The University of Memphis

Hernando Desoto I-40 Bridge Seismic Instrumentation Upgrade

Submitted To:

Tennessee Department of Transportation
Research Development and Technology Program

by

Shahram Pezeshk, Ph.D., P.E.
Department of Civil Engineering
The University of Memphis
spezeshk@memphis.edu

Mitch Withers, Ph.D.
Jim Bollwerk
Chris McGoldrick
Greg Steiner
Center for Earthquake Research and Information
The University of Memphis

Mathew Yarnold, Ph.D.
Tennessee Tech

Agency Tracking # 40100-16216
Edison ID – 47832
Project MSA #: RES2016-26

Technical Report Documentation Page

1. Report No. RES2016-26	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Hernando Desoto I-40 Bridge Seismic Instrumentation Upgrade	5. Report Date May 5, 2018
	6. Performing Organization Code
7. Author(s) S. Pezeshk, M. Withers, Jim Bollwerk, R. McGoldrick, G. Steiner, and Mathew Yarnold	8. Performing Organization Report No.
9. Performing Organization Name and Address The University of Memphis Department of Civil Engineering Memphis, TN 38152	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. RES2016-26
12. Sponsoring Agency Name and Address Tennessee Department of Transportation Long Range Planning Division Suite 900, James K. Polk Building Nashville, TN 37243-0334	13. Type of Report and Period Covered
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Over the past several years, The Hernando Desoto Bridge carrying I-40 across the Mississippi river at Memphis has been the scene of an intensive strong motion monitoring project, involving the installation of numerous traditional and several non-traditional forms of instrumentation designed to characterize the response of the structure to shaking from seismic and induced sources. This bridge has been retrofitted to withstand a magnitude (m_b) 7 event at 65 km distance from the site at a depth of 20 km. The goal of the retrofit was to have this bridge fully operational following the maximum probable earthquake (2500-year return period).

In 2001, we had installed 114 sensors on the I-40 Hernando Desoto Mississippi River Bridge in Memphis, Tennessee to fully characterize the response of the bridge to strong ground motion. These original sensors had internal bearings that wore over time especially in the high vibrational environment of the I-40 bridge. Additionally, upgrade of the data acquisition systems in 2012 allowed real-time continuous data transfer to a data concentrator node at the AutoZone Headquarters building in downtown Memphis except that bandwidth was limited by the telemetry. The objective of this project was to replace the existing sensors with a higher quality, industry standard accelerometers. High quality static-based sensors were also purchased and installed. Additional sensors were added to monitor the ground motion at the foundation level located approximately 95 ft below the bottom of the existing riverbed and about 130 ft below the high-water level.

17. Key Words **Strong motion instrumentation**	18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Conference Publications

- Title: ***Structural Health Monitoring of the Hernando Desoto Bridge***
- Authors: Matthew Yarnold, Justin Alexander, and Timothy Huff

- International Conference on SHM of Intelligent Infrastructure
- Title: ***Evaluation and Monitoring of Friction-Pendulum Isolation Bearings***
- Authors: Matthew Yarnold and Justin Alexander

DISCLAIMER

This research was funded through the State Research and Planning (SPR) Program by the Tennessee Department of Transportation and the Federal Highway Administration under Research Project Title: “Hernando Desoto I-40 Bridge Seismic Instrumentation Upgrade,” RES# RES2016-26.

This document is disseminated under the sponsorship of the Tennessee Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Tennessee and the United States Government assume no liability of its contents or use thereof.

The contents of this report reflect the views of the author(s) who are solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Tennessee Department of Transportation or the United States Department of Transportation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Over the past several years, The Hernando Desoto Bridge carrying I-40 across the Mississippi river at Memphis has been the scene of an intensive strong motion monitoring project, involving the installation of numerous traditional and several non-traditional forms of instrumentation designed to characterize the response of the structure to shaking from seismic and induced sources. This bridge has been retrofitted to withstand a magnitude (mb) 7 event at 65 km distance from the site at a depth of 20 km. The goal of the retrofit was to have this bridge fully operational following the maximum probable earthquake (2500-year return period).

In 2001, we had installed 114 sensors on the I-40 Hernando Desoto Mississippi River Bridge in Memphis, Tennessee to fully characterize the response of the bridge to strong ground motion. These original sensors had internal bearings that wore over time especially in the high vibrational environment of the I-40 bridge. Additionally, upgrade of the data acquisition systems in 2012 allowed real-time continuous data transfer to a data concentrator node at the AutoZone Headquarters building in downtown Memphis except that bandwidth was limited by the telemetry.

The objective of this project was to replace the existing sensors with a higher quality, industry standard accelerometers. High quality static-based sensors were also purchased and installed. Additional sensors were added to monitor the ground motion at the foundation level located approximately 95 ft below the bottom of the existing riverbed and about 130 ft below the high-water level.

CHAPTER 1.

BACKGROUND

Memphis and Shelby County, Tennessee, are located geographically close to the southwestern segment of the New Madrid seismic zone (NMSZ), which is regarded by seismologists, engineers, and public officials as the most hazardous seismic zone in the Eastern United States. Thus, Memphis and Shelby County are potentially exposed to significant seismic hazards. A large earthquake occurring anywhere within the NMSZ could cause widespread loss of life with damage to buildings, bridges, and lifelines due to ground shaking and ground failure induced by the earthquake.

Over the past decade, the Hernando Desoto Bridge carrying I-40 across the Mississippi river at Memphis has been the scene of an intensive strong motion monitoring project, involving the installation of numerous traditional and several non-traditional forms of instrumentation designed to characterize the response of the structure to shaking from tectonic and induced sources. This bridge has been retrofitted to withstand a magnitude (m_b) 7 event at 65 km distance from the site at a depth of 20 km. The goal of the retrofit was to have this bridge fully operational following the maximum probable earthquake (2500-year return period).

Currently, in the United States and elsewhere in the world, there are very little data available on the response of long-span bridges during seismic events. Since such data are scarce, our ability to understand the behavior of such structures and to verify dynamic analyses performed on such structures during design/analyses/retrofit phases is limited. Therefore, data collected from instrumentation of the I-40 bridge in Memphis will be an invaluable asset in evaluating the structure. The data will be used to assess the performance of the bridge following the retrofit and in particular for the assessment of the performance of the base-isolation system. In addition, data collected on the behavior of the base-isolation system will be applicable to any structure incorporating the system. Furthermore, lessons learned from instrumentation of a bridge such as the I-40 bridge will provide important and needed information that will be applicable to structures built on similar seismological and geological settings as the I-40 bridge.

1.1 INSTRUMENTATION

In 2001, we had installed 114 sensors on the I-40 Hernando Desoto Mississippi River Bridge in Memphis, Tennessee to fully characterize the response of the bridge to strong ground motion. The sensors used had internal bearings that wore over time especially in the high vibrational environment of the I-40 bridge. Additionally, upgrade of the data acquisition systems in 2012 allowed real-time continuous data transfer to a data concentrator node at the AutoZone Headquarters building in downtown Memphis except that bandwidth was limited by the telemetry. The objective of this project was to replace the existing sensors with a higher quality and industry standard accelerometers. High quality static-based sensors were also purchased and installed. Additional sensors were added to monitor the ground motion at the foundation level located approximately 95 ft below the bottom of the existing riverbed and about 130 ft below the high-water level.

The location of the I-40 bridge is shown in Figure 1. Figure 2 and Figure 3 show the main two-span tied arch bridge and the Arkansas-side approach spans, respectively. The general location and sensing directions for sensors on the main span are marked in Figure 2. Figure 3 shows the general location and sensing direction for sensors on the approach spans.

The information to be measured from the sensors includes:

(1) free-field ground motion near the instrumented bridge,
(2) motion of the bridge foundation,
(3) site response,
(4) motion of the bridge below the isolation bearings,
(5) motion of the bridge above the isolation bearings,
(6) the spatial variation of ground motion along the total span; and
(7) lateral and torsional motion of the bridge.

Figure 4 illustrates a detailed drawing of the I-40 bridge data and power cabling.

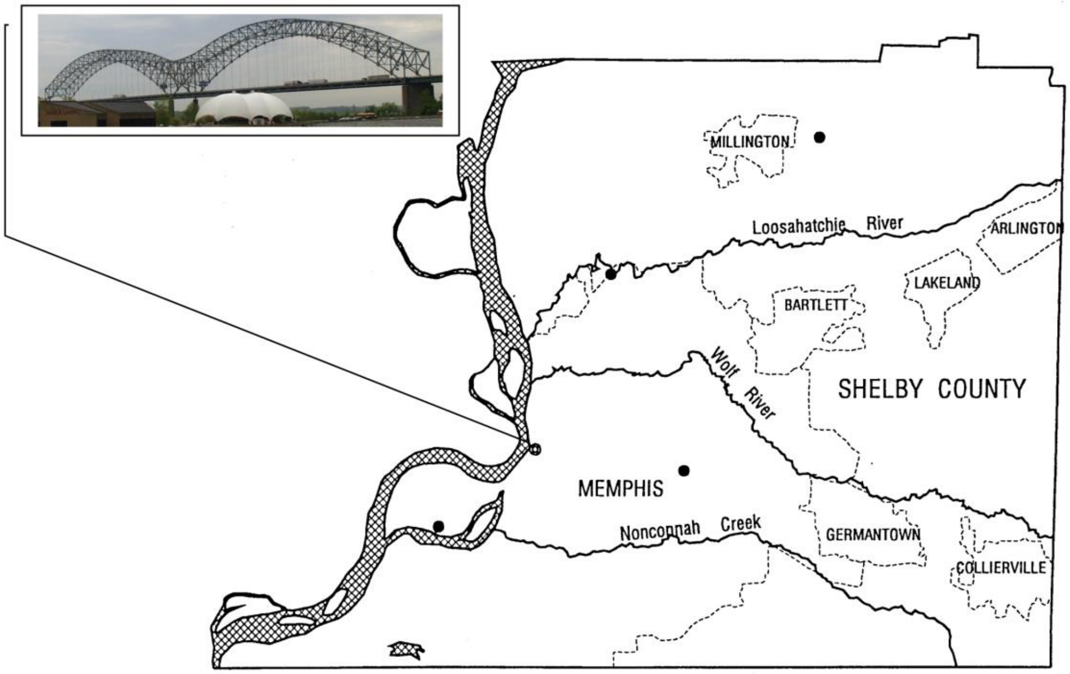


Figure 1. Location of the I-40 Hernando Desoto Mississippi river bridge.

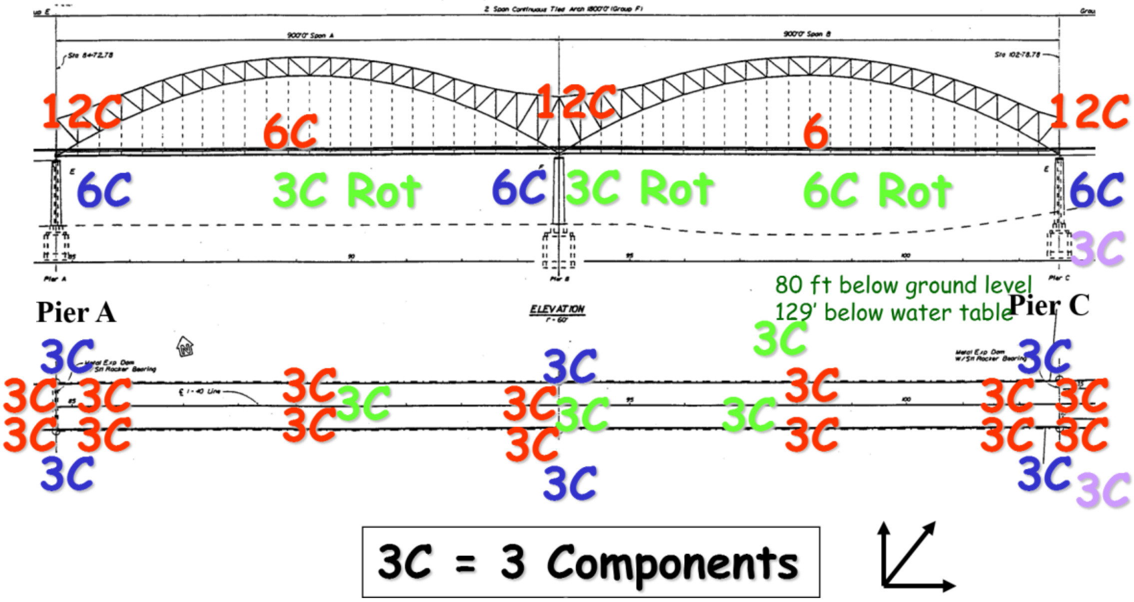


Figure 2. Main two span tied arch of the I-40 bridge and sensor locations.

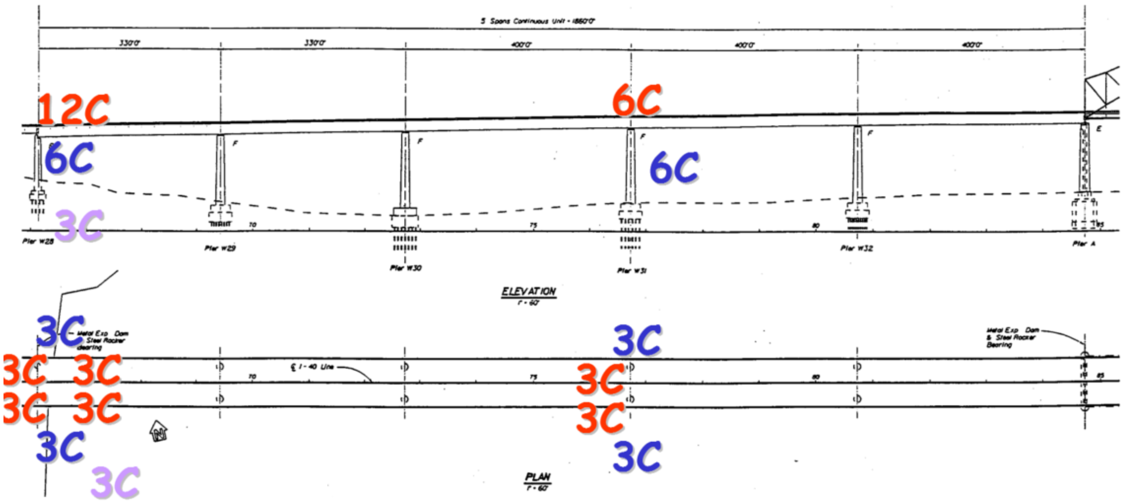


Figure 3. West approach to the I-40 bridge and sensor locations.

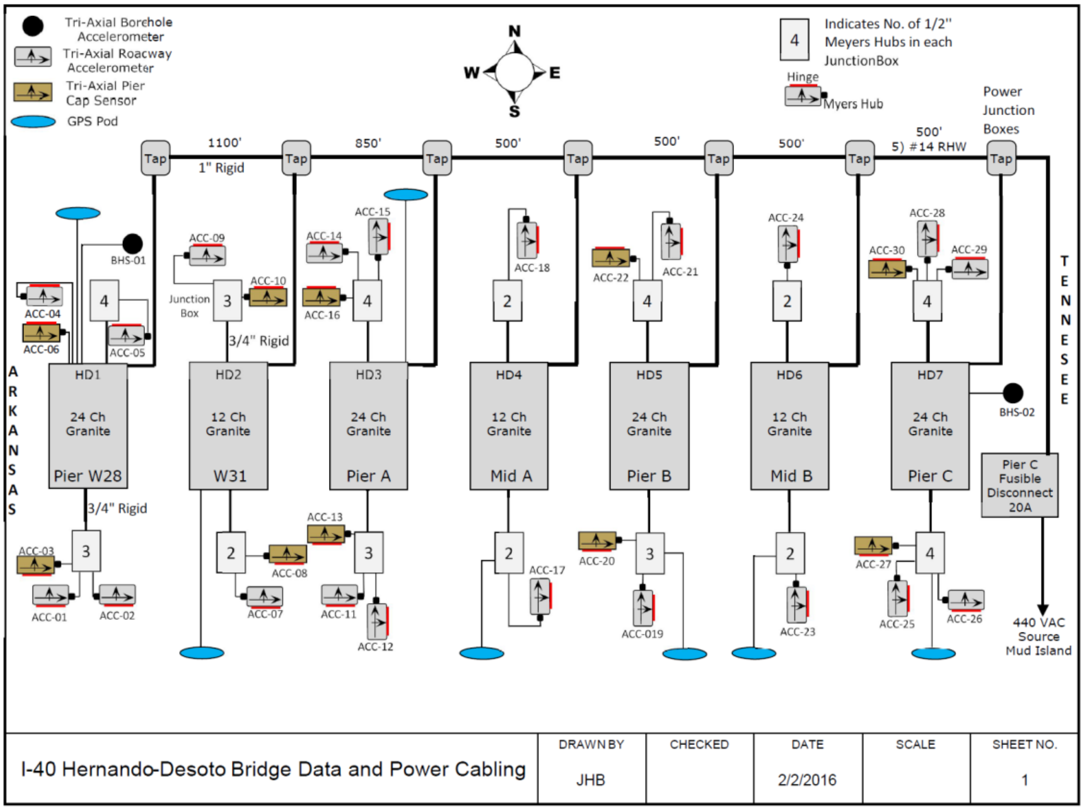


Figure 4. Bridge cabling schematics.

1.1.1 Measurement of Free-Field Motion

The free-field ground motion is the basic required information for a seismic response analysis of the bridge. It can be measured by a triaxial accelerometer located in Mud Island near the main span of the bridge (see Figure 5). These sensors record the ground motion in two horizontal directions and in the vertical direction. Placing free-field sensors on Mud Island will help avoid the effect of structural response (soil-structure interaction) on the recorded ground motion; thus, the free-field sensors should not be placed too close to the instrumented bridge. The other set of free-field senors are located at the weigh-station near on the Arkansas side of the bridge.

Figure 5. Free-field sensor locations. Note that this photo was taken during the May, 2011 flood. On May 10, 2011 the Mississippi river crested in Memphis at 47.8 feet above flood stage. Normally the weigh station is about a mile west of the unflooded river bank.

1.1.2 Measurement of Bridge Foundation Motion

The motion at the bridge foundation can be measured by two downhole triaxial sensors placed in the boreholes in the footings at either end of the monitored section of the bridge. These sensors record ground motion at the foundation level in two horizontal directions and the vertical direction. An estimate of the soil-structure interaction effect may be obtained by comparing the motion recorded at the bridge foundation to that in the free field. In addition, in the event of an earthquake, we can use the data collected by the downhole and free field sensors to determine the soil amplification effects at the bridge site.

Figure 6 shows the location of the downhole sensor at Pier C. Figure 7 shows the location of the piping and conduits for the downhole instruments at Pier C and the location of downhole systems at 100 ft and 200 ft below grade (the downhole sensors on Mud Island are currently inoperable pending funding for instrument replacement). Figure 8 shows the location of the downhole sensor at Pier 28. Figure 9 shows the installation of the downhole sensor.

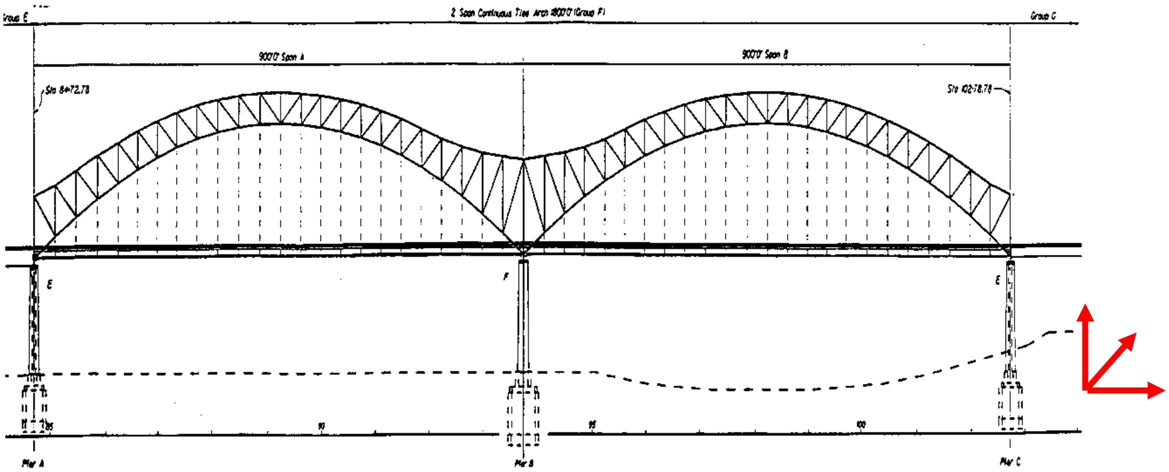


Figure 6. Existing downhole sensor location at Pier C.

Figure 7. The location where the piping and of the downhole instruments at Pier C and the location of the downhole systems at 100 ft and 200 ft below grade. The sensors at 100 and 200 ft below grade were part of a separate activity and are currently inoperable pending funding to replace the instruments.

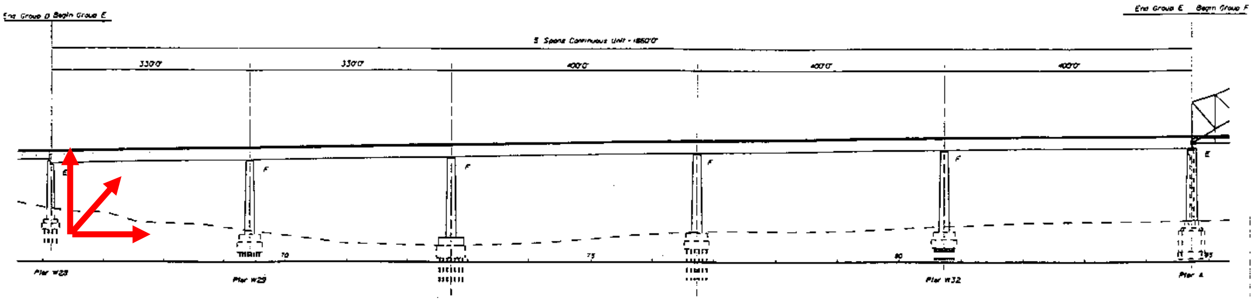


Figure 8. Sensor location at Pier 28.

Figure 9. Sensor installation.

1.1.3 Measurement of Bridge Motion

The bridge motion is measured by sensors in transverse, longitudinal, and vertical directions as shown in Figure 2 and Figure 3. These sensors record the motion at bridge piers above and below their isolation bearings and at the mid-spans of the main span. These sensors measure the transverse, longitudinal, and vertical motions of the approach spans. Data recorded by these sensors, can be used to establish the dynamic characteristics of the bridge, such as vibrational mode shapes, structural periods, and main span deflections in the longitudinal, the transverse, and the vertical direction. The torsional response can be estimated from the motion recorded by pairs of sensors on opposite sides of the bridge deck. The effect of base-isolation is estimated by comparing the motion recorded above and below the isolation bearings.

1.2 OBJECTIVE

The objectives of the project were to:

1. Replace the existing sensors with a higher quality and industry standard accelerometers.
2. The new instrumentation will enable the measurement of bridge movements during ground shaking for mild events which occur frequently and this data may be used to calibrate models for expected large magnitude earthquakes to better understand and define the effects of the deep soil deposits of the Mississippi embayment upon bedrock ground motions.
3. Supplement the dynamic data with static displacement, strain, and tilt angle measurements

1.3 SCOPE

The scope of this work included:

1. Replacement of accelerometers,
2. Replacement of the Microsoft Windows PC with a rack mount Linux server,
3. Upgrade of the power infrastructure and surge suppression to be compatible with the new instrumentation,
4. Work with United States Geological Survey (USGS) in data collection and dissemination of data to general public, and
5. Installation of a static based monitoring system.

CHAPTER 2. UPGRADING AND REPLACING ACCELEROMETERS

We purchased the sensor decks from Kinemetrics along with one shallow borehole Episensor package. The sensor decks were installed in the weatherproof enclosures and the electronics interface card was installed in each package (Figure 10 and Figure 11). All of the sensors were mechanically centered and then electronically calibrated using static tilt acceleration tests (Figure 12). They were then installed on the bridge and all are currently operational.

Figure 10. *Episensor packages deployed on the bridge.*

Figure 11. *Inside of the Episensor package enclosure.*

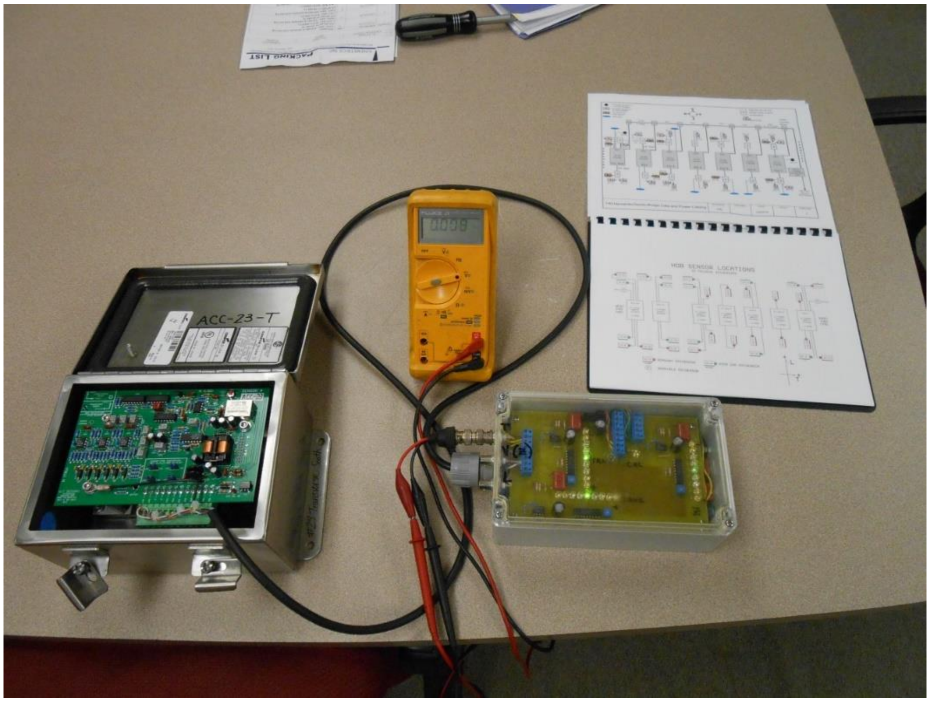


Figure 12. *Inside of the Episensor package enclosure checked through a mechanical centering and then an electronic calibration using static tilt acceleration tests.*

The borehole sensor and its interface/ transient suppression card were tested and calibrated as a unit. Centering spiders and an orientation yoke were added to the borehole sensor.

A second borehole sensor was received from the USGS. This sensor was found to have too short of a cable (80 ft). Kinemetrics provided a 50 ft length of shallow borehole cable and this was spliced using a waterproof splicing block. The sensor was reset to ± 4G to be similar to the other instrumentation. Both sensors were set to single ended output with ±2.5 V full-scale output level, so that they would be similar to the episensor decks installed elsewhere on the bridge. This sensor was then calibrated and centering spiders and orientation yoke added to the sensor package. Both borehole sensors are installed on the bridge (Figure 13) and are operational.

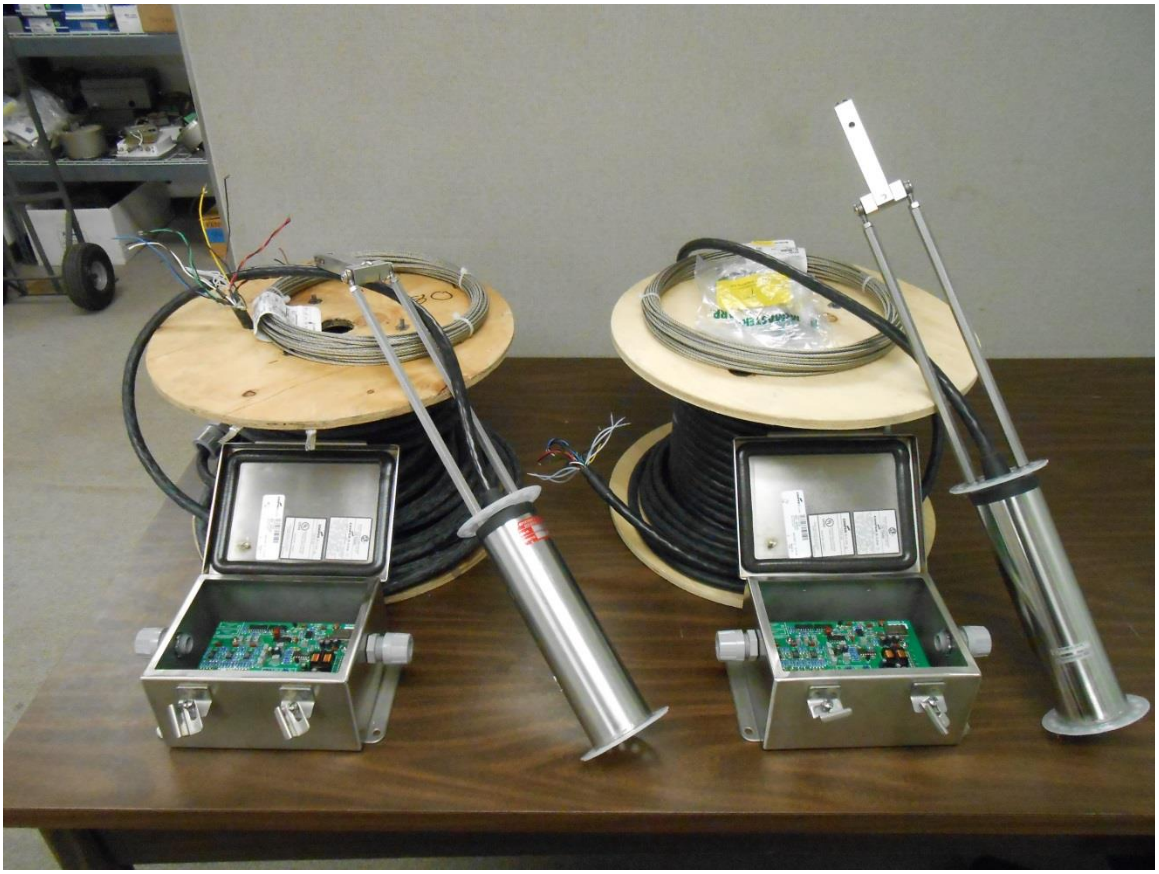


Figure 13. *Two borehole sensors packages before installation.*

1) <u>Replacing the Microsoft Windows PCs with rack mount Linux servers</u>

The Linux server is installed at the University of Memphis Law School and is operational.

2) <u>Upgrading the power infrastructure and surge suppression to be compatible with the new instrumentation</u>

All sensors have been assembled and calibrated.

2.1 DATA STREAMING

Data collected on the bridge are streamed to the AutoZone building and then the University of Memphis Law school where they are available on a publicly accessible IP address. Figure 14 shows the communication schematic between sensors and the Auto Zone building.

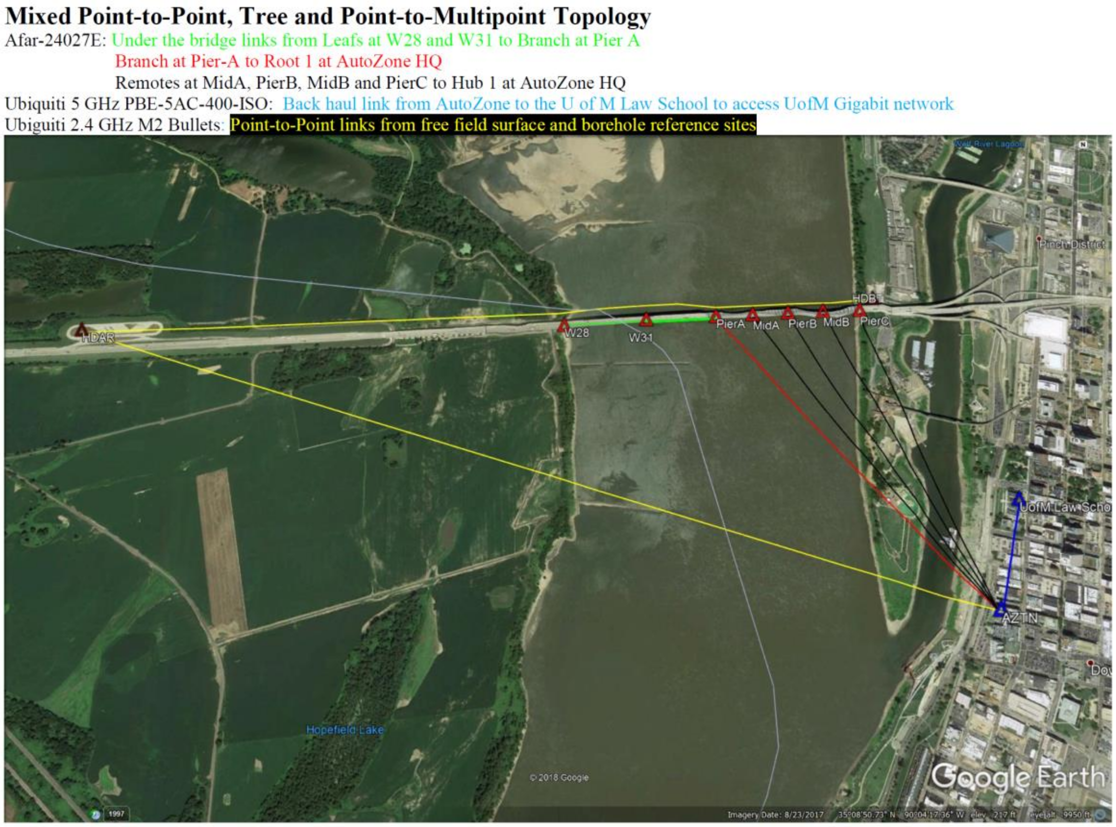


Figure 14. Data communication to a central location.

CHAPTER 3. TECHNICAL INFORMATION ABOUT SENSOR REPLACEMENTS

3.1 OVERVIEW

In this phase of the retrofit, all of the accelerometers on the bridge were replaced by triaxial Kinemetrics Episensors. The new sensors have a full-scale range of ± 4G and a wider bandwidth of 200 Hz. The Episensors used in the retrofit are the internal sensor deck version that was found in the Altus line of recorders. VLF Designs provided an interface card which contains a regulated power supply and transient protection and is fully compatible with the wiring installed with the previous hardware. Sensor replacement was then accomplished using an adapter plate with mounting and leveling hardware that accommodated the new larger box that fitted to existing clamps and sensor bases. All of the equipment is housed in T304 stainless steel enclosures per TDOT specifications.

Both the east and west borehole sensors were replaced with 3” diameter shallow borehole Episensors. Bends in the existing 4” borehole pipes made it impossible to emplace the 4” diameter sensors from the original 2001 installation, in the footings. The new sensor packages had no trouble negotiating the bends in the pipes. The borehole sensors are equipped with corrosion proof yokes that allowed the use of loading poles to preset the orientation of the borehole Episensors. New splicing enclosures were installed on the pier caps adjacent to the boreholes and the same interface card was used with the borehole sensors to provide protection and sensitivity normalization to the devices.

The new interface cards perform the same functions as the previous ones and have identical connector pin outs so that no connector wiring changes were required. The Center for Earthquake Research and Information (CERI) provided electronic leveling tool will continue to work with the new hardware providing an easy means of leveling the individual sensor packages as they were installed. Isolated power converters on each card also helps to break any ground loops in the signal wiring, and further protect components in the signal path from lightning induced transients. Each interface card contains a calibration signal generator that provides an approximate 1/2G triangle wave capable of linearly exercising the mass as well as the standard positive and negative pulses. The cal circuit is triggered by the basalt recorders, activation of a switch in the sensor enclosure, or activation through the 220MHz auxiliary command and control system. The buffer amps on these cards have a gain of 4 so that the full-scale sensor output is 40 Vp-p differential. The gain of these amplifiers is made slightly variable so that during initial sensor test and calibration, the sensors can be normalized to a gain of exactly 5V / G. There is also provision for electronically removing slight offsets present at the accelerometer outputs after the cases have been leveled. A tightly regulated accelerometer and calibrator power supply also insures that no noise or parameter shifts will occur when AC power is lost and the system is running on slowly discharging batteries. Common mode filtering on the power supply inputs insures that no high frequency switching noise from the isolated power converter will cross talk onto the signal wiring in the cable connecting the accelerometer to the recorder. The isolated power converters maintain a regulated output for DC input voltages between 9 and 18 VDC thus encompassing all possible voltages to which the sensors may be exposed during normal operation.

The sensor locations are shown in Figure 15. When the sensor decks were acquired from Kinemetrics, they were labeled as; spare-01, spare-02 and so forth. The decks were installed in the same numbered enclosures, so that Spare-01 becomes ACC-01 and so forth.

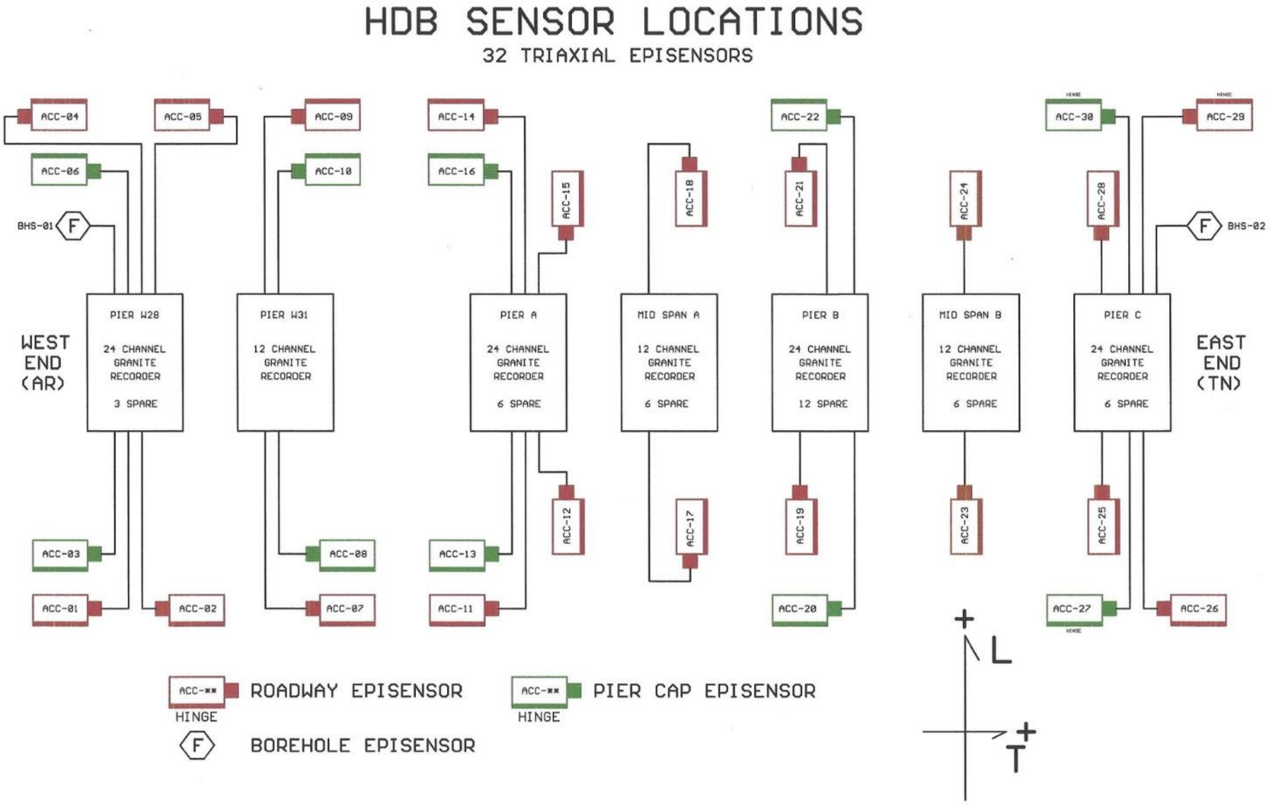


Figure 15. Sensor Locations.

3.2 SENSOR ENCLOSURES

A larger box was required to house the new sensors than those previously installed. The new box mounts via an adapter plate. The plate has several sets of holes so that all possible mounting situations were able to be accommodated. When the old sensor box was removed, the nuts and locking hardware were saved and reused to install the adapter plate. The adapter plate also contains one set of holes for mounting the new enclosures and a provision for leveling the new enclosure. Nylon insert hex nuts are used in all locations to reduce loosening caused by the incessant motion of the bridge. Leveling is now by means of three point adjusting bolts and nuts that considerably simplified leveling the enclosures and prevented accidental warping of the enclosures. The plate can be installed either side up to facilitate cable take outs on either side of the box.

The cable entrance hole is for a ½” Meyers type hub and is in close to the same position as on the previous enclosure, so that no rerouting of conduits was required. The Meyers hub and lock nut were removed from the existing enclosure and reinstalled on the new enclosure. The Meyers hub o-rings were cleaned and regreased prior to reuse to insure the watertight integrity of the fitting. It was necessary to remove the Phoenix connector from the end of the cable in order to remove the existing cable from the box and reinstall in the new box, however it was not necessary to remove the cold shrink or loosen the nylon cord seal where the flex conduit connects to the cord seal. Fresh desiccant was placed in the enclosure before the lid was closed.

All sensor enclosures were installed in the same orientation as with the previous sensors. Provision was made on the interface board so that the connector wiring is the same for all sensors regardless of whether the boxes were installed longitudinally or transverse to the structure. Note that in the upper left hand corner of the interface board, there is a check-box that indicates whether the box was set up as longitudinal or transverse. Four shunt jumpers in the top center of the board determine this status, so that any replacement card can be used in any orientation through proper setting of the jumpers. Longitudinal sensors installed on the North side of the structure are installed so that the box lid opens toward the North, while longitudinal sensors installed on the South side of the structure are installed so that the box lid opens toward the South. Internally though, the sensor orientation remains the same. All transverse sensors are mounted on the West side of structural members; therefore, all the box lids open toward the East.

It was necessary to mechanically re-center some of the accelerometers so the episensor deck was removed from the enclosure and placed on a dead level plate. Parallel bars were placed between the base of the accelerometer deck and the level plate in order to miss various screw heads protruding from the underside of the sensor base plate.

All of the boxes are fashioned from type T304 stainless steel and carry a NEMA 4x or IP66 rating which is maintained by use of the stainless-steel Meyers hubs. The equivalent Hoffman part number of the enclosures is A8064CHNFSS.

The internal mounting panel is 3/16" thick 6061-T6 aluminum and was custom made and drilled for this project. The external adapter panel is 3/16" thick T304 annealed stainless steel and was custom made and drilled for this project.

Figure 16 shows the senor box conduit locations. Figure 17 shows the box internal plate layout.

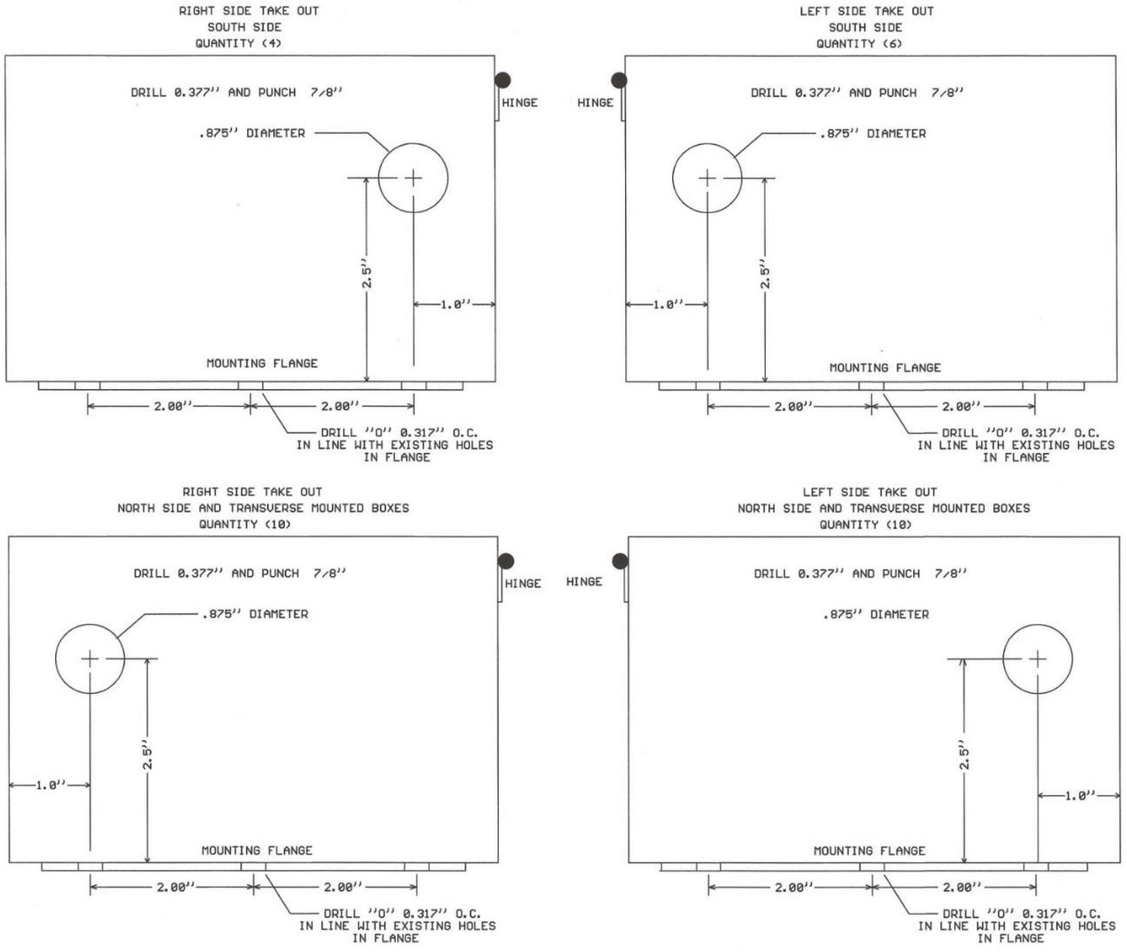


Figure 16. Sensor Box Conduit Locations.

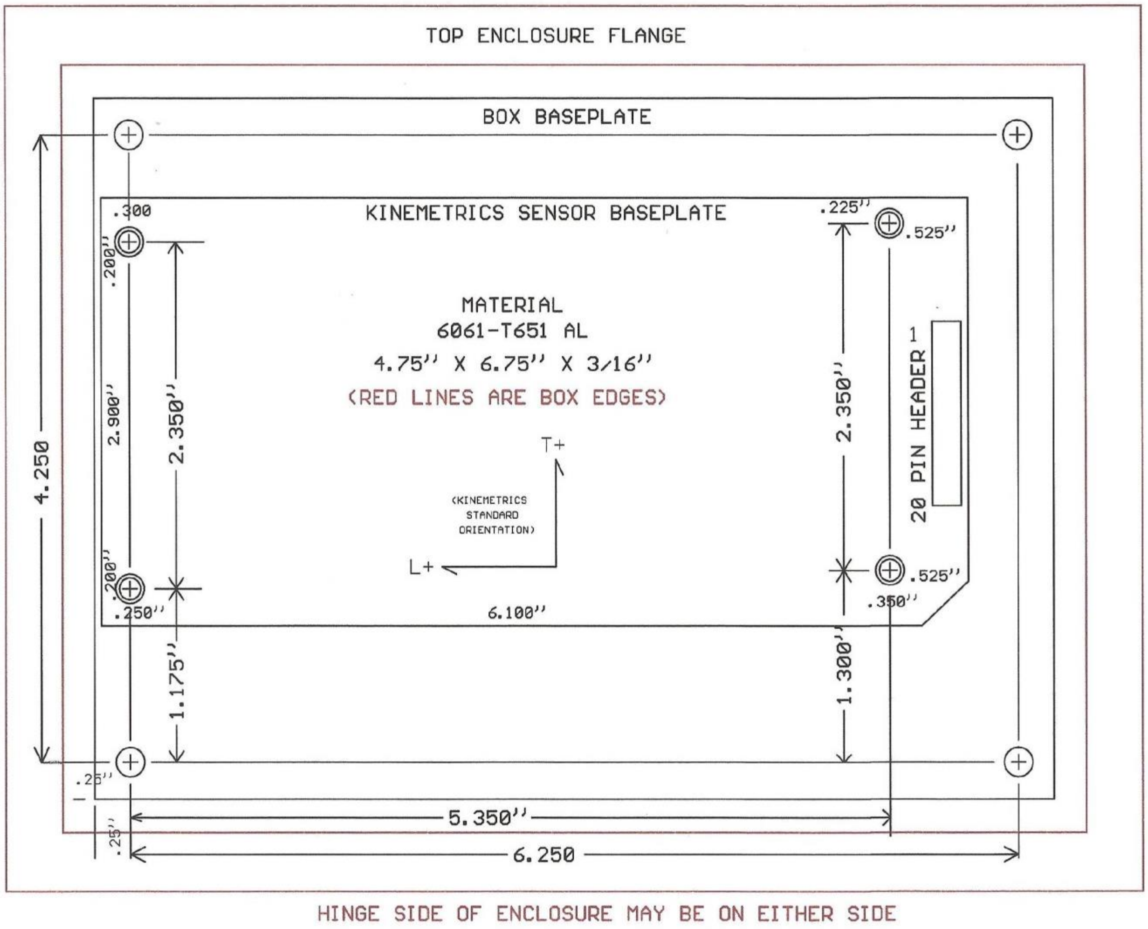


Figure 17. Sensor Box Internal plate layout.

3.3 SENSOR INTERFACE CARD FUNCTIONAL DESCRIPTION

The main function of the sensor interface card (Figure 18) is to provide stable operating voltages for the episensor deck as well as to isolate the deck from any transients that may be induced in the wiring from lightning or accidental cross connections with AC power wiring on the bridge.

The interface card mounts directly to the episensor deck with three 10-32 socket head cap screws. There are three 9/16" nylon spacers underneath the interface card to provide proper clearance spacing between the card and the episensor deck. All electrical connections to the underlying sensor deck are by means of direct connection to the standard 20 pin male connector on the episensor deck.

All of the sensors bear the same sensor designations as those previously assigned. The sensor designation is written on the outside and inside of the box as well as on the interface card. Note that if an interface card is replaced, it will be necessary to recalibrate the individual sensor in order to achieve maximum accuracy. The worst-case inaccuracy that can result from card replacement without recalibration is approximately ± 5%.

Input power is routed to the wide input range DC to DC converter through a common mode filter and transient suppression consisting of C1,2,3,32, L1, D1 and V1 (Figure 18). V1 protects the converter from input to output breakdown due to overvoltage and D1 protects for reversed polarity connection and overvoltage above 18VDC.

The converter has been programmed to output approximately ± 10.5 VDC. This power is further filtered by L3, L4, C6 and C7 to reduce any remaining switching noise from the converter to negligible levels. Input power common and signal common are isolated by means of DC to DC converter U9. V2 provides overvoltage protection to all of the devices inside the enclosure during transient episodes. Power for the internal buffer amplifiers and calibrator is supplied from filter components L2, L5, C8 and C9.

The buffer amps operate with a variable gain of 4 and convert the single ended sensor output to differential for transmission to the recorder. The outputs also are very low impedance and have been compensated to tolerate cable capacitance of up to 50 pF per foot. When the sensors were initially tested the -1G value was set to -5V / G on all components of all sensors. There is also provision to remove sensor output offsets of up to ± 100 mV by means of an electrical adjustment. A single stage transient suppressor was used to protect each analog output line.

In the case of the vertical component, the outputs of the buffer amps are directly connected to the cable going to the recorder. Switching is provided on the horizontal outputs so that proper polarity and azimuth are maintained regardless of sensor box orientation. For a longitudinally mounted box, the episensor X component becomes the transverse signal and the inverted Y component becomes the longitudinal signal. For transverse mounted boxes, the X component is used directly as the longitudinal component and the Y component is the transverse component. Four shunts are mounted on 4 headers, and all four shunts must be in either the longitudinal or transverse position for proper programming of the outputs.

A highly regulated ± 5VDC power supply (U8b and U8C) provides operating power and input signals for the calibration signal generation circuitry. The calibration circuit can be enabled by an external voltage input to optocoupler U5 or by depressing the cal enable switch (SW1). Either of these conditions sets analog flip flop U4a and U4b. The output of the flip-flop applies power to 0.5 Hz triangle wave generator consisting of U7a and U7b, and also enables the cal circuits inside the episensor. The output of the triangle wave generator is converted to a square wave by U7d. This square wave is used to clock the calibration sequence through binary counter U6. The counter output changes state every 8 clock cycles, or approximately every 8 seconds. The counter output lines control a multiplexer U7 that generates the actual calibration sequence. Once the sequence has been started it will go on for approximately 64 seconds until completion. The initial 8 seconds are not used as the triangle wave generator offset is settling from the startup transient during this time. The output of the multiplexer is amplified by U8a and the amplitude of the triangle wave portion of the calibration is set to exactly 20 Vp-p. The calibration pulses are approximately ± 10V peak. This amplifier has a very high current drive capability required by the relatively low impedance of the cal circuit of the episensor deck. The Cal sequence is provided in Table 1.

Table 1. Cal Sequence.

0-7 seconds:	No output
8-15 seconds:	Triangle wave output 20Vp-p 4 cycles
16-23 seconds:	Triangle wave output 20Vp-p 4 cycles (continues uninterrupted)
24-31 seconds:	No output
32-39 seconds:	Positive Output +10V
40-47 seconds:	No output
48-55 seconds:	Negative Output -10V
56-63 seconds:	No output
64 seconds:	Control flip flop reset (new cal sequence may be started if desired)

Use of this Cal signal was required because only 2 wires were available in the original signal cable for Cal function. The episensor requires a ground referenced Cal and Cal enable signal which would have otherwise required 3 wires. The triangle wave has been found to be very diagnostic for accelerometers with “sticky” suspensions caused by magnetic materials in the air gap of the torquing coil.

All I/O connections to the interface card are made through a 12 pos. 5.08mm locking type Phoenix connector on the edge of the card. Test points are provided on the card by means of octagon shaped pads and their functions are labeled on the PCB.

NOTE: The polarity of the Cal sequence is inverted on the longitudinal component of all longitudinally mounted sensor boxes, because the sensor output polarity needed to conform to structural monitoring standards.

3.4 OUTPUT POLARITIES

The output polarities of all components derived from surface mounted accelerometers are as follows. A **positive** voltage is generated at the input to the recorder for **Motion UP, Motion toward the North, and Motion toward the East**. In any case, the transverse (Y) component is 90˚ clockwise from the longitudinal (X) component when viewed from above.

Figure 18 shows the interface card schematics.

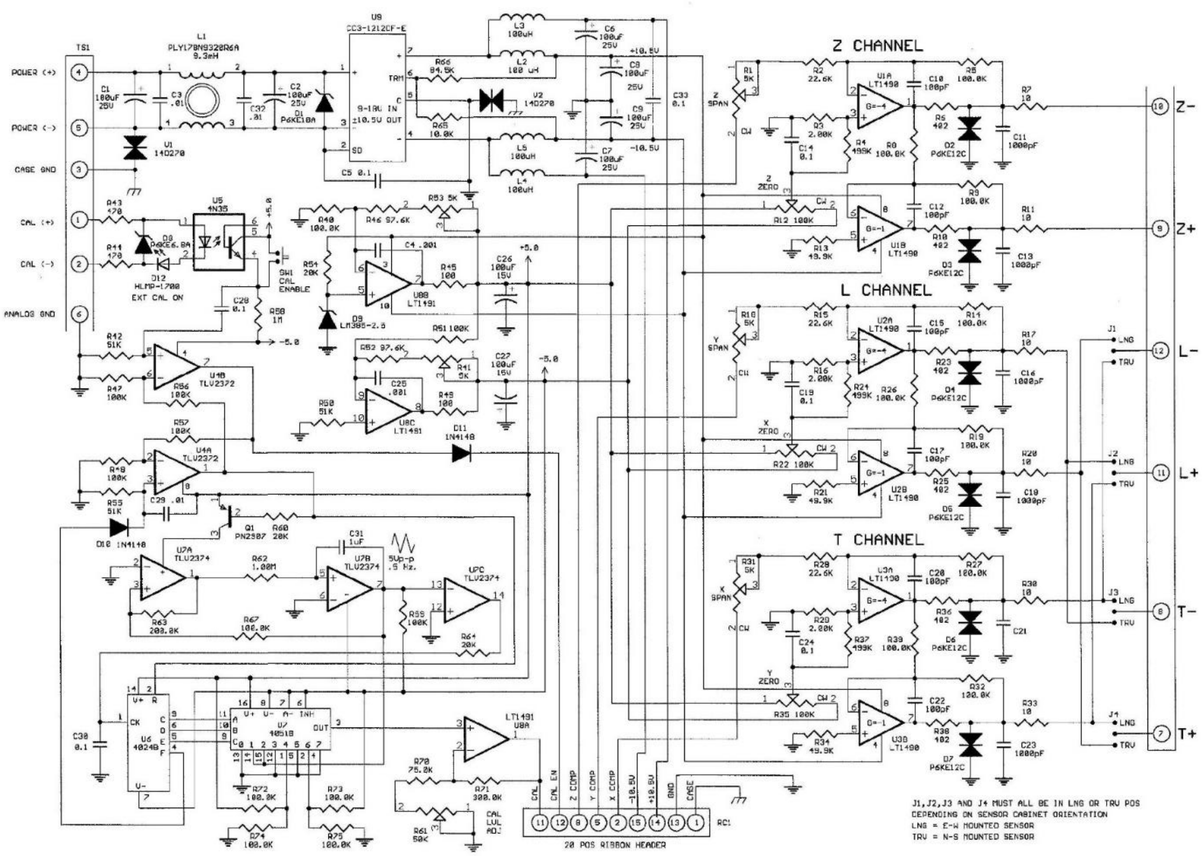


Figure 18. Interface Card Schematics.

3.5 INTERFACE CARD CONNECTIONS

The cable from the sensor box to the recorder contains 12 conductors, a foil shield and a bare drain wire. The drain wire (shield) is connected at the recorder end and should not be connected to case ground at the sensor end. Doing so may allow 60Hz leakage currents flowing from the bridge lighting circuits thought the steel super structure to increase the recorded background noise. Position #12 is nearest the center of the board. The existing mating connector will be reused with the new interface card. Table 2 provides the color scheme used.

Table 2. Interface Card Connection Color Scheme.

Pos. #	Color	Function
1	Tan	Cal Enable (+)
2	Vio	Cal Enable (-)
3	N.C.	Case Ground
4	Red	Power (+)
5	Blk	Power (-)
6	Grn	Analog Common
7	Yel	Transverse (+)
8	Gry	Transverse (-)
9	Org	Vertical (+)
10	Blu	Vertical (-)
11	Wht	Longitudinal (+)
12	Brw	Longitudinal (-)

3.6 HDB SURFACE ACCELEROMETER CALIBRATION PROCEDURE

Adjustments must be performed in the order listed to assure accuracy. The power supply must be adjusted prior to any other adjustments as calibration voltages are derived from the power supply.

3.6.1 Power Supply

1. Set Power supply current limit for approximately 150 mA. Set output voltage to 13.0 VDC. Connect accelerometer system to power supply using test cable. Current consumption should be approximately 55mA.
2. Adjust +5v supply (R53) for +5.000 ± .001 VDC between the +**5V** octagon test pad and COM test pad.
3. Adjust -5v supply (R41) for -5.000 ± .001 VDC between the -**5V** octagon test pad and **COM** test pad.

3.6.2 Calibrator

1. Connect Peak reading voltmeter between **Cal** test pad (or pin 1 of U8) and **Gnd** test pad.
2. Depress momentarily and release the cal enable switch (or the external test cable switch), wait 8 seconds for the 0.5 Hz triangle wave to begin. Adjust **cal lvl** pot (R61) for 20.00 ±.01 Vp-p amplitude of the triangle wave.
3. Measure and record Cal+ pulse output voltage.
4. Measure and record Cal- pulse output voltage.

3.6.3 Accelerometer Offset Adjustment

1. Place sensor enclosure in an upright position on a dead level plate. Hold down against level plate if necessary to prevent wobbling.
2. Connect voltmeter to Z output. Adjust Z offset for 0.000 ±.002 VDC.
3. Follow step 3a for longitudinal mounted sensor or step 3b for transverse mounted sensor.
    (a) Connect voltmeter to L output. Adjust Y offset for 0.000 ±.005 VDC.

    (b) Connect voltmeter to T output. Adjust X offset for 0.000 ±.005 VDC.
4. Connect voltmeter to L output. Adjust X offset for 0.000 ±.005 VDC.
5. Connect voltmeter to T output. Adjust Y offset for 0.000 ±.005 VDC.

3.7 ACCELERATION SPAN ADJUSTMENT

The sensor span adjustments are also based on the final orientation of the sensor box, longitudinal or transverse. Jumpers on the interface board are used to connect the X and Y sensors to the L and T outputs and correct for proper overall polarity. All jumpers must be in the LNG position for longitudinal oriented sensors or TRV for a transverse mounted sensor. The span adjustment for the vertical (Z) sensor is the same for either orientation.

3.7.1 Vertical span adjustment

1. Rotate sensor box 90˚ from the upright position around the long axis so that it is lying on a long side. Hold the base of the box against the upright of a right angle plate.
2. Measure output voltage at the Z output. Adjust Z span (R1) for -5.000 ±.005 VDC.
3. Turn sensor enclosure upside down and measure voltage on the Z output, record as -2G out. (it should be close to -10V)

3.7.2 Longitudinal Oriented Sensor Boxes

Longitudinal boxes may be used on either the North or South side of the structure. In either situation the lid of the case will open to either the North or South to facilitate adjustment and connections. Because of this their orientations during calibration will be opposite.

1. Rotate the sensor box from the dead level position 90˚ around the long axis so that the long side of the sensor box remains horizontal and parallel to the dead level plate, but the PCB is now facing you. Hold the base of the box against the

upright of a right angle plate, while maintaining the long side of the box parallel to the dead level plate.

2. Connect a voltmeter to the T output. If the voltage is approximately -5V proceed to step 3. If not it will be necessary to rotate the box 180˚ so that the other long side of the box is now parallel to the dead level plate and the PCB is still facing you. Then proceed to step 3.
3. Adjust X span (R31) for -5.000 ±.005 VDC on the T output.
4. Rotate the box 180˚ around the long axis with the PCB still facing you and the other long side of the box parallel to the dead level plate. Hold the base of the box against the upright of the right angle plate and measure and record the voltage as the T +1g value on the cal sheet. (It should be close to +5VDC.)
5. Rotate the box 90˚ so that *long* axis is now vertical, (the short side of the box is parallel to the dead level plate) and the PCB is facing you. Hold the base against the upright of the right angle plate.
6. Connect a voltmeter to the L output. If the voltage is approximately -5V proceed to step 7. If not it will be necessary to rotate the box 180˚ to its other vertical position with the PCB still facing you and the other short side of the enclosure parallel to the dead level plate. Then proceed to step 7.
7. Adjust Y span (R18) for -5.000 ±.005 VDC on the L output.
8. Rotate the box 180˚ around the long axis with the PCB still facing you and the other short side of the box now parallel to the dead level plate. Hold the base of the box against the upright of the right angle plate and measure and record the voltage as the L +1g value on the cal sheet. (It should be close to +5VDC.)

3.8 TRANSVERSE ORIENTED SENSOR BOX

All transverse oriented boxes are mounted on the west side of structural members, so their calibration orientations are identical.

1. Rotate the sensor box from the dead level position 90˚ around the long axis so that the long side of the sensor box remains horizontal and parallel to the dead level plate, but the PCB is now facing you. Hold the base of the box against the upright of a right angle plate, while maintaining the long side of the box parallel to the dead level plate.
2. Connect a voltmeter to the L output. If the voltage is approximately -5V proceed to step 3. If not it will be necessary to rotate the box 180˚ so that the other long side of the box is now parallel to the dead level plate and the PCB is still facing you. Then proceed to step 3
3. Adjust X span (R31) for -5.000 ±.005 VDC on the L output.
4. Rotate the box 180˚ around the long axis with the PCB still facing you and the other long side of the box parallel to the dead level plate. Hold the base of the box against the upright of the right-angle plate and measure and record the voltage as the L +1g value on the cal sheet. (It should be close to +5VDC.)
5. Rotate the box 90˚ so that *long* axis is now vertical, (the short side of the box is parallel to the dead level plate) and the PCB is facing you. Hold the base against the upright of the right-angle plate.
6. Connect a voltmeter to the T output. If the voltage is approximately -5V proceed to step 7. If not it will be necessary to rotate the box 180˚ to its other vertical position with the PCB still facing you and the other short side of the enclosure parallel to the dead level plate. Then proceed to step 7.

7. Adjust Y span (R18) for -5.000 ±.005 VDC on the T output.
8. Rotate the box 180˚ around the long axis with the PCB still facing you and the other short side of the box now parallel to the dead level plate. Hold the base of the box against the upright of the right angle plate and measure and record the voltage as the T +1g value on the cal sheet. (It should be close to +5VDC.)

3.8.1 Determination of Calibration Constants

The calibration constants represent the output of the sensors in response to the calibration signals derived from the on board calibrator. They should not change significantly over time. Any significant changes should be investigated for possible component failures. The calibration signal commences approximately 8 seconds after a cal enable occurs from either the recorder or by pressing the cal enable button on the buffer PCB. The calibration sequence consists of 8 cycles of 0.5Hz triangle wave signal followed by 8 seconds of dead time, then an 8 second duration positive pulse, then 8 second dead time, and finally an 8 second positive pulse. The polarity of the calibration sequence is inverted only on the longitudinal component of all longitudinally oriented sensors from that seen in the longitudinal component of transverse mounted sensors.

1. Place the sensor box in normal position (base down) on a dead level plate. Perform the accelerometer offset procedure as outlined earlier in this procedure before continuing.
2. Connect a peak reading voltmeter to the Z output. Momentarily depress the cal enable switch. Measure and record the peak to peak values of the triangle wave and the DC voltages associated with the calibration pulses as they are applied to the sensor during the calibration sequence.
3. Connect a peak reading voltmeter to the L output. Momentarily depress the cal enable switch. Measure and record the peak to peak values of the triangle wave and the DC voltages associated with the calibration pulses as they are applied to the sensor during the calibration sequence. Note that on the longitudinal oriented sensor packages, the polarity of the output signals will be reversed, and should be recorded as a negative value even though it was caused by a positive voltage from the calibrator. The absolute value of the voltage is what is important.
4. Connect a peak reading voltmeter to the T output. Momentarily depress the cal enable switch. Measure and record the peak to peak values of the triangle wave and the DC voltages associated with the calibration pulses as they are applied to the sensor during the calibration sequence.

3.9 POLARITY CHECK

1. Place the sensor box on a level surface. Connect an oscilloscope to the Z output. Lift the box quickly from the surface and a positive voltage should be seen at the output.
2. Connect an oscilloscope to the L output. Move the box in an easterly direction as indicated by the East arrow in the checked legend box on the PCB and a positive voltage should be seen at the output.
3. Connect an oscilloscope to the T output. Move the box in an Northerly direction as indicated by the North arrow in the checked legend box on the PCB and a positive voltage should be seen at the output.

This completes the calibration of a surface sensor box.

CHAPTER 4.

STATIC-BASED MONITORING SYSTEM

4.1 PROJECT BACKGROUND

Tennessee Technological University (TTU), with Dr. Matthew Yarnold serving as Principal Investigator, supplemented the dynamic instrumentation monitoring on the Hernando Desoto Bridge (performed by the University of Memphis) with a targeted static-based monitoring system. The goal of the system is to track the position of the structure and member force distribution before and after a seismic event to ensure adequate structural performance. There were five primary tasks within the scope of work that include: (A) instrumentation design, (B) installation of equipment, (C) quality control field checks, (D) setup of data visual display, and (E) basic alerting capabilities. An overview of the work completed for each task is described below. In addition, the overall findings from the project are summarized in two conference papers that are attached to this report.

4.2 TASK A: INSTRUMENTATION DESIGN

This task initiated with a document review. All existing documents (plans, bearing calculations, and inspection reports) were obtained from TDOT and thoroughly reviewed. The measurements target bearing displacements and member strains (forces). A preliminary instrumentation design and attachment details were created and discussed in-person with the University of Memphis team. This included a field visit to the Hernando Desoto Bridge, which was coordinated with TDOT for maintenance of traffic and the use of under-bridge equipment. The preliminary instrumentation design and attachment details were revised and submitted to TDOT on May 13, 2016. Approval (with comments) was given on May 17, 2016. The final instrumentation plan is provided below in Figure 20.

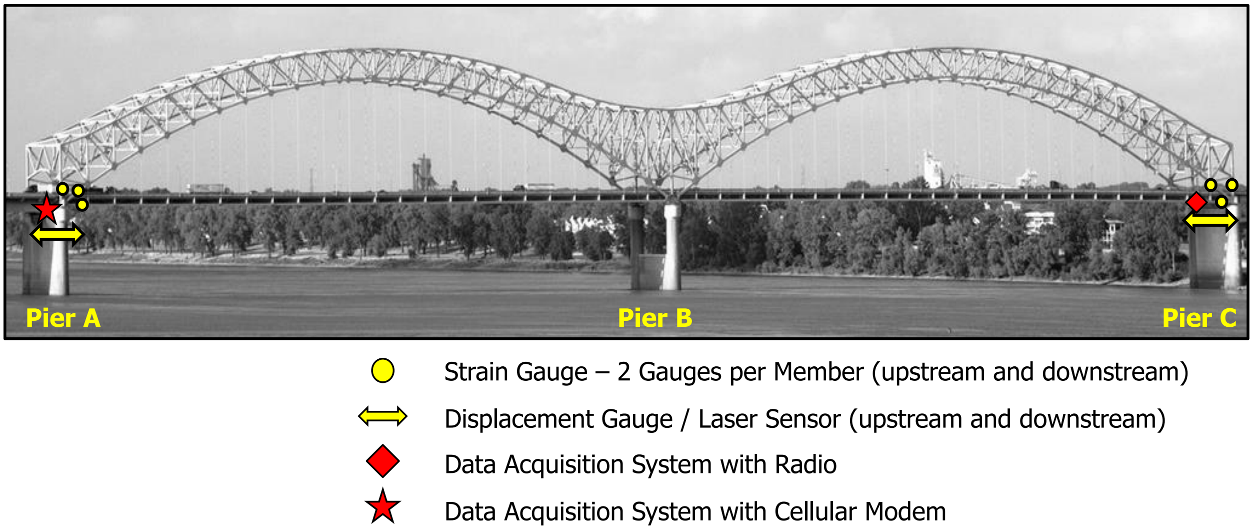


Figure 19. Instrumentation Plan

Different displacement sensors were utilized due to the two different movement mechanisms of the bearings. The first is slow speed movement due to daily temperature variations. In order to capture these movements, vibrating wire (VW) displacement gages (Geokon Model 4420) were selected (including internal thermistors) with a sampling rate of once every five minutes. These gages were aligned to measure longitudinal movement of the bridge (parallel to traffic). The second mechanism is rapid movement due to seismic ground motion. Non-contact laser displacement sensors (Acuity AR1000) were selected to capture this movement. These sensors provide a maximum sampling rate of 50 Hz. They were mounted in the longitudinal and transverse directions.

Deformations of the arch members framing into the bearings are obtained using VW strain gages (Geokon Model 4000) (including internal thermistors). Again a sampling rate of once every five minutes was chosen. This setup allows for the identification of the member forces due to thermal loads and the force changes before and after a seismic event.

As shown in Figure 19, the instrumentation is concentrated at Pier A (west end) and Pier C (east end) of the double arch spans. Pier A is the primary setup that includes VW strain gages on all members framing into the bearings, VW displacement gages at the arch and approach bearings (longitudinal direction) along with laser sensors at the arch bearings (longitudinal and transverse directions). Figure 20 graphically shows a detailed view of the setup at Pier A.

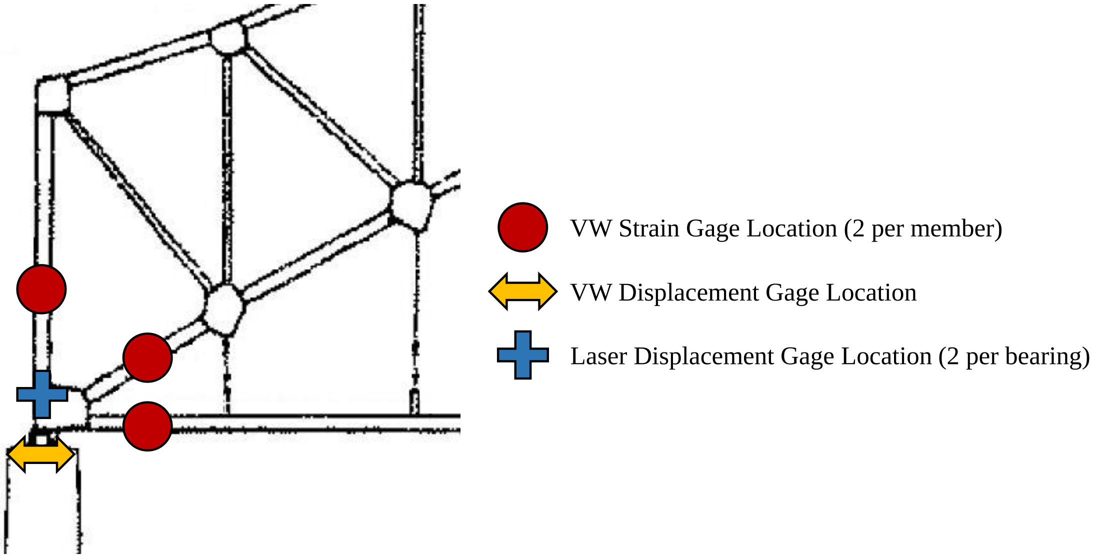


Figure 20. Pier A Instrumentation Setup (upstream and downstream sides)

The instrumentation at Pier C is similar to Pier A. The VW strain and displacement sensor locations are the same. However, no laser sensors are located at Pier C due to data acquisition limitations. In addition, the approach bearings at Pier C are not instrumented. The east side approach does not include friction-pendulum bearings.

The data acquisition system for the project is from Campbell Scientific (CR1000) and is located at Pier A. The data from Pier C is collected and periodically sent to Pier A through a radio. A cellular modem is located at Pier A allowing for the data to be wirelessly accessible. Note significant internal memory and battery backup power is included in the event communication and power are lost during an earthquake.

4.3 TASK B: INSTALLATION OF EQUIPMENT

This task began with the selection of the most appropriate sensors and data acquisition equipment to obtain the measurements shown earlier. In summary, three suppliers were selected. The data acquisition equipment was purchased from Campbell Scientific due to their systems being utilized in many similar applications. The vibrating wire strain and short-range displacement sensors were purchased from Geokon. Geokon is the leader in vibrating wire sensors and was therefore chosen. Finally, Acuity was selected for purchase of the long range non-contact displacement sensors. The PI is familiar with this product from a prior project and was confident in the performance of the lasers sensors.

The next portion of the work was purchase of the equipment and then assembly. This included all wiring and other connections needed. In addition, code was written to properly record the measurements at specified sampling rates. Figure 21 shows the initial wiring and testing of the system at TTU.

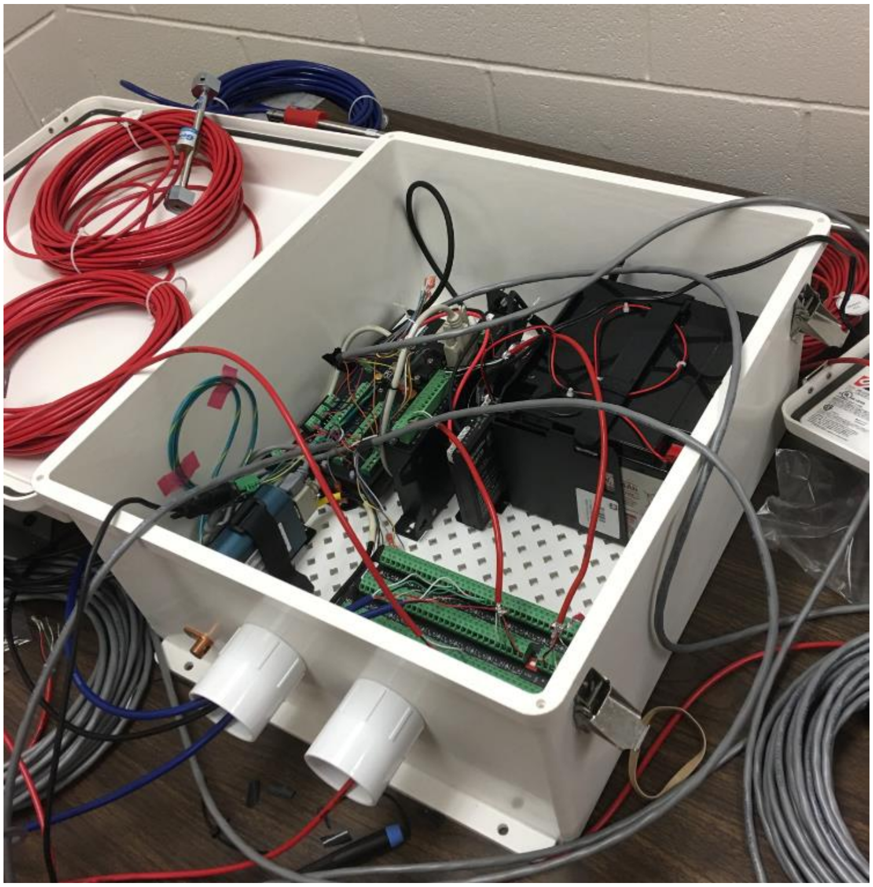


Figure 21. Initial Testing of the Data Acquisition System

The final task was to physically install the equipment on the structure, which was conducted the week of August 29, 2016. Installation was completed in five days with the last day designated for quality controls checks (discussed further in the next section). All sensors were attached according to the approved attachment plan.

Throughout the installation, TDOT provided lane closures to allow for the use of their Aspen A-62 snooper truck for strain gage attachment. These gages were epoxy mounted to the member surfaces. Figure 22 and Figure 23 show attachment of the strain gages along the lower chord.

Figure 22. Installation of VW Strain Gages along the Lower Chord

Figure 23. Installation of the VW Strain Gages by Graduate Student Justin Alexander

The VW displacement gages were mounted to the surface of the bearings and attached to a vertical bracket that was anchored to the pier cap (Figure 24). This assembly was installed at all four arch bearing locations. A slightly different setup was provided for the Pier A approach bearings.

Figure 24. VW Displacement Gage Installation at Pier A (Pier C similar)

The laser displacement sensors were u-bolted to the steel railing and targeted on a flat surface directly above the bearings. Figure 25 shows the laser sensor along with the orientation. Note these sensors are only provided at Pier A (upstream and downstream).

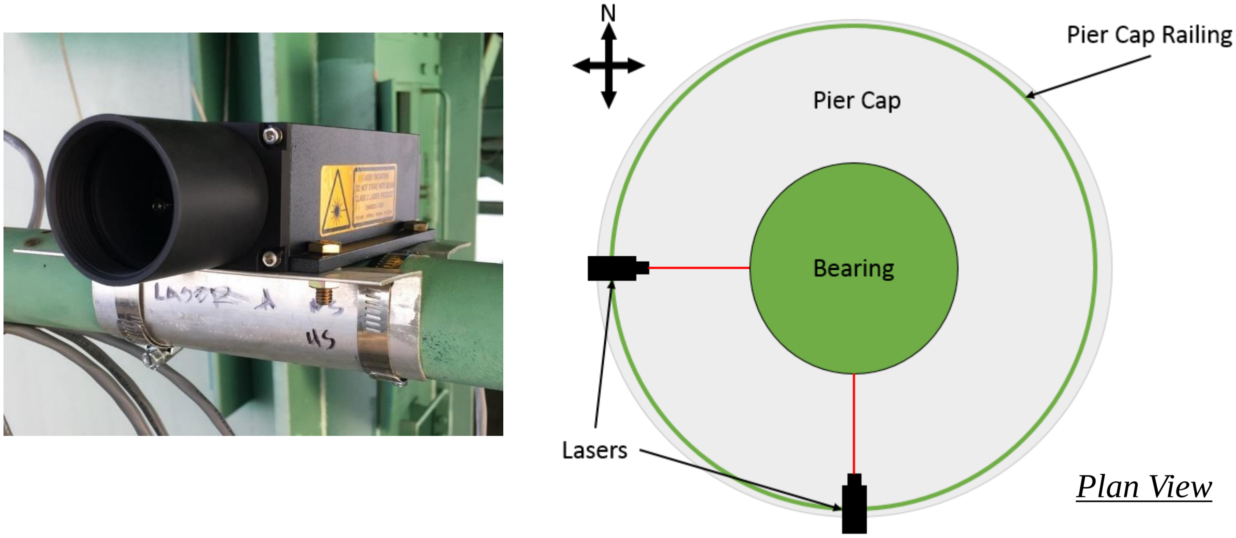


Figure 25: Laser Displacement Sensor Installation and Orientation

Once all the sensors were attached, cabling was performed for connection to the data acquisition systems, which was housed in a weatherproof enclosure at the center of the pier caps (Figure 26).

Figure 26. Data Acquisition System at Pier A (Pier C similar)

4.4 TASK C: QUALITY CONTROL FIELD CHECKS

This task included quality checks to ensure proper functionality of the system. A list of checks was developed and then executed in the field. This included scrutinizing the gage attachments and wiring. Superglue was applied on nuts and bolts on the attachments to prevent any back-off from occurring due to long-term vibration experienced on the bridge. A field review of the data was performed to ensure the daily strain and displacement trends were reasonable due to thermal variations. Note the monitoring system has been operational since it was installed.

4.5 TASK D: SETUP OF DATA VISUAL DISPLAY

A visual display was created to clearly illustrate the current and recent data. Therefore, users can access the system and monitor the structure in real time. This interface makes monitoring the structure less tedious than looking through tables of numbers. The layout of the monitoring system interface first consists of an overview of the instrumentation locations (similar to Figure 19). The remaining eight screens consist of time history plots for all the different sensor types along with relational plots such as displacement versus temperature. Figure 27 shows an example page that includes the arch span bearing displacements.

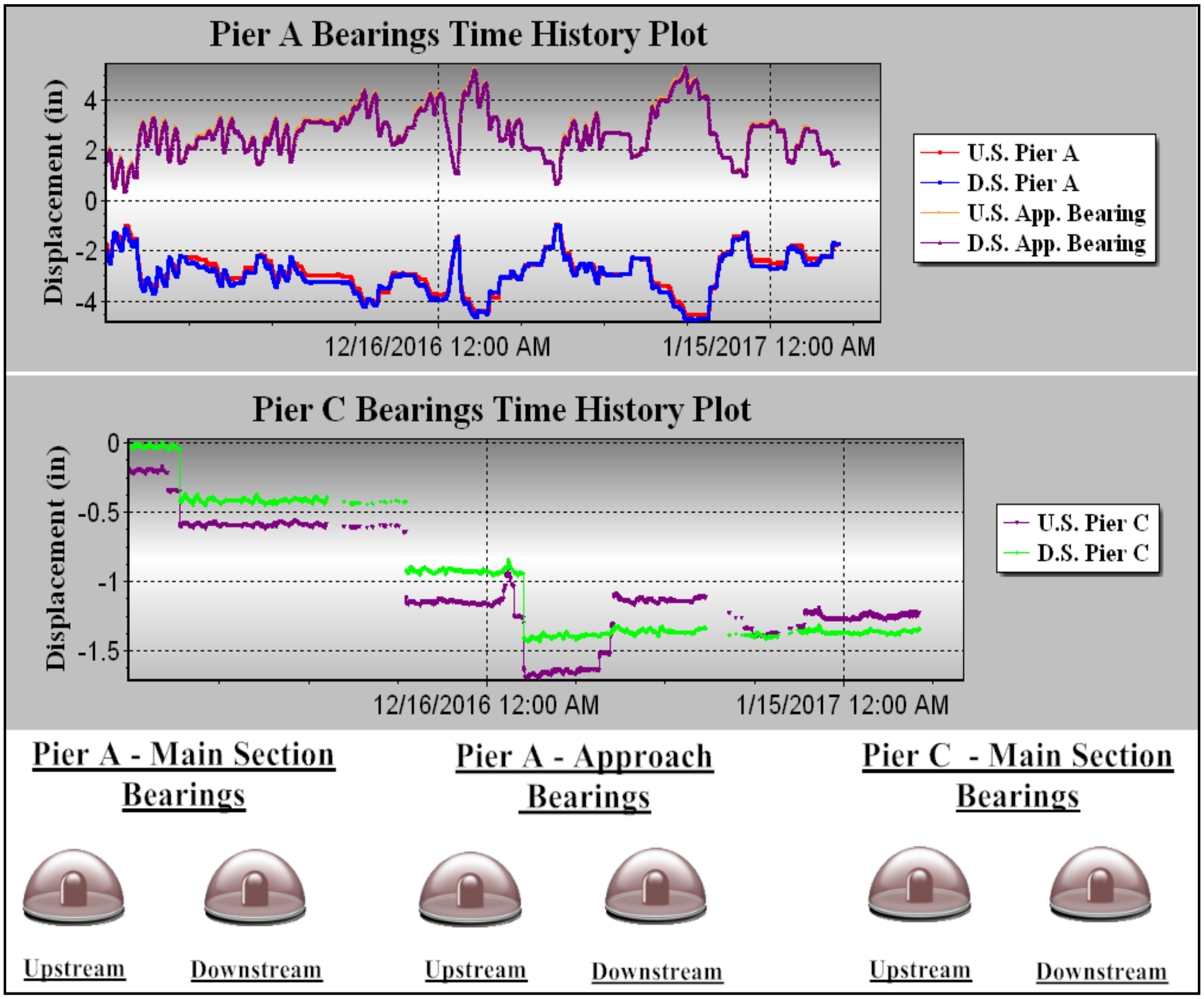


Figure 27. Real-Time Monitoring Page for the Arch Displacement Gages

4.6 TASK E: ALERTING SYSTEM

A basic alerting system was added to the visual display. These alerts simply check specified thresholds which were developed through months of data analysis. Figure 27 shows some example alert icons on the visual display. If the threshold is exceeded the icon turns red.

CHAPTER 5.

CONCLUSIONS AND RECOMMENDATIONS

The main objectives of the project were to: (1) replace the existing sensors with a higher quality and industry standard accelerometers; (2) be able to measure bridge movements during ground shaking for mild events which occur frequently and this data may be used to calibrate models for expected large magnitude earthquakes to better understand and define the effects of the deep soil deposits of the Mississippi embayment upon bedrock ground motions; and (3) Supplement the dynamic data with static displacement, strain, and tilt angle measurements.

We were able to successfully accomplish all tasks. The Instrumentation of the I-40 is a state-of-the-art strong motion instrumentation system. It is done very efficiently and is a top of the line system. Henando Desoto bridge is a one of the only bridges in the Central and Eastern United States region with such a comprehensive strong motion instrumentation.

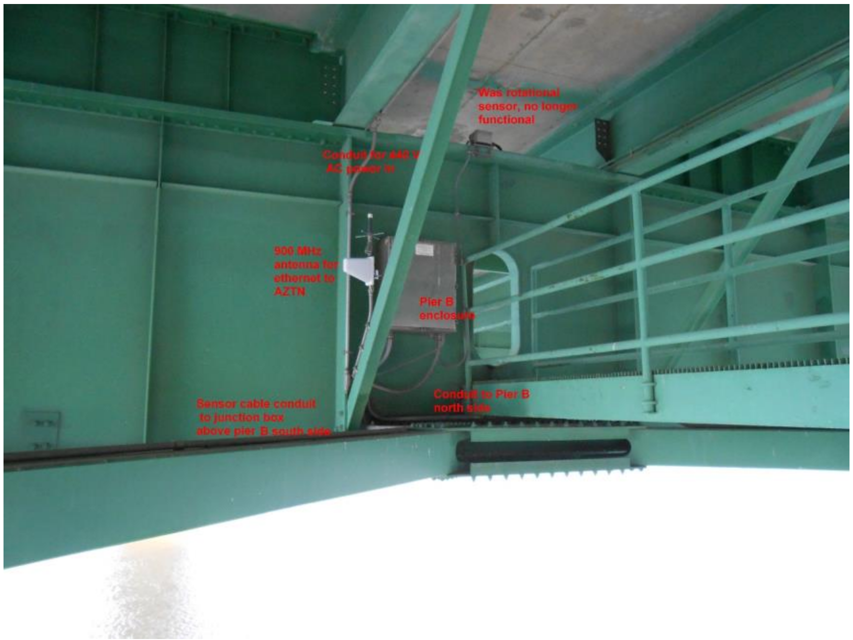
In case of an earthquake, we are able to collect valuable data from sensors at free field stations in Tennessee and Arkansas sides of the bridge, sensors on the bridge structure, and sensors located at the bridge foundation. In collaboration with the United States Geological Survey (USGS) researchers, we will be able to stream data online for use by researchers and TDOT engineers. Data can be used various aspect of seismic design considerations for bridges in the Central and Eastern United States regions as well as for the health monitoring of the bridge and early warning system in case of an earthquake.

APPENDIX A. PHOTO GALLERY


DIS
Your Partner in
Earthquake Protection


W28
W31


N (LNG)
SENSOR #
357
N (TRU)
COOPER B-Line
TYPE 4X


Was rotational sensor, no longer functional
Conduit for 440 V AC power in
900 MHz antenna for ethernet to AZTN
Pier B enclosure
Sensor cable conduit to junction box above pier B south side
Conduit to Pier B north side


KLEIN TOOLS
5416


24 Ch Kinemetrics
Granite Recorder
PIER C
GRANITE-12


ASPEN A-62


ASPEN A-62

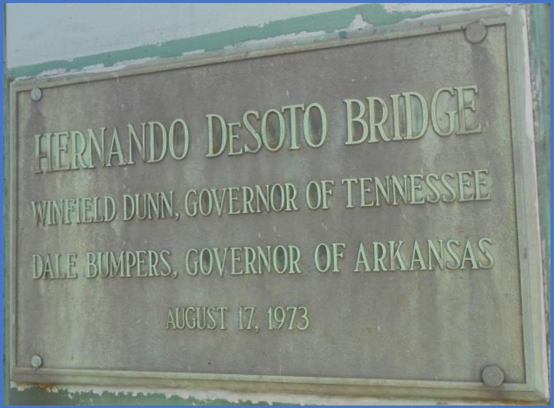

502
W28

APPENDIX B. FINAL REPORT PRESENTATION

TDOT Tennessee Department of Transportation

Seismic Instrumentation of the Hernando-DeSoto I-40

Mississippi River Bridge in Memphis, Tennessee


HERNANDO DESOTO BRIDGE
WINFIELD DUNN, GOVERNOR OF TENNESSEE
DALE BUMPERS, GOVERNOR OF ARKANSAS
AUGUST 17, 1973

Shahram Pezeshk, P.E., Ph.D., Chair, Dept of Civil Engineering
Mitch Withers, Ph.D., Seismic and IT Networks Director
Chris McGoldrick, Steve Brewer, David Steiner, Jim Bollwerk
Greg Steiner/VLF Designs
TDOT Region 4 Bridge Inspection Teams

USGS
science for a changing world

U.S. Department of Transportation
Federal Highway Administration

ARKANSAS STATE HIGHWAY AND TRANSPORTATION DEPARTMENT
Provide a safe, efficient, aesthetically pleasing and environmentally sound intermodal transportation system for the user

CERI

THE UNIVERSITY OF MEMPHIS
Center for Earthquake Research and Information


2002. 5. 27 09:29

Seismic Retrofit and Instrumentation Installation Timeline

1992: TDOT and AHTD begin seismic evaluation and retrofit of the I-40 Bridge and approaches

2000: TDOT awards TRC construction and engineering contract estimated at $268 million to be completed in 2015. (Over $500 million in contracts to date)

January 2001: CERI portion of planning begins

Summer 2002: Equipment enclosures, electrical conduits and wire run to seven recording nodes along 3660 ft from Pier W28 on the Arkansas bank to Pier C on the Tennessee bank.

October & November 2004: Installation of sensor cabling conduits, sensors, recorders and telemetry hardware

Summer & Fall 2007: HDBT (Mud Island) Free field ground motion Reference station installed. 100’ & 200’ cased boreholes drilled. Installation of equipment enclosures, sensors, electronics and telemetry hardware.

October 2007 & Spring 2009: HDAR (I-40 Arkansas weight station)
Free field ground motion reference station installed. 100’ & 200’ cased boreholes drilled. Installation of equipment enclosures, sensors, electronics and telemetry hardware.

Seismic Retrofit and Instrumentation Installation Timeline Continued

2011: TDOT funds proposal to upgrade recorders and telemetry to Kinemetrics 12 and 24 channel Granites. Recorder and telemetry upgrades completed in October 2012

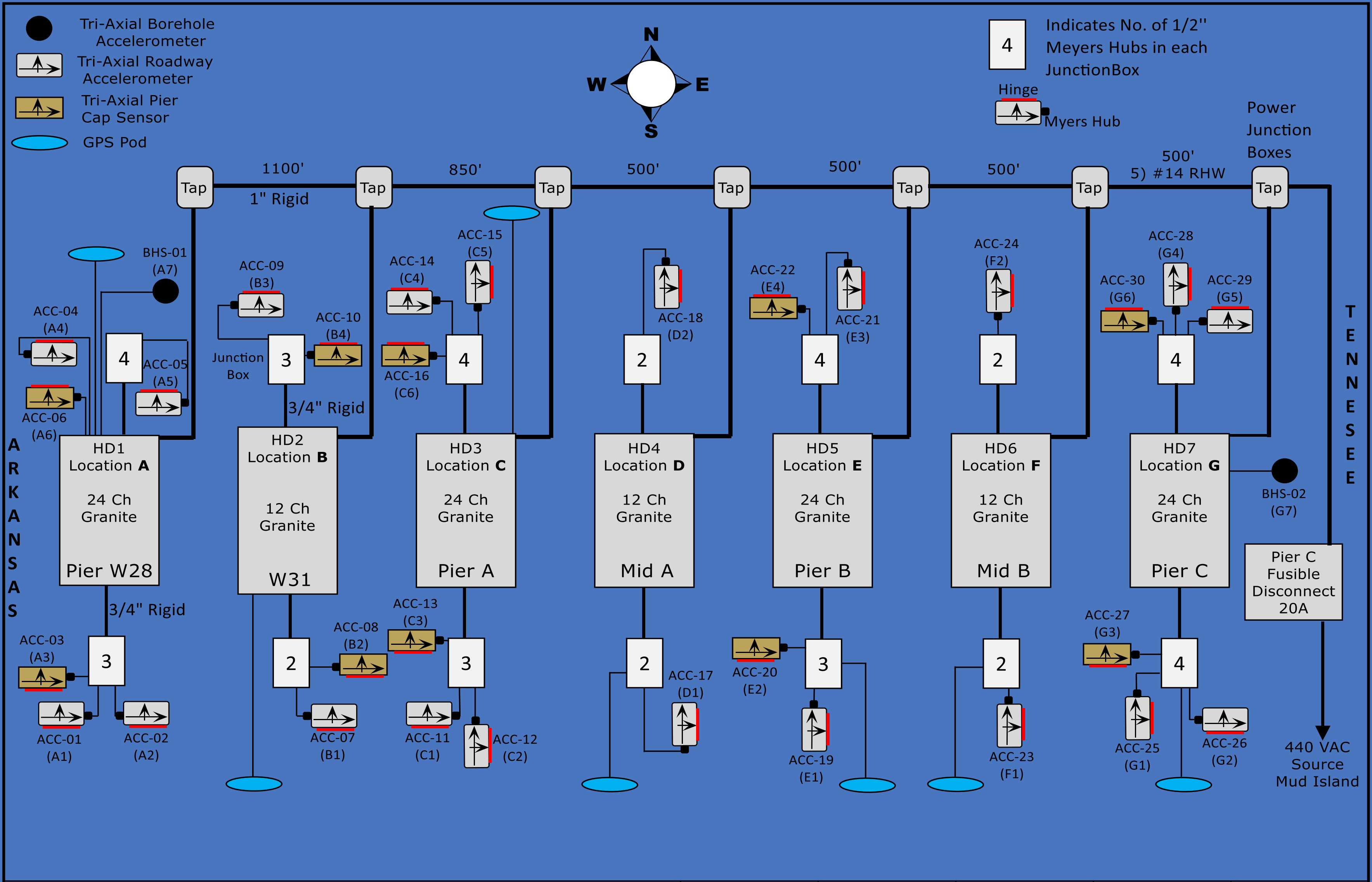
December 2016: TDOT funds proposal to upgrade 30 structural sensors and 2 borehole sensors.   All sensors installed and as of 1 September 2016. HD Bridge instrumentation now up to ANSS standards.

May 2016: USGS NSMP crew makes a site and bridge inspection to discuss options for telemetry upgrades to enable CERI to export all HD Bridge and free field data back to the USGS Center for Engineering Strong Motion Data (CEMSD) once telemetry upgrades are completed

14 September 2016: All sensors installed and healthy as of 14 September 2016. HD Bridge instrumentation now up to ANSS standards.

Fall 2017 and Spring 2018: Installation of telemetry upgrades to enable export of all HD Bridge and free field data back to CEMSD in real-time.

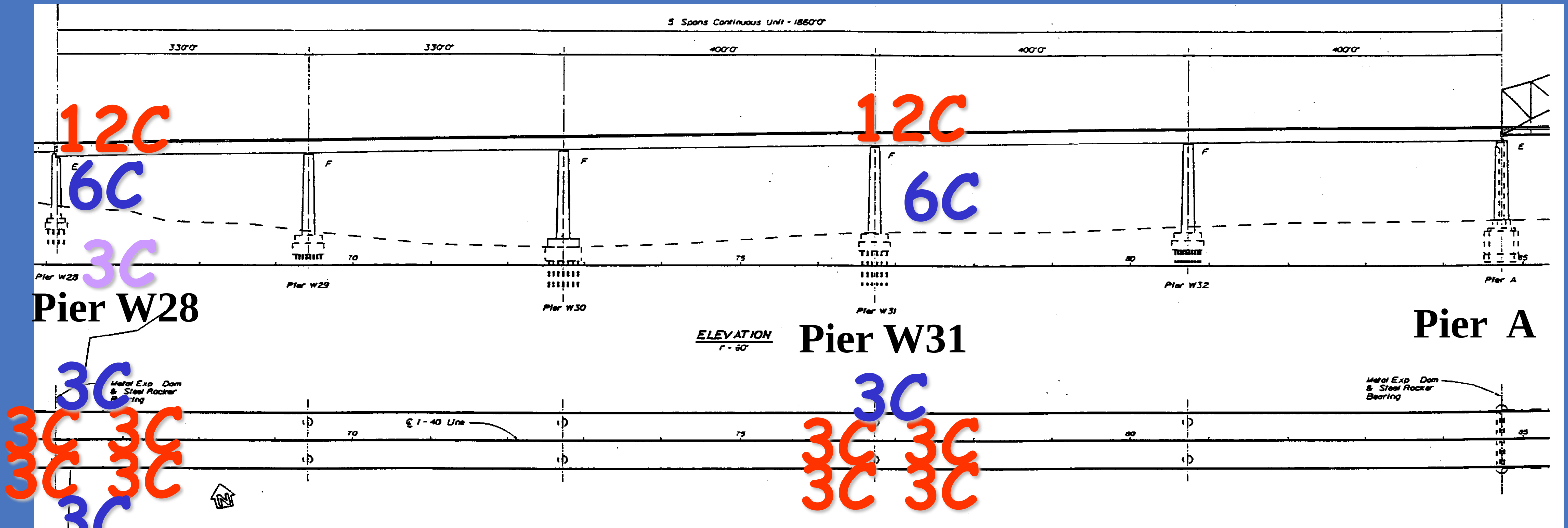
17 Years of CERI Seismic Networks Effort



I-40 Hernando-Desoto Bridge Recorder and Sensor Locations	DRAWN BY	CHECKED	DATE	SCALE	SHEET NO.
	JHB		9/2/2016		1

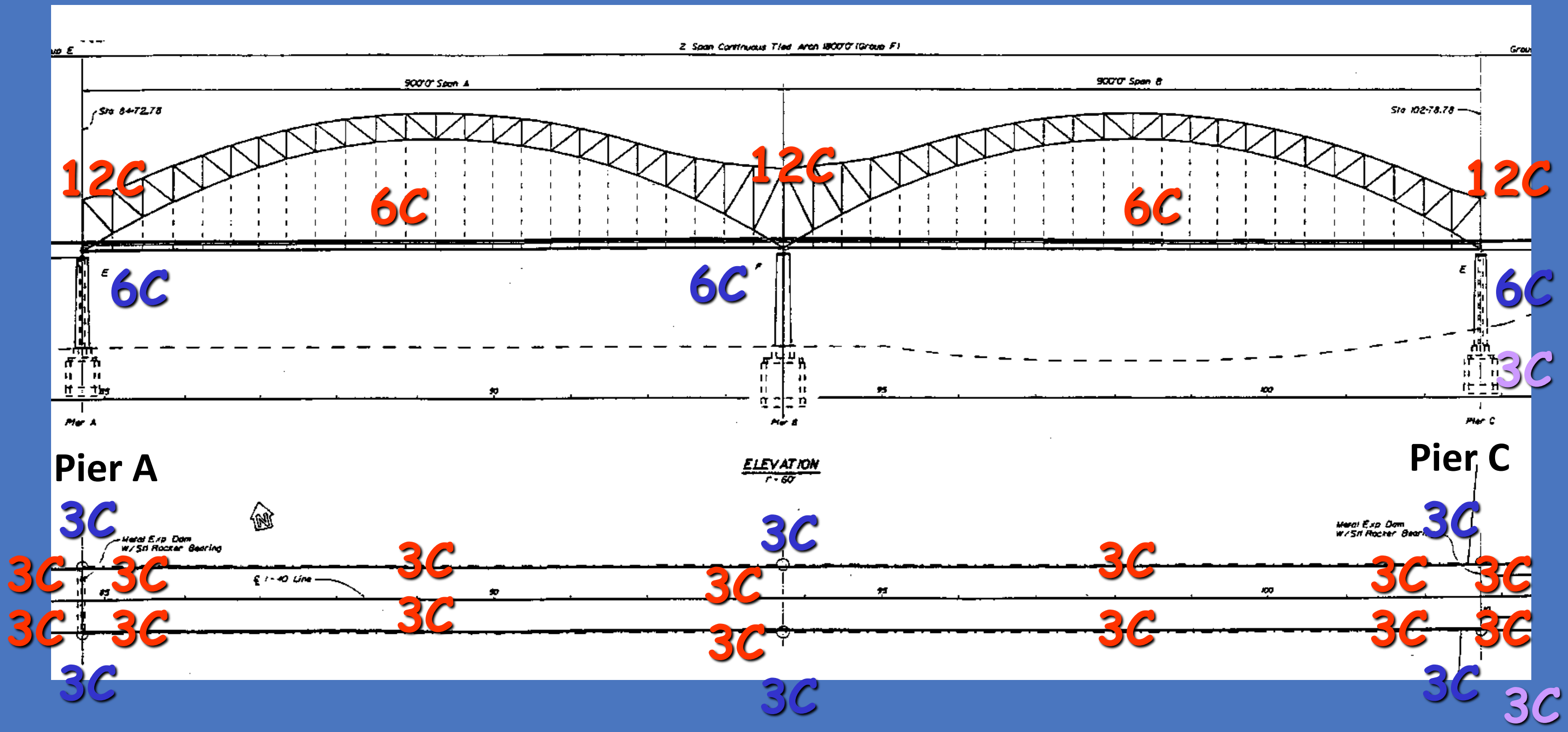
THE UNIVERSITY OF MEMPHIS
Center for Earthquake Research and Information

West Approach to the I-40 Bridge



West Approach from Pier A looking West

Main Two - Span Tied Arch



3C = 3 Components

2011 Recorder Upgrades

7 Kinemetrics 12 and 24 channel Granite recorders with new recorder end transient supression and 900 MHz Freewave ethernet radios

2016 Sensor Upgrades

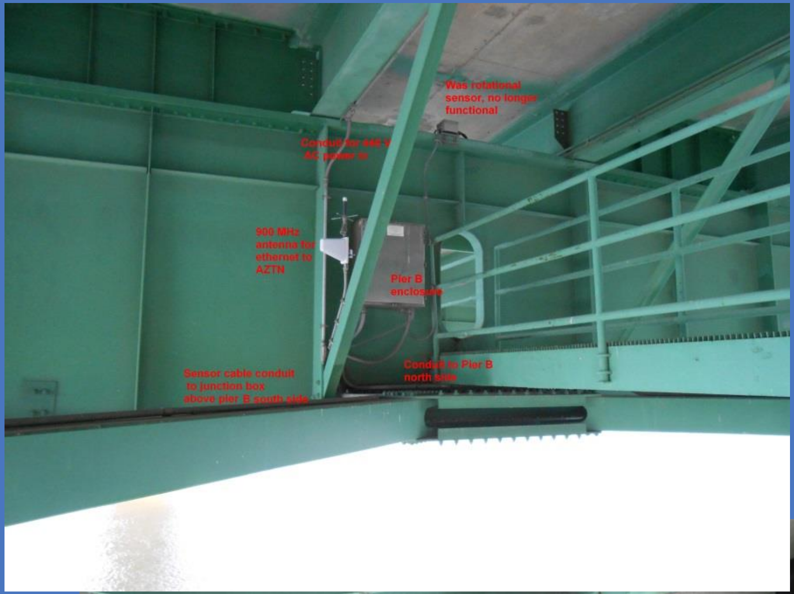
30 Triaxial Kinemetrics Episensors
with a full scale
range of ± 4g and a
sensitivity of 5V/g

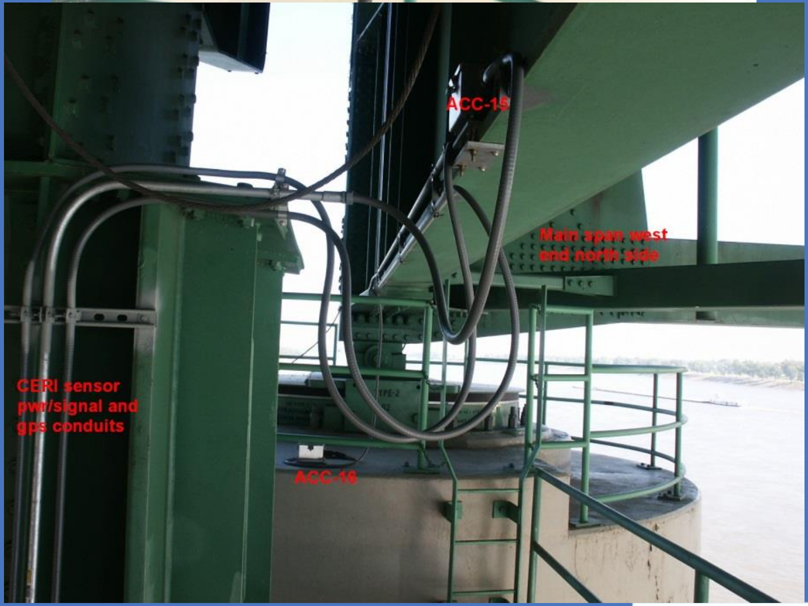
2 Triaxial Kinemetrics Borehole
Episensors with a
full scale range of ± 4g and a
sensitivity of 5V/g

2016 Sensor Upgrades

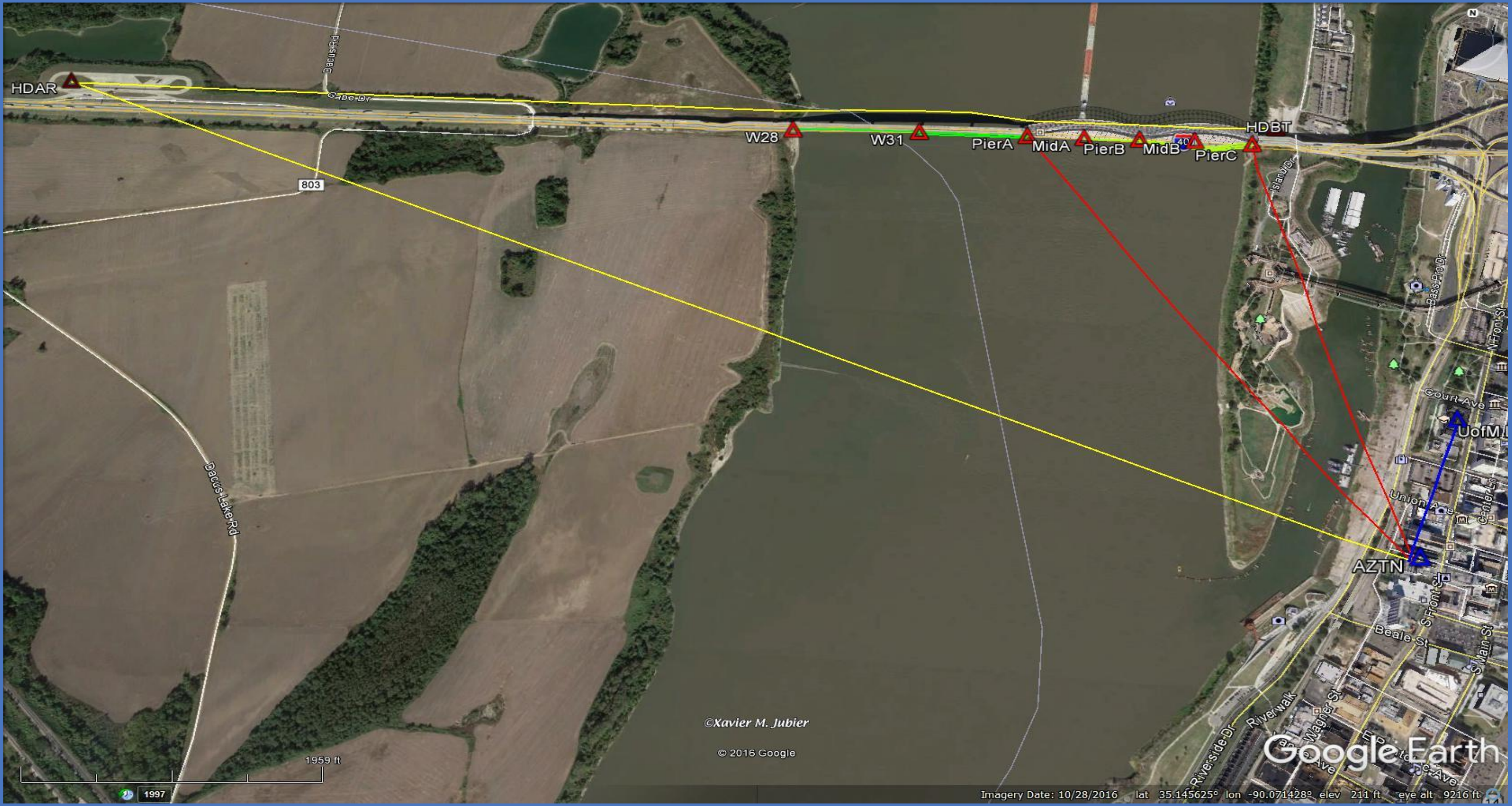
2016 Sensor Upgrades

2016 Sensor Upgrades





2017-18 Telemetry Upgrades



Ubiquiti links from HBDT and HDAR free field sites to AutoZone at 2.4 GHz

Under the bridge Afar links to Mid-A at 2.4 GHz

Under the bridge Afar links to Pier-C at 2.4 GHz

Branch Afar radios at Pier-A and Pier-C to root Afar radios on AutoZone at 2.4 GHz

Backhaul Ubiquiti link from AutoZone to the U of M Law school at 5 GHz

THE UNIVERSITY OF MEMPHIS
Center for Earthquake Research and Information

Afar Communications 2.4 GHz Industral Wireless Ethernet Bridge

Ubiquiti Power Beam 5 GHz
Industral Wireless Ethernet Bridges