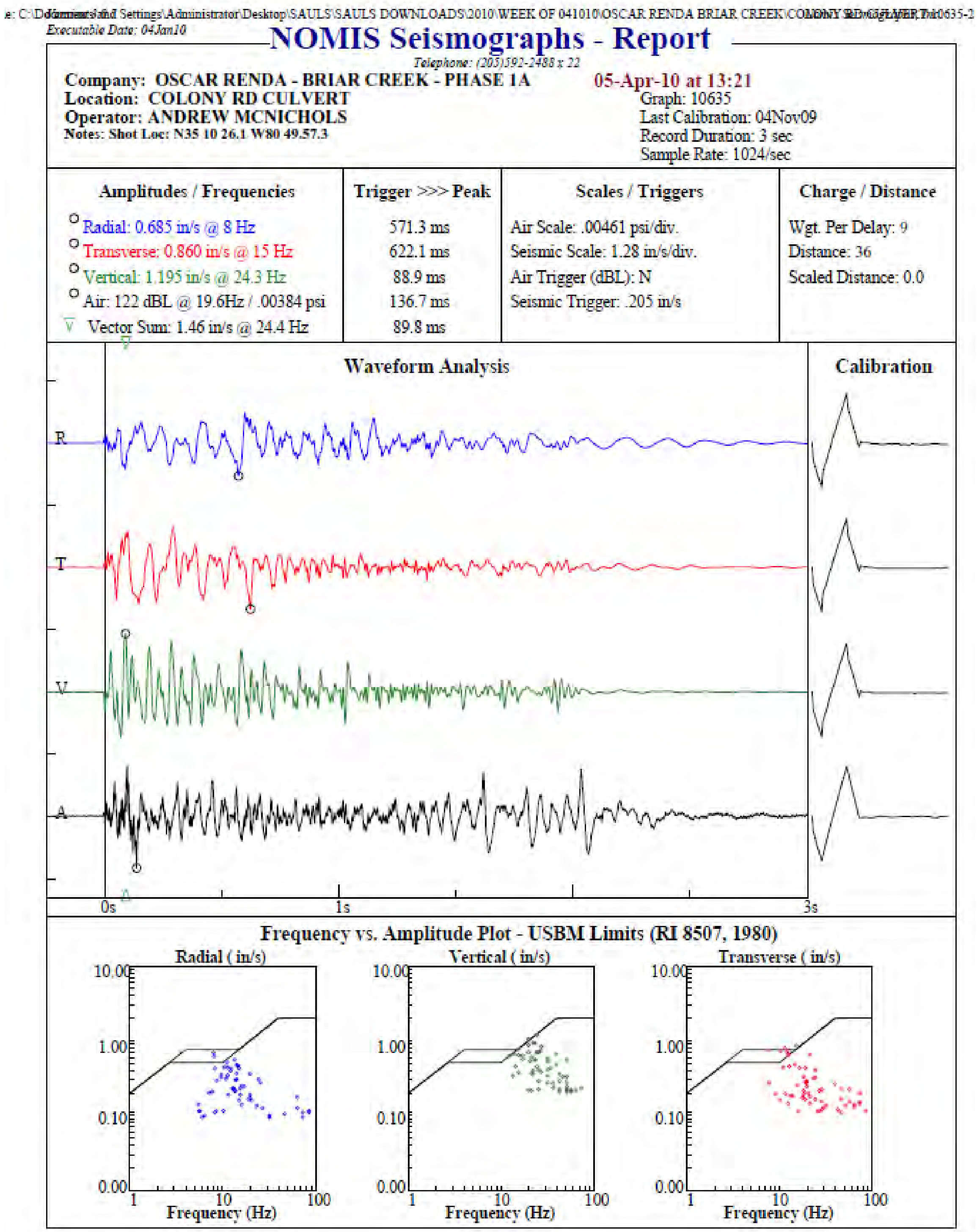
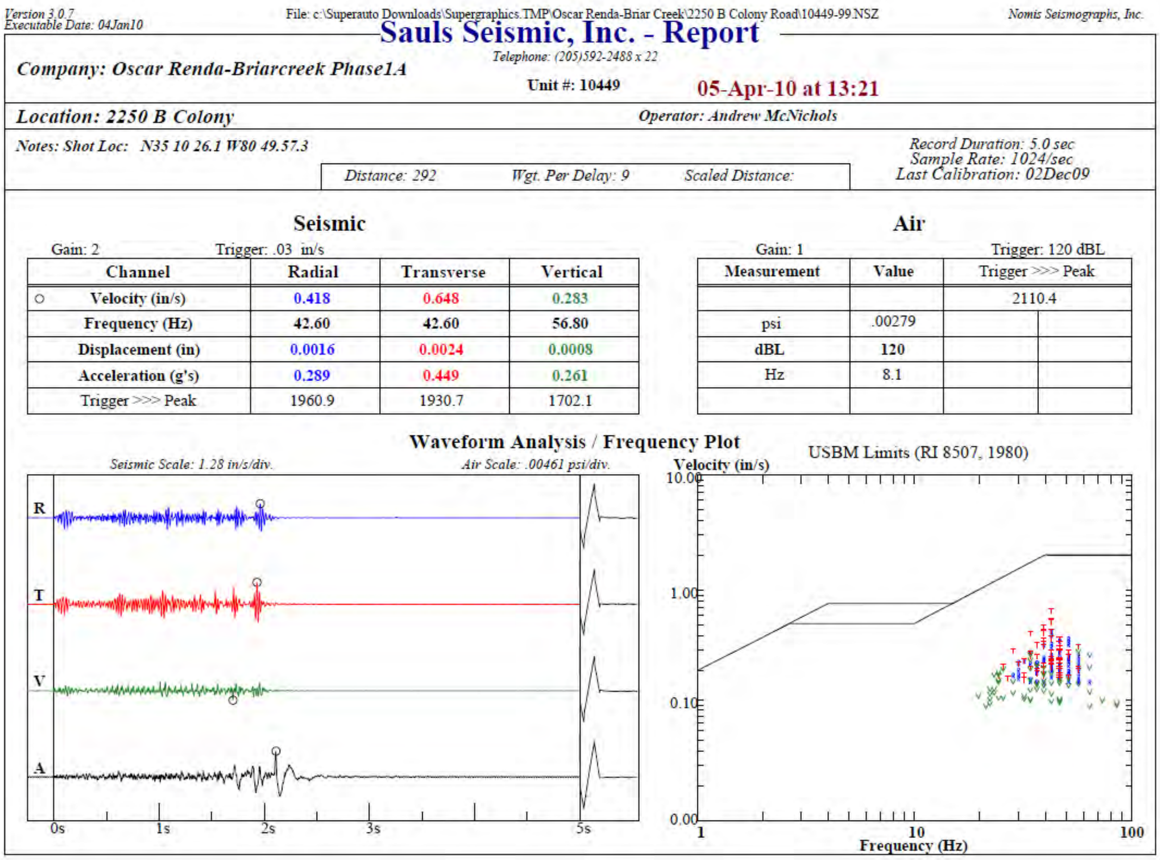


Figure C. 2 Seismograph – Report 2



Version 3.0.7
Executable Date: 04Jan10

File: c:\Superauto Downloads\Supergraphics.TMP\Oscar Renda-Briar Creek\2250 B Colony Road\10449-99.NSZ

Nomis Seismographs, Inc.

Sauls Seismic, Inc. - Report

Telephone: (205)592-2488 x 22

Company: Oscar Renda-Briarcreek Phase1A

Unit #: 10449

05-Apr-10 at 13:21

Location: 2250 B Colony

Operator: Andrew McNichols

Notes: Shot Loc: N35 10 26.1 W80 49.57.3

Record Duration: 5.0 sec
Sample Rate: 1024/sec
Last Calibration: 02Dec09

Distance: 292 *Wgt. Per Delay: 9* *Scaled Distance:*

Seismic

Gain: 2 Trigger: .03 in/s

Channel	Radial	Transverse	Vertical
○ Velocity (in/s)	0.418	0.648	0.283
Frequency (Hz)	42.60	42.60	56.80
Displacement (in)	0.0016	0.0024	0.0008
Acceleration (g's)	0.289	0.449	0.261
Trigger >>> Peak	1960.9	1930.7	1702.1

Air

Gain: 1 Trigger: 120 dBL

Measurement	Value	Trigger >>> Peak	
		2110.4	
psi	.00279		
dBL	120		
Hz	8.1		

Waveform Analysis / Frequency Plot

Figure C. 3 Seismograph – Report 3

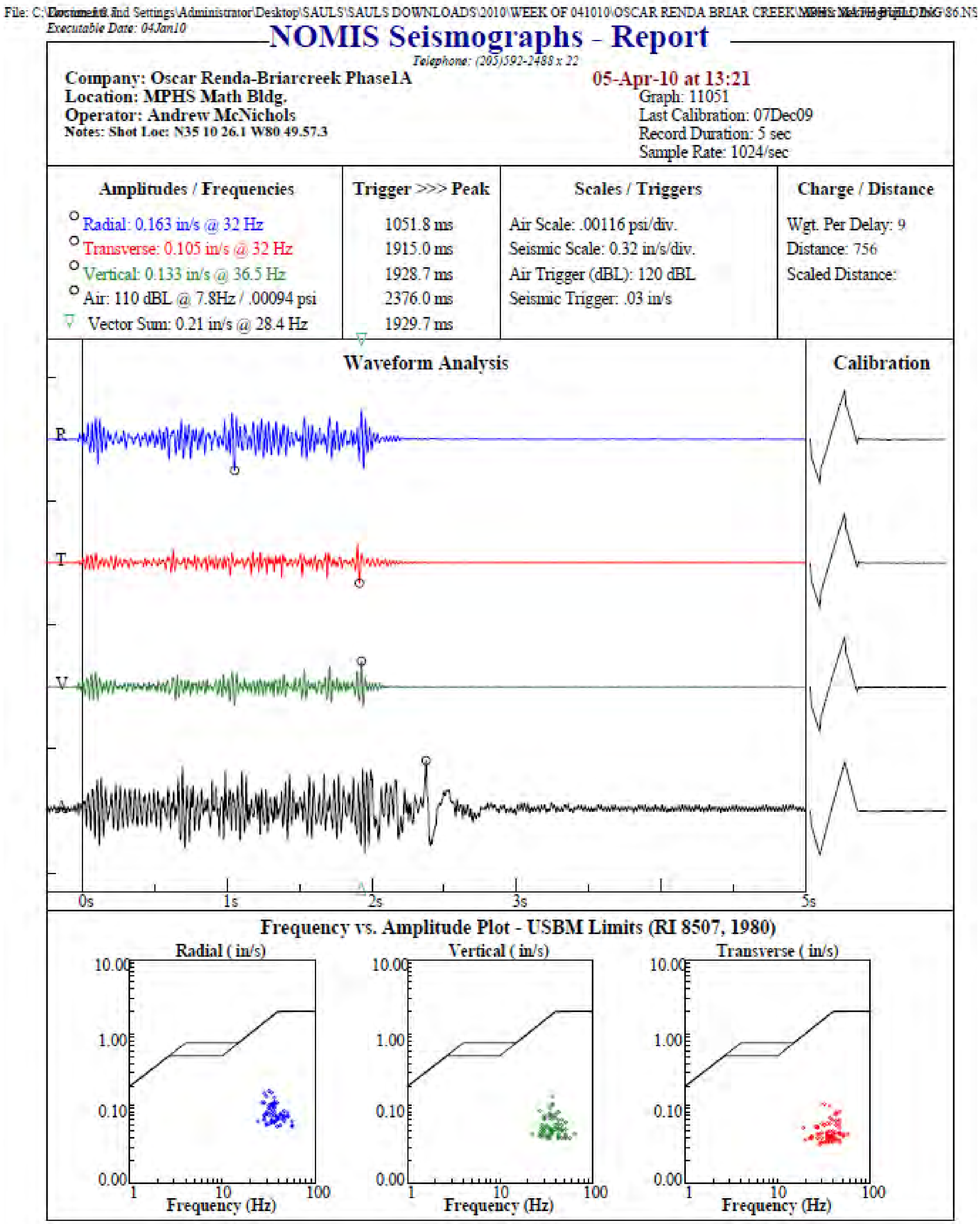


Figure C. 4 Seismograph – Report 4

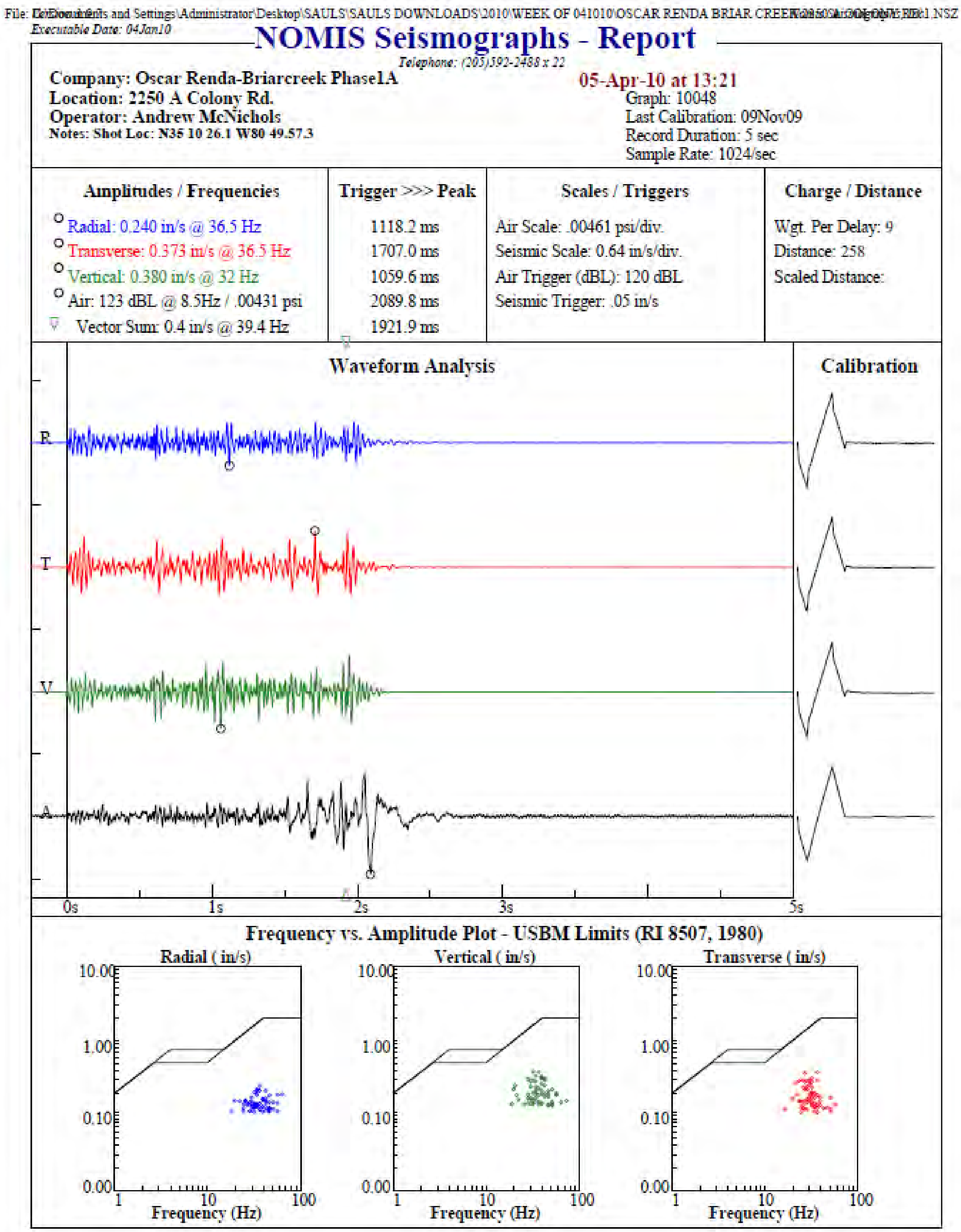


Figure C. 5 Event Report 1

Instantel

Event Report

Date/Time	Vert at 13:18:37 April 5, 2010	**Serial Number**	BE7790 V 8.12-8.0 MiniMate Plus
Trigger Source	Geo: 0.0300 in/s	**Battery Level**	6.3 Volts
Range	Geo :10.00 in/s	**Calibration**	March 27, 2009 by Instantel Inc.
Record Time	5.0 sec at 1024 sps	**File Name**	I790D6KC.Z10

Notes

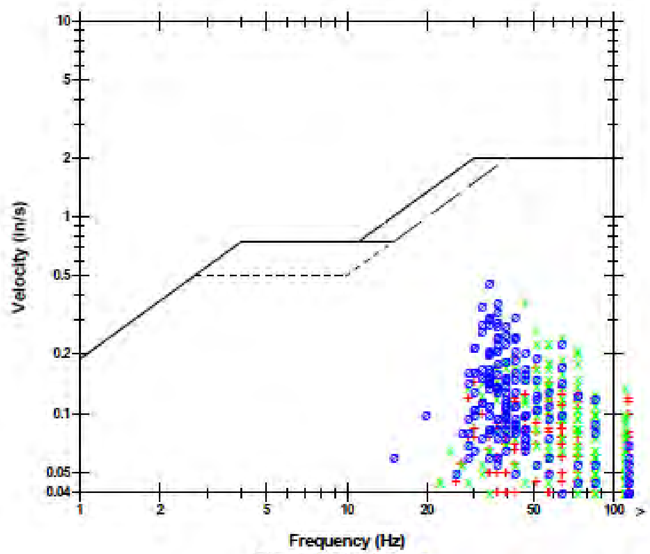
Post Event Notes
Location: 2757 Picardy
Blast: Colony Road Crossing

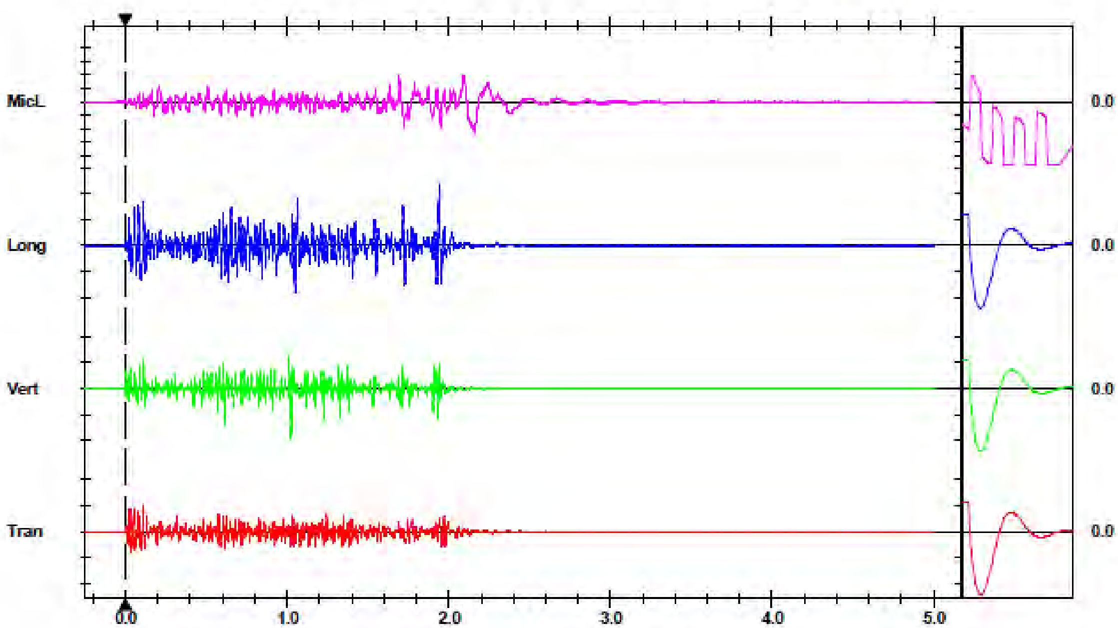
Microphone	Linear Weighting
PSPL	117.8 dB(L) at 2.157 sec
ZC Freq	7.0 Hz
Channel Test	Passed (Freq = 20.5 Hz Amp = 689 mv)

	Tran	Vert	Long	
PPV	0.195	0.375	0.470	in/s
ZC Freq	43	47	34	Hz
Time (Rel. to Trig)	0.106	1.024	1.941	sec
Peak Acceleration	0.252	0.265	0.265	g
Peak Displacement	0.00071	0.00110	0.00204	in
Sensorcheck	Passed	Passed	Passed	
Frequency	7.5	7.4	7.5	Hz
Overswing Ratio	3.3	3.4	3.8	

Peak Vector Sum 0.510 in/s at 1.940 sec

USBM RI8507 And OSMRE





Time Scale: 0.20 sec/div **Amplitude Scale:** Geo: 0.200 in/s/div Mic: 0.00100 psi(L)/div
Trigger = ▶—— ——◀

Sensorcheck

Printed: April 6, 2010 (V 8.12 - 8.12)

Figure C. 6 Event Report 2

Instantel

Event Report

Date/Time	Vert at 13:18:38 April 5, 2010	**Serial Number**	BE7412 V 8.12-8.0 MiniMate Plus
Trigger Source	Geo: 0.0300 in/s	**Battery Level**	6.3 Volts
Range	Geo :10.00 in/s	**Calibration**	March 27, 2009 by Instantel Inc.
Record Time	5.0 sec at 1024 sps	**File Name**	I412D6KC.Z20

Notes

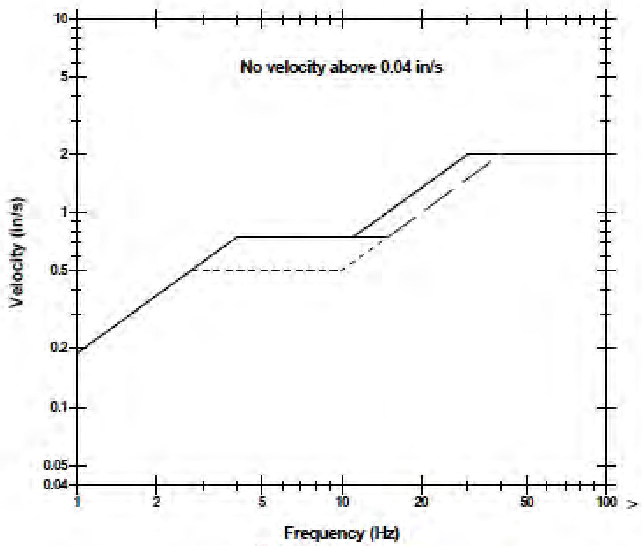
Post Event Notes
Location: 2645 Normandy
Blast: Colony Road Crossing

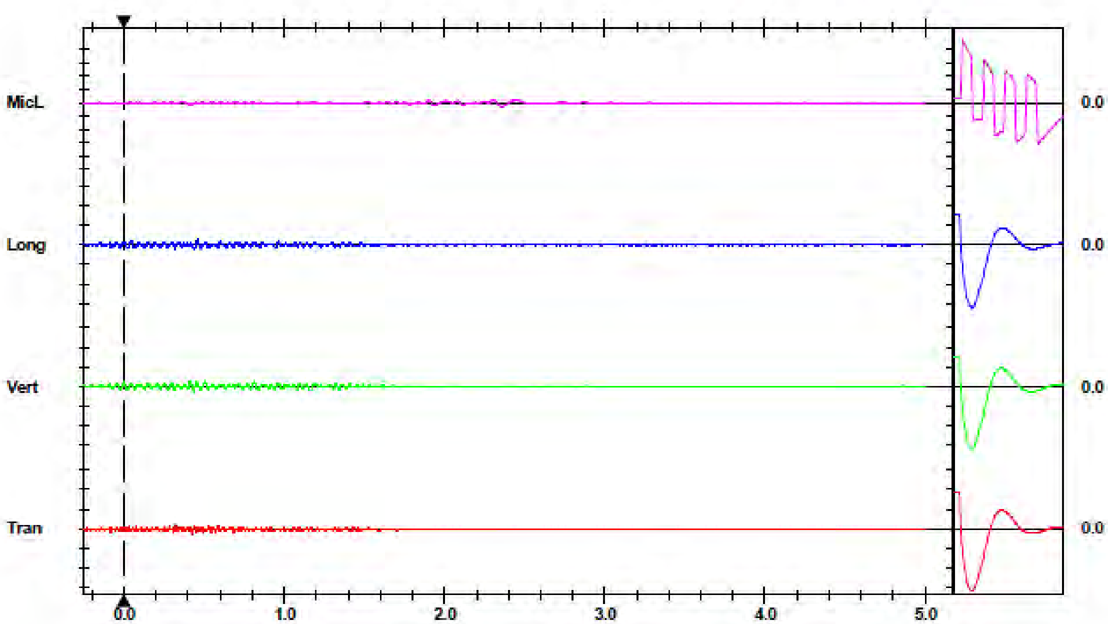
Microphone	Linear Weighting
PSPL	101.9 dB(L) at 2.352 sec
ZC Freq	7.4 Hz
Channel Test	Passed (Freq = 20.5 Hz Amp = 640 mv)

	Tran	Vert	Long	
PPV	0.0300	0.0300	0.0250	in/s
ZC Freq	39	34	47	Hz
Time (Rel. to Trig)	0.423	0.000	0.317	sec
Peak Acceleration	0.0265	0.0133	0.0265	g
Peak Displacement	0.00012	0.00017	0.00016	in
Sensorcheck	Passed	Passed	Passed	
Frequency	7.5	7.6	7.3	Hz
Overswing Ratio	3.5	3.4	3.7	

Peak Vector Sum 0.0367 in/s at 0.437 sec

USBM RI8507 And OSMRE





Time Scale: 0.20 sec/div **Amplitude Scale:** Geo: 0.100 in/s/div Mic: 0.00100 psi(L)/div
Trigger = ▶—— ——◀

Sensorcheck

Printed: April 6, 2010 (V 8.12 - 8.12)