# FWD Calibration Center and Operational Improvements: Redevelopment of the Calibration Protocol and Equipment

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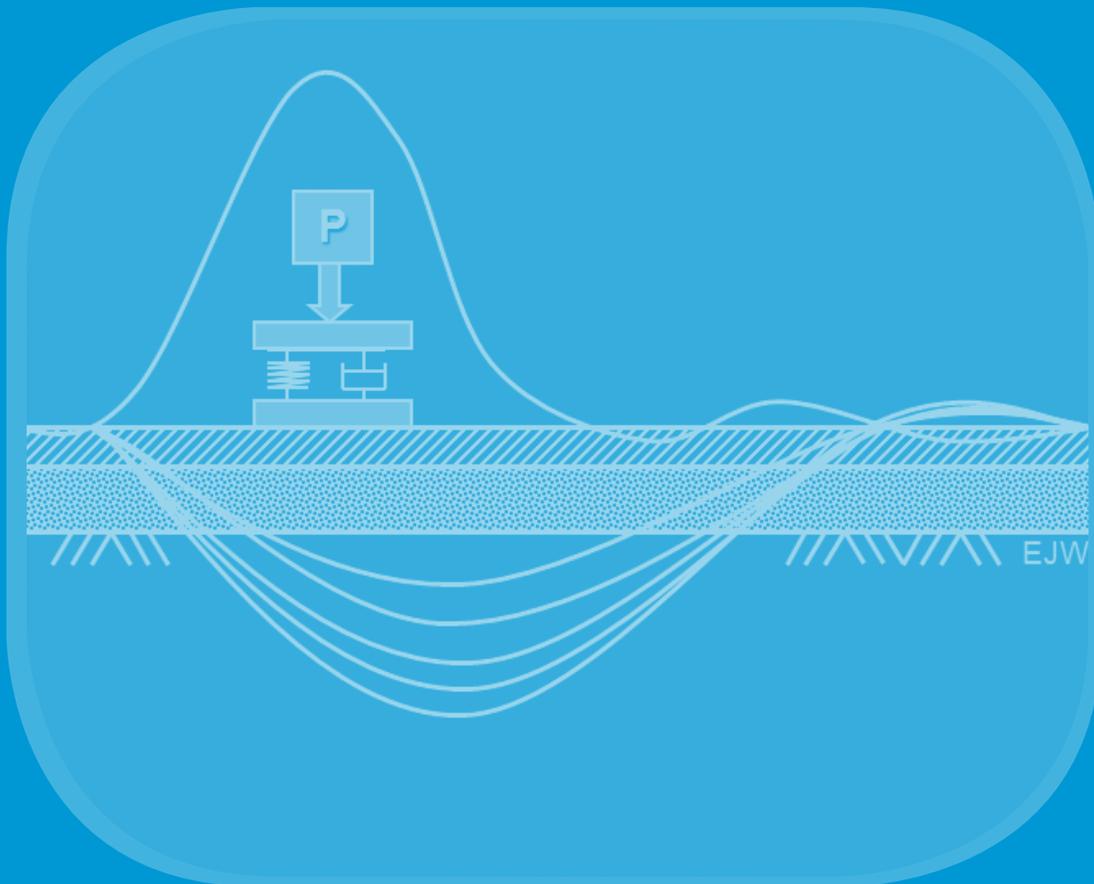
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LTPP

Long-Term Pavement Performance Program
www.fhwa.dot.gov/pavement/ltpp

FOREWORD

This report details the critical updates to the Strategic Highway Research Program falling weight deflectometer (FWD) calibration procedure. This has led to the revision of the American Association of State Highway and Transportation Officials R32-09 calibration procedure.[1] The report describes the procedural improvements and provides information on how to calibrate an FWD according to the updated procedure. Appendices provide the updated protocol for FWD calibration, drawings and specifications of the hardware needed, an updated specification for the pavement deflection data exchange (PDDX) protocol, and a flowchart for the new calibration software, *WinFWDCal*. This report will be of interest to engineers who perform structural evaluation of pavements. This final report covers the initial 2-year phase I and the subsequent task orders 1 and 2 of the pooled fund study TPF-5(039).

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Director, Office of Infrastructure
Research and Development

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16. Abstract The objective of this project is to upgrade the existing falling weight deflectometer (FWD) calibration system to make calibration sustainable for the next decade without a loss of quality while ensuring that any new procedures are compatible with all brands of FWDs sold in the United States. This involves upgrading the hardware and software used in calibration to take advantage of improvements in technology. The primary result of the FWD calibration procedure is to obtain gain factors used to correct FWD load and deflection sensor data to agree with the calibration instrumentation. Changes incorporated in the new FWD calibration procedure include replacing the reference linear variable differential transducer with an accelerometer for deflection sensor calibration, developing a stiff multiple-sensor stand to allow calibration of all deflection sensors simultaneously, updating the calibration software to a modern programming language with the ability to electronically read data from each brand of FWD, and using modern data acquisition techniques to eliminate sensitivity problems from the older Strategic Highway Research Program FWD calibration protocol. The time to complete an FWD calibration was greatly reduced. This report outlines the updated procedures and provides details about the equipment and methods needed to perform the updated protocol.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AMRL	AASHTO Materials Reference Laboratory
ANOVA	Analysis of variance
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CLRP	Cornell Local Roads Program
DAQ	Data acquisition board
EMI	Electromagnetic interference
FHWA	Federal Highway Administration
FWD	Falling weight deflectometer
HWD	Heavy weight deflectometer
INDOT	Indiana Department of Transportation
ISA	Industry standard(s) architecture
LTPP	Long-term pavement performance
LVDT	Linear variable differential transducer
MDT	Montana Department of Transportation
MEMS	Microelectromechanical systems
micron (μm)	One millionth of a meter or 0.0039 mil
mil	One thousandth of an inch or 25.4 microns
Mn/DOT	Minnesota Department of Transportation
NIST	National Institute of Standards and Technology
PCI	Peripheral component interconnect
PDDX	Pavement deflection data exchange
PennDOT	Pennsylvania Department of Transportation
QC/QA	Quality control/quality assurance
SHRP	Strategic Highway Research Program
TxDOT	Texas Department of Transportation
USB	Universal serial bus

CHAPTER 1. INTRODUCTION

SOURCES OF ERRORS IN FALLING WEIGHT DEFLECTOMETER MEASUREMENTS

Deflection data from falling weight deflectometers (FWDs) are used for structural evaluation of pavements and can be used to calculate remaining pavement life, load-supporting capacity, and the required thickness of structural overlays. The results of these calculations can be used to manage pavement systems at the project or network level.

Various mechanistic models of pavements are used in analysis including the elastic layer theory, the finite element theory, the discrete element theory, etc. These analytical methods utilize the moduli of elasticity of the pavement layers as an input. Pavement deflections, combined with backcalculation methods, can provide the layer moduli. However, the accuracy of the deflections has a major influence on the accuracy of the backcalculated moduli and subsequent analyses.[2]

FWD data have the following sources of error:

- Seating errors.

- Random errors.

- Bias or systematic errors.

Repeated deflection measurements plot as a bell-shaped frequency distribution as shown in figure 1.
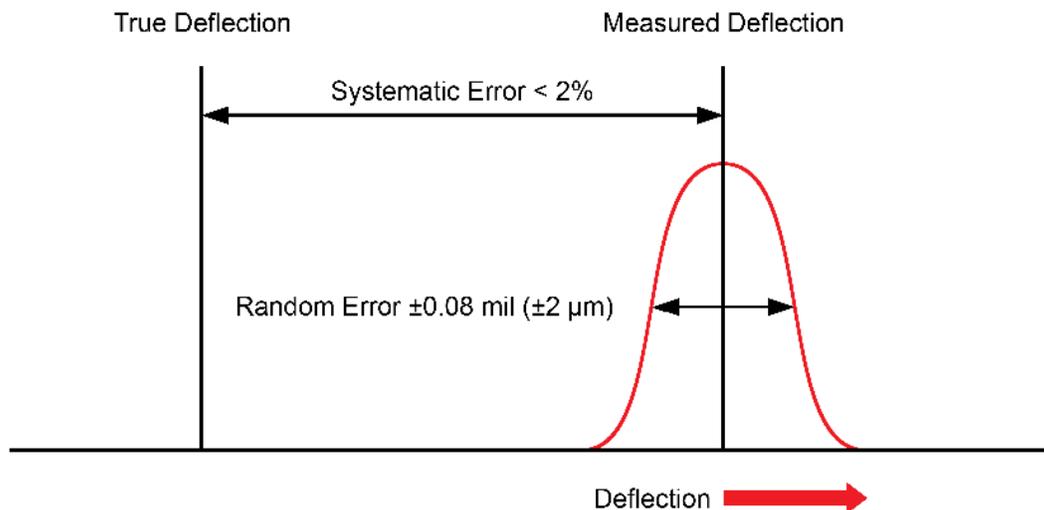
Figure 1. Illustration. Random and systematic (bias) errors.

Seating Errors

When an FWD first occupies a new test point, seating errors arise from the mechanical placement of the sensors (i.e., geophones or seismometers) on the pavement. Because of

roughness and loose debris on the road surface, the sensors are not always seated firmly. Deflection sensors can be seated fairly easily by dropping the FWD mass two times without recording data. It is seldom necessary to perform more than two drops to achieve good seating. However, extensively cracked pavements, such as alligator cracking, may pose a seating problem regardless of the number of seating drops.

In addition to the deflection sensors, the FWD load plate must also be seated squarely on the pavement. For most types of FWDs, all that is needed is to keep the load plate swivel well lubricated.

Random Errors

Random errors are mainly attributable to the digitization of the analog (voltage) signal from the deflection sensors. Analog-to-digital devices convert the voltage so it can be read and processed by a computer. Using an operating system (also known as the field program) provided by the FWD manufacturer, the digitized signal is converted to displacement in engineering units (mils, microns, and other units). Digital conversions include a small amount of error, typically one or two least significant bits. Equipment manufacturers state that the random error is on the order of 0.04–0.08 mil (1–2 μm) per reading. The magnitude of the error varies from one drop to the next independent of the peak amplitude.

Thus, each deflection reading includes a small component of random error. Because they are random, some of the errors are positive and some are negative. For any drop, it is impossible to know the magnitude of the random error or whether it is positive or negative. However, by averaging the results of several deflection peaks taken at essentially the same load level on the same test point, the random error of the average is reduced (but not totally eliminated).

To avoid changing the properties of the pavement by performing too many drops on a single point, typically no more than three to five drops per load level are taken and averaged. If the random error in one measurement is X, the random error of the average of n drops is $X/n^{0.5}$. Specifically, the random error of the average is equal to the random error of one observation divided by the square root of the number of observations. For example, by performing and averaging four drops, the random error can be reduced by half (since $\sqrt{4} = 2$).

The random error exhibited by a set of deflection sensors is quantified by the calibration procedure outlined in this report.

Bias Errors

Bias errors (also known as systematic errors) arise from the need to calibrate the sensors and are directly proportional to readings. For example, if the deflection doubles, the bias error in the reading will be approximately twice as large in magnitude. Bias errors can occur for any number of reasons; however, regardless of the reason, FWD manufacturers generally state that they will comprise no more than ±2 percent of the total reading. Therefore, bias errors could be zero, slightly positive, or slightly negative. Unlike random errors, they will be constant (as a percentage of the reading) for a given sensor from one drop to the next.

The main reason for performing FWD calibration is to reduce the bias error of each load and deflection sensor using the procedure outlined in this report. The procedure uses a reference sensor (i.e., a reference load cell for load calibration and a reference accelerometer for deflection calibration) that is independently calibrated to a high degree of accuracy and reliability. The peak result from the FWD is compared with the peak recorded by the reference sensor. The ratio (reference device divided by the FWD reading) becomes the calibration factor (also referred to as the gain factor).

Deflections must be fairly large to be able to detect bias error. In figure 1, if the measured deflection is close to the true deflection, the random error will mask the bias error. For example, if measured deflection is 2 mil (50 μm) and the bias error is 2 percent, the bias error is only 0.04 mil (1 μm). With a random error of 0.08 mil (2 μm), the bias error is so small that it is nearly impossible to detect using statistical methods.

Similarly, there are limits to how much bias error can be reduced, even with a large deflection. In the calibration procedure, there is typically an average deflection of about 20 mil (500 μm). When the bias error is reduced to 0.3 percent, the difference between the measured deflection and the true deflection is only about 0.06 mil (1.5 μm). Again, in this range, bias error is difficult to detect reliably, so 0.3 percent is effectively the practical lower limit that FWD calibration can achieve.

Significance of Errors

In 1988, Irwin et al. reported on the effect of random deflection errors on backcalculated layer moduli.[2] They found that random error, without any additional bias error, could cause the backcalculated modulus of the surface layer to be off by a factor of two or more. The effect on base and subgrade layer moduli was less dramatic.

When a deflection is greater than 4 mil (100 μm), a 2 percent bias error in an uncalibrated FWD will be larger than the ±0.08-mil (±2-μm) random error. Thus, the combined effect of random and bias errors could be substantially more detrimental to the backcalculated moduli than random error alone.

DEVELOPMENT OF THE FIRST SHRP CALIBRATION PROTOCOL

In 1988, the dramatic effect of FWD errors on backcalculated moduli led the Strategic Highway Research Program (SHRP) to begin developing an FWD calibration procedure with the goal of reducing the bias error to as close to 0.3 percent as possible. This goal was achieved by the *SHRP/LTPP FWD Calibration Protocol.*[3] Reducing the bias error to 0.3 percent ensures that a 0.08-mil (2-μm) random error is larger than the bias error for deflections up to 26 mil (667 μm). Deflections measured on most good-quality roads are seldom that large, especially for sensors at or beyond 12 inches (300 mm) from the load plate. For a calibrated FWD, random error, which is not preventable, controls the accuracy of backcalculated layer moduli in most circumstances.

Four regional FWD calibration centers were established by SHRP in 1992 and were operated by the State transportation departments in Pennsylvania (PennDOT), Texas (TxDOT), Minnesota (Mn/DOT), and Nevada. The western center in Nevada was later moved to Colorado. Since

their inception, the demand for FWD calibration services has risen steadily.[4] In August 2001, the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Materials adopted a resolution supporting the continued operation of the calibration centers.[5]

Because of changes in technology, the original calibration hardware and software became obsolete. There was a particular need to update the *FWDREFCL* software.[6] It was originally written as a disk operating system (DOS) program and utilized a Metrabyte DAS-16G data acquisition board (DAQ). DOS has been replaced by Microsoft Windows®, and the industry standard architecture (ISA) bus used by the Metrabyte board has been phased out by the computer industry.

Orr and Wallace reported that the 1992 SHRP calibration procedure had several shortcomings.[4] Among them were the following:

- The procedure was not well adapted to all types of FWDs.

- The procedure was a slow process, requiring nearly a full day to complete.

- Movement of the inertial block holding the linear variable differential transducer (LVDT) was sometimes a problem.

- Manual data entry was time consuming and prone to typing errors.

The procedure was not field portable; hence, the FWDs had to go to a calibration center, and the need for out-of-State travel posed a problem for some agencies.

REDEVELOPMENT OF THE PROTOCOL

Pooled Fund Study Tasks

In 2002, the Federal Highway Administration (FHWA) initiated a pooled fund study, TPF-5(039), with the financial support of 17 State transportation departments (see the acknowledgements section) to overcome the problems noted above. Overall, the primary goal of the study was to modernize and streamline the calibration procedure compared to the earlier SHRP approach without reducing the accuracy and precision of the results.

To meet this goal, the various FWD manufacturers and FWD calibration centers were contacted for suggestions and ideas. Based on their suggestions as well as those from annual meetings of the FWD User Group, a series of tasks was developed. The tasks accomplished during the pooled fund study were as follows:

- A universal calibration protocol was developed. Equipment and software were redesigned to work with all four brands of FWDs currently sold in the North American market.

- The calibration process was expedited. The time to perform a calibration was reduced to less than 3 h.

- New hardware and procedures were developed that sped up the calibration process and overcame the beam movement issue. The old procedure used a linear variable differential transducer (LVDT) as the reference deflection sensor; however, at certain times of the year, movement of the inertial system holding the LVDT was a problem. To correct this problem, the LVDT was replaced with an accelerometer whose signal was double integrated to obtain deflection.

- A Microsoft Windows®-based software program was developed to perform all activities of FWD calibration. The entire FWD calibration procedure is now controlled by *WinFWDCal*. This software provides a dual-unit option in metric and U.S. customary units. Data checks for quality control (QC) are built into the software. Electronic data transfer speeds up the calibration process. *WinFWDCal* also provides a mechanism for storing data for historical review. Software updates have been issued quarterly since the original release in November 2006. Version 2 of the software was released in May 2010.

ADDITIONAL ACCOMPLISHMENTS OF THE POOLED FUND STUDY

The four original SHRP calibration centers have been outfitted with new equipment, and their personnel have been trained and certified. In addition, two new calibration centers have been established, operated by the Montana Department of Transportation (MDT) and the California Department of Transportation (Caltrans). The calibration center operated by the Indiana Department of Transportation (INDOT) has also been updated, but it is not available to outside agencies.

While they are not part of the pooled fund study project, calibration centers have also been set up at other manufacturing facilities: Foundation Mechanics Inc. (JILS) in El Segundo, CA; Dynatest® in Starke, FL; and Carl Bro in Kolding, Denmark. Additionally, the calibration center operated by Main Roads Western Australia in Perth, Australia, has been updated, and new calibration centers have been established at the Australian Road Research Board in Melbourne and Brisbane, Australia, and at Fugro PMS in Hamilton, New Zealand.

The new equipment and procedure are fully portable. Onsite calibrations conducted by certified technicians have been performed in Hawaii and Chile, and nine different FWDs have been calibrated at remote locations in Australia. Four agencies (Dynatest®, Foundation Mechanics Inc. (JILS), Carl Bro, and Fugro PMS) are currently offering onsite calibrations, and others have expressed interest in doing so.

A spinoff product of the project arose from the need to electronically transfer calibration data from the FWD computer to the calibration computer. Each different type of FWD has its own native file format, and the formats are not interchangeable. This incompatibility led to the development of *PDDXconvert*, which is a software program that converts each native FWD data file to the pavement deflection data exchange (PDDX) standard (see appendix C).[7,8] It is used integrally with *WinFWDCal* to seamlessly transfer FWD data to the calibration computer. *PDDXconvert* can also be used in a standalone mode in support of other software, such as those used for backcalculation. For example, the *MODTAG* backcalculation program uses *PDDXconvert* to process all types of FWD data to determine pavement layer moduli.

Quality Assurance Procedures

Quality assurance (QA) procedures have been developed to annually recertify the calibration center operators. Procedures and checklists have been applied successfully and updated several times during four annual cycles of QA visits. Currently, all FWD calibration centers are operated by certified technicians.

At the conclusion of the pooled fund project in October 2010, the AASHTO Materials Reference Laboratory (AMRL) in Gaithersburg, MD, took over the responsibility of certifying calibration technicians. In preparation of this responsibility, the AASHTO personnel worked and trained with Cornell University staff for more than 1 year.

Adoption of the Calibration Procedures by AASHTO

The SHRP FWD calibration protocol was originally adopted by AASHTO as AASHTO R32-03.[9] The AASHTO R32-03 procedure has been revised to reflect the changes brought about by the pooled fund study, and in January 2009, the AASHTO Subcommittee on Materials approved and adopted the revised procedure. The revised procedure was published as AASHTO R32-09.[1]

There have been additional revisions and improvements in the calibration procedure since 2009. As of October 2010, a revised AASHTO R32-09 procedure was under review by AASHTO, and it is expected to be published in 2011.[1]

The AASHTO R33-03 for annual calibration of the reference load cell has also been updated.[10] It was submitted for review and approval by AASHTO in May 2010. As of October 2010, it was under review by AASHTO, and it is expected to be published in 2011.[10]

Revision of the PDDX Standard

In April 1998, AASHTO adopted a standard for PDDX.[7] The initial intent of the standard was to facilitate electronic input of FWD data to the *DARWin* pavement design program. At the 2001 meeting of the FWD User Group in Gulfport, MS, all four FWD manufacturers confirmed they would provide an output file in their field programs that complied with the PDDX standard.

As noted previously, the pooled fund study used the PDDX standard output as the means for electronic exchange of FWD calibration data. However, several problems became evident. First, the PDDX file input requirements for *DARWin* were not fully compliant with the 1998 AASHTO PDDX standard. In addition, the AASHTO PDDX standard did not provide a placeholder for all of the FWD identification data that are needed for FWD calibration.

To overcome these problems and continue with the project, the *PDDXconvert* computer program was created.[8] In addition, a revised version of the PDDX standard was created to ensure compatibility of the PDDX files and satisfy the original intent of the AASHTO PDDX standard (see appendix C).

Development of an Informational Video

An 11-min video was produced to familiarize FWD owners with the new calibration procedure and encourage State transportation departments to utilize the calibration facilities. The video is available at the Long-Term Pavement Performance (LTPP) Web site, and CD-ROM copies can also be obtained from FHWA.

Long-Term Calibration Center Support Stewardship

Responsibility for the long-term support for the calibration centers is being transferred to AMRL. From March 2009 to June 2010, training was provided to two AMRL technicians and their supervisor. The training placed emphasis on the QA visit and operator certification processes (see appendix D). Each of the nine calibration centers was jointly visited one or more times by both AMRL and Cornell personnel. AMRL was slated to take over the QA visit responsibility starting in late 2010. Cornell expects to continue to support the centers' needs for technical assistance, reference load cell calibrations, and software upgrades for at least 1–2 years.

CHAPTER 2. OVERVIEW OF THE NEW FWD CALIBRATION PROCEDURE

Philosophically, the new AASHTO calibration procedure is similar to the old SHRP procedure; however, the manner in which the new procedure is carried out is different. The basic steps of the procedure are as follows:

1. Independently calibrated reference transducers are used to calibrate the load and deflection measurement systems on an FWD. This is called reference calibration.

2. After reference calibration, relative calibration of the deflection sensors is used to refine the calibration factors (also known as gain factors).

3. The gain factors are checked for acceptability and then entered into the FWD operating system (i.e., the field program) in the FWD computer.

4. The gain factors are used as multipliers to the internal results from the FWD.

Few changes were made in the load system calibration procedure, which is carried out in a similar manner to the old SHRP protocol. However, more flexibility is allowed in the number of load levels used.

The deflection sensors are calibrated simultaneously by placing them in a rigid columnar stand along with a reference accelerometer. This expedites the procedure, as the old SHRP protocol specified performing reference calibration one sensor at a time. Data from the accelerometer are double integrated to yield a precise peak reference deflection.

Relative calibration is performed in the same stand as reference calibration, and the procedure checks the quality of the calibration. Sensors are rotated in the stand to remove any bias due to position. Only one rotation is required, which also helps expedite the procedure.

The new protocol requires two operators: the FWD system operator and the calibration system operator. The protocol takes less than 3 h to perform, provided the FWD is in working condition. The detailed FWD calibration protocol is given in appendix A.

WINFWDCAL

The AASHTO protocol is conducted using a new software program, *WinFWDCal*.[11] The program reads input from the FWD computer and produces all required outputs. The Microsoft Windows® user interface is graphically oriented, showing the time history data for each drop during reference calibration. Typical screens are shown in figure 2 and figure 3.

Data from FWD are transferred electronically to the calibration computer using a flash drive, floppy disk, or CD, which enhances accuracy and speeds up the calibration process. *WinFWDCal* utilizes an FWD data file format conversion program called *PDDXconvert*.[8] The program reads data files from all types of FWDs in their native format and converts them to an AASHTO standard PDDX format.
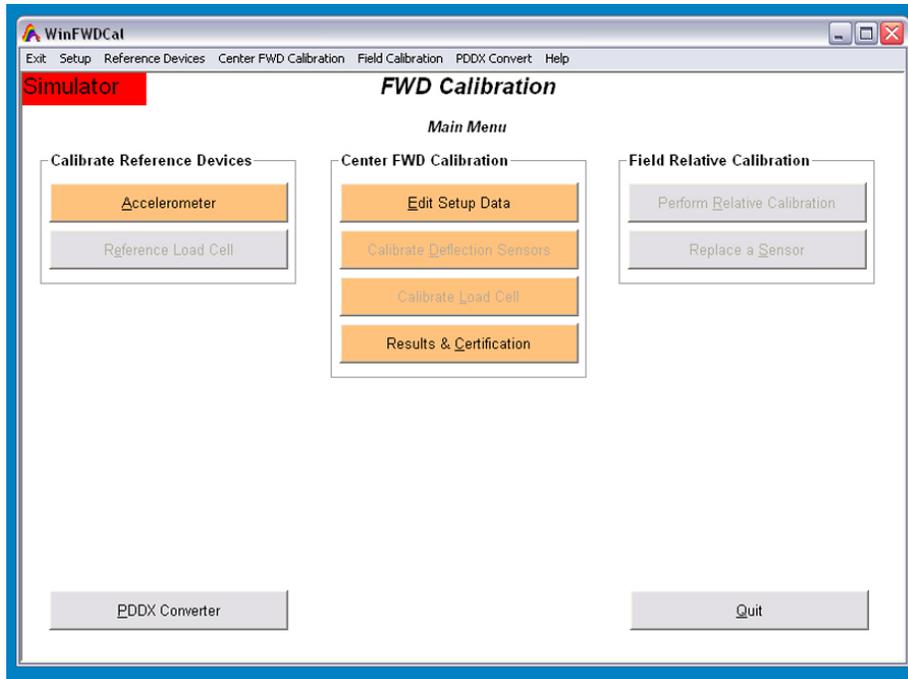
Figure 2. Screen shot. *WinFWDCal* **software program FWD calibration screen.**
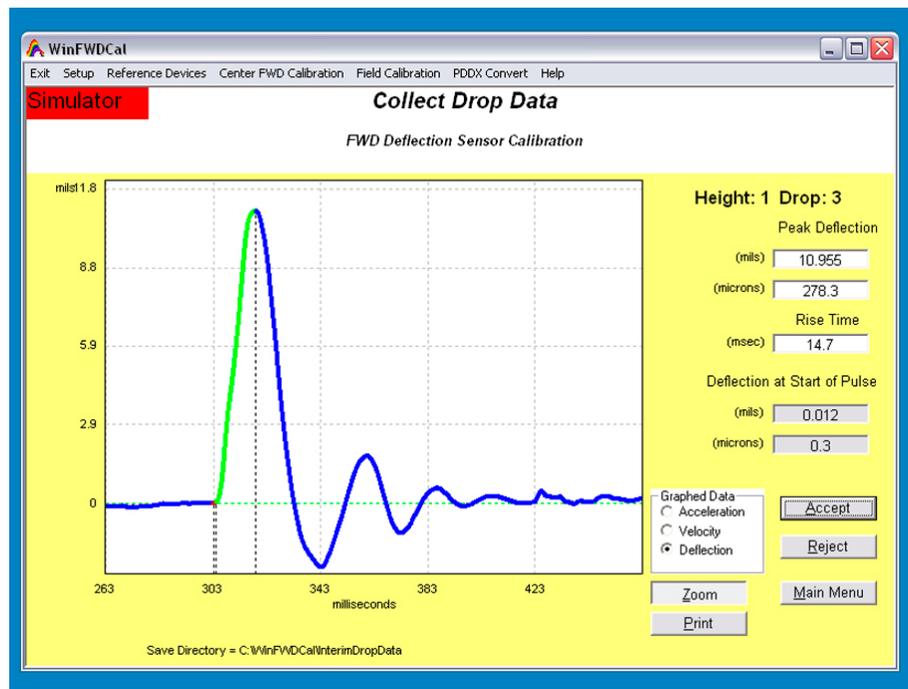
Figure 3. Screen shot *WinFWDCal* **software program collect drop data screen.**

Data are checked during acquisition to ensure accurate, high-quality results. A calibration certificate is produced, and, in instances where prior calibration results are available for a particular FWD, the history is reviewed as part of the acceptance process. At the completion of the calibration, data are retained for historical and forensic analyses.

CALIBRATION OF THE REFERENCE DEVICES

The two reference calibration devices (load and displacement) are calibrated against independent reference systems. The reference load cell is calibrated annually with a National Institute of Standards and Technology (NIST) traceable universal testing machine. A load algorithm is developed using a polynomial statistical fit between a corrected load in pounds from the universal testing machine and the output from the reference load cell in volts. This adjusts for the typical nonlinear response of the reference load cell, allowing it to achieve accuracy approaching 0.1 percent of full scale. In the new procedure, the calibrated range of the reference load cell is also increased from 20,000 lbf (89 kN) to 24,000 lbf (107 kN) to accommodate a higher preload force from the FWD. A study performed by Orr and Wallace in 2002 confirmed the need to calibrate the reference load cell annually.[4]

The reference accelerometer is calibrated daily using the Earth's gravitational field. Daily calibration accounts for temperature, hysteresis, and other known variations in the response of the reference accelerometer. Nonlinear characteristics of the accelerometer are corrected using factors provided by the manufacturer. However, gravitational differences between regional calibration centers can result in a small difference in the results of daily calibration. The maximum difference in gravity constants between the Pennsylvania and Colorado calibration centers (at the lowest and highest elevations) can result in a difference of about 0.1 percent or less than 0.02 mil (0.5 μm) for a deflection of 20 mil (500 μm).[12]

SIGNAL CONDITIONER AND DATA ACQUISITION SYSTEM

The Vishay 2310 signal conditioner is still used in the new protocol. The major change is the use of a Keithley model KUSB-3108 universal serial bus (USB) DAQ rather than the industry ISA bus Metrabyte board. The USB DAQ is an improvement since it is small and can be shipped with the reference load cell for its annual calibration. In addition, the newer USB board uses a 16-bit conversion of the analog signal rather than the older 12-bit ISA board.

Data acquisition is controlled by *WinFWDCal* via commands to the DAQ. If the DAQ is not plugged into the computer when *WinFWDCal* is running, the program runs in a "simulation mode" that allows data for previously completed calibrations to be reviewed.

The DAQ has been upgraded by use of triggering. By using buffers, the rise of the first major peak on the time history triggers data collection (both before and after the peak); this improves the ability to detect the FWD impulse.

FWD CALIBRATION

The new protocol provides two types of FWD calibration: monthly and annual calibration. Monthly calibration is performed by the FWD operator at any suitable location to verify that the FWD is working correctly. *WinFWDCal* can assist with data evaluation. Annual calibration, which historically has been performed at calibration centers, can also be performed onsite wherever an FWD is located. The calibration equipment is sufficiently portable and can be transported to the FWD. A certified technician must perform the annual calibration whether it is performed at a center or onsite. Annual calibration of an FWD is completed in four steps: (1) setup, (2) FWD deflection sensor calibration, (3) FWD load cell calibration, and (4) documentation. *WinFWDCal* must be used in the process.

Step 1: Setup

Setup involves inputting information about the FWD and its current calibration settings. The FWD calibration operator inputs details about the calibration, and the FWD owner determines the number of load levels to be used. During setup, the FWD is used to determine the recommended number of drops needed for each load level and the trigger level for the reference accelerometer. The reference accelerometer is also calibrated daily during setup. A special calibration stand is used for this purpose.

Drop Sequence

Under the old SHRP reference calibration procedure, the drop sequence was fixed at 20 total drops (5 drops at 4 load levels). The number of drops required was based on having a 16-mil (400-μm) deflection at the largest load level used in the calibration, but many of the existing FWD calibration centers cannot achieve this deflection during different times of the year because of seasonal variations in the response of the test slab.

During setup, *WinFWDCal* determines the minimum number of drops needed to meet the precision requirements on the day of calibration when the FWD is in position. Determining a minimum also allows the number of load levels to be selected as needed for different brands of FWDs. Some FWDs can be calibrated more easily using only three load levels rather than four.

Step 2: FWD Deflection Sensor Calibration

The FWD deflection sensors are calibrated in two sequential procedures: reference and relative calibration. Reference calibration uses a series of replicate drops to determine a relationship between the deflections recorded with the reference accelerometer and the deflection sensors.

All of the FWD sensors are placed into a columnar calibration stand with the reference accelerometer in the middle. The multiple drop sequence is repeated after the sensors are inverted relative to the accelerometer to eliminate a small bias in the stand. In the case of KUAB seismometers, there are two columns instead of one. The calibration stand is rotated 180 degrees in the ball-joint anchor to eliminate the bias in the stand.

At least two trials are performed to ensure repeatability and improve precision. Data collected from each trial are used to determine the relationship between the reference accelerometer and

the FWD deflection sensors. The slope of the regression line that is forced through (0, 0) is used to define an interim gain factor for each sensor. This interim gain is stored internally in *WinFWDCal* and used as part of the second procedure, relative calibration, to provide the final gain factors for the deflection sensors.

Next, 40 drops are performed in each of the two sensor arrangements used during reference calibration. This eliminates any bias from the stand and provides a large number of drops that are used in a statistical analysis of variance (ANOVA) to improve the precision of the FWD gain values. Relative calibration is also a means of detecting any anomalous behavior of the deflection sensors.

Step 3: FWD Load Cell Calibration

The FWD load cell is calibrated with a series of replicate drops from at least three different load levels. Data collected from each trial are used to determine the relationship between the reference load cell and the FWD load cell. The slope of the regression line that is forced through (0, 0) is used to modify the existing gain of FWD. At least two trials are performed to ensure repeatability and improve precision.

Step 4: Documentation

The final step in annual calibration of an FWD is to review the data and document the calibration through a series of QA data checks. *WinFWDCal* alerts the user to perform additional tests or repeat the calibration if needed.

WinFWDCal produces a certificate of calibration along with an electronic data file containing the calibration gains. The electronic file is transferred to the FWD operator, and the new gain settings are manually input into the FWD. This process may be automated in the future when the FWD operating systems have a means to read the electronic file.

RELATIVE CALIBRATION OF THE DEFLECTION SENSORS

The major difference in relative calibration when using the new annual calibration protocol is the elimination of the need to fully rotate the sensors in the calibration stand. Since the new stand is very stiff, the sensors only need to be inverted around a common average point to eliminate bias due to position in the stand. Although this constitutes a relatively small time savings, the process is much easier to perform than the full rotation needed in the SHRP procedure.

Monthly Calibration of the Deflection Sensors

Frequent relative calibration of the deflection sensors will ensure that FWD is operating properly. It should be completed at the home base on a monthly basis using a relative calibration stand provided by the FWD manufacturer. Relative calibration involves multiple drops and full rotation of all sensors in all positions in the stand. By rotating the sensors through all positions, any bias due to position in the stand is removed. If a sensor needs to be replaced, the relative calibration procedure can be used to compare it with the remaining sensors to determine a temporary gain factor for the new sensor.

SETTING UP NEW FWD CALIBRATION CENTERS

The pooled fund study allowed for the creation of two new FWD calibration centers. These centers are located in Helena, MT, and Davis, CA, and they will be operated by MDT and Caltrans/University of California Davis. New equipment and training were provided at both locations, and both centers were fully operational in summer 2009.

In addition, two new calibration centers were created at the Foundation Mechanics, Inc. (JILS) manufacturing facility in El Segundo, CA, and at the Carl Bro manufacturing facility in Kolding, Denmark (these centers are not part of the pooled fund study). Two new centers have also been established in Melbourne and Brisbane, Australia, operated by the Australian Road Research Board. Installation and training has been provided, along with operator certification.

Sites for new FWD calibration centers must meet certain minimum specifications. Calibration center needs are well known and are based upon experience gained from the first 15 years of FWD calibration. Appendix F provides details about setting up the equipment found in figure 4, but certain basic operational issues must be discussed prior to ordering equipment and installing a test pad.

Figure 4. Photo. Calibration system hardware set.

Calibrating an FWD at a center controls or eliminates as many variables as possible by using the actual ground wave created by the FWD. Choosing an appropriate site at the center to install the test pad is important. A site should be large enough for the FWD and tow vehicle to be placed entirely indoors during calibration, which allows the calibrations to be performed year round. If

possible, a trailer-mounted FWD should be driven into the facility prior to construction to ensure that the location is appropriate. In addition to the space, the site should have enough room to store and secure the FWD calibration equipment, including the testing stands, load cell, electronics, and the calibration computer. The computer can be a laptop or a desktop, but it should be dedicated to FWD calibration.

Once a site has been chosen, the test pad can be installed. Test pads are recommended to provide consistent deflections. If the test pads are built well, deflections will be consistent from season to season. Test pads can also be designed to provide larger deflections than might be found on normal industrial floors. Test pads that are 12 by 15 ft (4.0 by 4.5 m) are preferred, but 12- by 12-ft (4- by 4-m) pads are acceptable if space is limited. Test pad slabs must be accessible by all brands and models of FWDs. Space around the test pad should be sufficient for personnel to move and to allow the FWD to be maneuvered. A larger area is better, and at least 5 ft (2.5 m) of clear space is recommended on all sides. Table 1 lists the estimated cost for a new FWD calibration center.

Table 1. Hardware cost estimate for a new FWD calibration center.

Component	Notes	Cost[1]
Accelerometer box AB-01	Includes Silicon Designs Model 2220-5 accelerometer and cables	$1,600
Geophone stand GCS-01	Includes hardware for 10 Carl Bro and 10 JILS//Dynatest® geophone adapters	$1,600
Geophone adapters	Includes 10 adapters to mount KUAB geophones in GCS-01 stand	$200
Seismometer stand SCS-01	For up to 10 KUAB seismometers	$1,600
Floor mount BJ-01	Includes ball-joint and mounting clamp	$1,200
Signal conditioner	Vishay 2310B and 2310-A20	$2,200
Data acquisition system	Keithley KUSB-3108, with cables to signal conditioner and computer	$1,250
Load cell	Includes calibration certificate, cable, and shipping case	±$11,000
Computer	Laptop model with four USB ports	±$1,500
Total		**$22,150**

[1]Prices current as of February 2009. Prices do not include shipping, installation, or training.

UPGRADING THE EXISTING SHRP CALIBRATION CENTERS

The pooled fund study provided support for upgrading all existing calibration centers in the United States. These included the centers operated by the Colorado Department of Transportation (CDOT), INDOT, Mn/DOT, PennDOT, and TxDOT (see figure 5). Installation and training has been provided to all centers. In addition, the calibration center operated by Dynatest® in Starke, FL, and the center operated by Main Roads Western Australia were also upgraded, although they are not part of the pooled fund study. The only existing center that has not been upgraded as of November 2010 is the center operated by the South African Bureau of Standards.
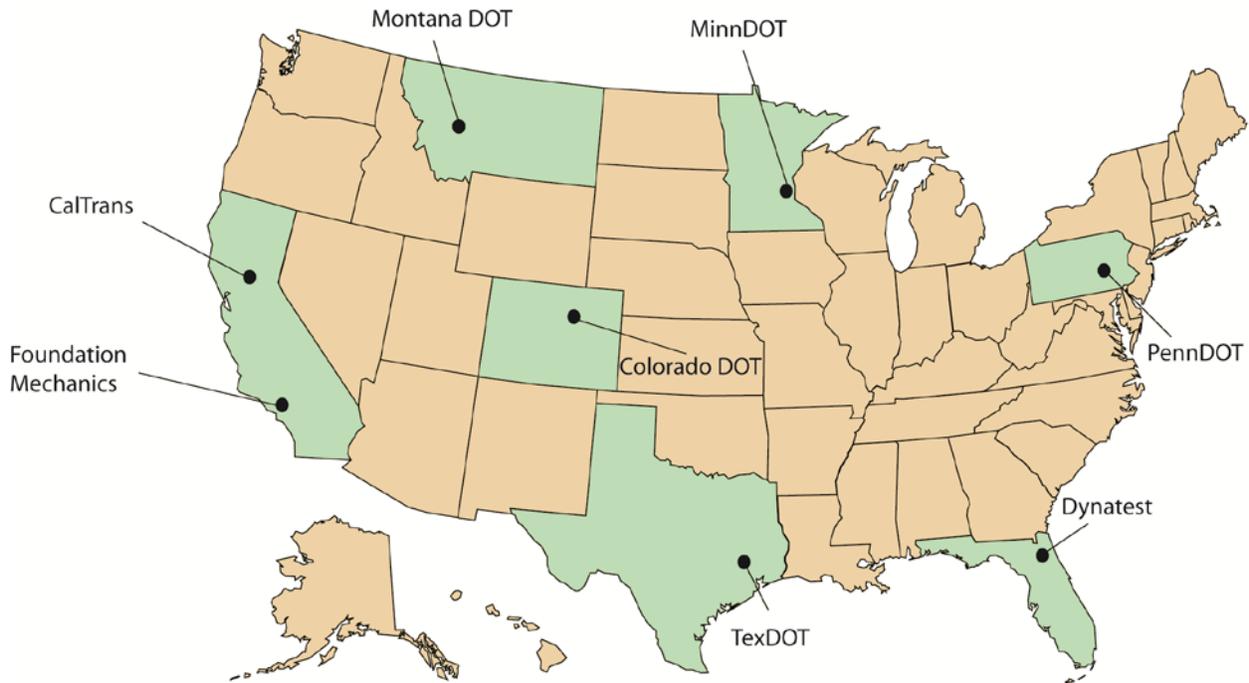
Figure 5. Map. Calibration center locations in the United States.

As a part of the upgrade, old beams and concrete blocks were removed, and new hardware equipment listed was installed (see table 1 and appendix E). Centers continued to use their existing test pads but with the new ball-joint anchor located close to the rear edge. New laptop computers were provided in most locations. During a 3-day training program, operators demonstrated their proficiency with the new procedure and were certified.

TRAINING AND OPERATOR CERTIFICATION

Calibration operators require training to use the equipment and software. Although training and certification only takes 3 days, it is recommended that new calibration operators also perform several trial calibrations prior to their first calibration for a client.

At the conclusion of the training, operators demonstrate their proficiency at carrying out the protocol detailed in appendix A, which is the same as the AASHTO R 32-09 procedure.[1] A certificate is issued to each operator who passes this review, and the certificate must be renewed annually during a QA visit. The procedures and checklists used during the QA visit are included in appendix D. All FWD calibrations must be conducted or supervised directly by a certified calibration technician.

CHAPTER 3. DEVELOPMENT OF THE NEW PROTOCOL

FWD SPECIFICATIONS AND CALIBRATION ISSUES

A primary goal of the updated calibration protocol is universal compatibility with the four brands of FWDs used in North America. Interviews conducted with the FWD manufacturers, calibration operators, some owners, and other FWD experts determined what problems were encountered during calibration with the old SHRP procedure. The following sections discuss calibration of the four brands of FWDs as well as known issues associated with their calibration. Table 2 provides an overview of the technical specifications for all four brands of FWDs.

Table 2. FWD manufacturer specifications.

FWD Brand	JILS	Carl Bro	Dynatest®	KUAB
Trailer or truck mounted	Both	Both	Both	Trailer
FWD typical maximum load	20,000 lbf (89 kN)	34,000 lbf (150 kN)	30,000 lbf (130 kN)	16,000 lbf (71 kN)
Heavy weight deflectometer (HWD) typical maximum load	50,000 lbf (222 kN)	56,200 lbf (250 kN)	54,000 lbf (240 kN)	135,000 lbf (600 kN)
Typical pulse time range	20–34 ms	20–30 ms	25–30 ms	23 ms[1]
Typical maximum deflection	80 mil (2,032 μm)	87 mil (2,200 μm)	78 mil (2,000 μm)	78 mil (2,000 μm)
Optional maximum deflection	None	None	98 mil (2,500 μm)	197 mil (5,000 μm)
Deflection sensor types	Geophone	Geophone	Geophone	Geophone, seismometer
Typical number of deflection sensors	7	9	9	7
Maximum number of deflection sensors	9	18	15	None specified
Deflection sensor mounting	Spring coupling	Spring coupling	Spring and magnetic coupling	Spring coupling
Typical load plate diameter	12 inches (305 mm)	11.7 inches (300 mm)	11.7 inches (300 mm)	11.7 inches (300 mm)
Optional load plate diameter	17.82 inches (457 mm)	17.55 inches (450 mm)	17.55 inches (450 mm)	17.55 inches (450 mm)
Data taking trigger type	About triggering[2]	Proximity sensor	Proximity sensor	See note[3]
When trigger occurs	At peak load[2]	Just before mass strikes	Just before mass strikes	See note[3]

[1]KUAB specifications are for rise time, not pulse duration time.
[2]JILS constantly monitors and buffers the load cell signal. When a peak is detected by the data acquisition system, it then uses the buffered data to look 20 ms before the peak load was recorded.
[3]KUAB has used four different triggering techniques: (1) data recording at all times, (2) end switch activated between 0.39 and 1.17 inches (10 and 30 mm) before the buffers strike the load plate, (3) end switch activated about 0.39 inches (10 mm) after the weight is released, and (4) activation when the magnet holding the weight turns off.

Dynatest®

The first Dynatest® FWD was manufactured in Denmark in 1976, and the first one was sent to the United States in 1981.[13] Dynatest® manufactures two varieties of FWDs, the model 8000 FWD and the model 8081 HWD. Both systems are trailer-mounted with 11.7-inch (300-mm) loading plates (with an optional 17.55-inch (450-mm) plate available) and can have between 7 and 15 deflection sensors. Figure 6 shows a model 8000 FWD. A truck-mounted FWD unit has recently been developed.

Figure 6. Photo. Dynatest® model 8000 trailer-mounted FWD.

Dynatest® FWDs consist of a hydraulically controlled single-mass system. Weights can be removed or added to change the magnitude of the load pulse. The standard equipment places one deflection sensor directly under the load plate, and at least six additional deflection sensors are placed along a raise-lower bar. The geophone sensor bar runs from the load plate toward the tow vehicle. Additional deflection sensors can be positioned on a rear or transverse extension bar. The deflection sensors are velocity transducers (geophones), and the deflections are calculated using a single integration of the velocity response.

The HWD normal load levels exceed the usual 6,000-, 9,000-, 12,000-, and 16,000-lbf (27-, 40-, 53-, and 71-kN) range specified in the original SHRP calibration procedure. In order for the HWD to achieve the preferred load levels, all attached weights must be removed. This causes some concern about whether the calibration is valid for the HWD since it is not normally used with all weights removed.

However, both load and deflection calibration procedures under the old and the new protocols have very tight tolerance requirements for sensor linearity. This assures that the sensors are performing linearly over the calibration range.

JILS

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The first JILS FWD was made in 1987 in the United States.[14] JILS manufactures the following four varieties of FWDs:

- JILS-20C: A single-axle trailer-mounted FWD.

- JILS-20: A two-axle trailer-mounted FWD.

- JILS-20T: A truck-mounted FWD (see figure 7).

- JILS-20HF: A trailer mounted high-force model designed for airports.

All JILS FWDs use a 12-inch (305-mm) rigid steel loading plate and have an optional 12-inch (305-mm) segmented or 18-inch (457-mm) rigid loading plate. The deflection sensors are velocity transducers, and their response is single-integrated to determine the deflection. A unique feature of a JILS FWD is its ability to report both the first and second peaks of each drop. The second peak is not calibrated in the AASHTO R32-09 procedure.[1]

Previously, the lack of a swivel on the load plate has made calibration difficult in some locations (although the manufacturer has recently announced that a swivel is now an available option). Without a swivel, the calibration operator must ensure that the load plate is squarely seated on the reference load cell without any gaps around the perimeter. Since the standard JILS load plate is slightly larger than the 11.7-inch (300-mm) diameter of the reference load cell, adjustments have been made to the original design of the reference load cell. The guide fingers have also been adjusted to accommodate the JILS load plate.

Two additional issues posed challenges for calibrating JILS using the SHRP procedure. The machine uses a large mass with a short drop height. As a result, it was difficult to achieve optimal triggering at the low drop height due to the short free fall time as well as mechanical vibration. Additionally, JILS applies a large static preload on the pavement. This frequently causes clipping of the load response at the high drop height. These problems have been reduced in the new AASHTO R32-09 procedure.[1]

Figure 7. Photo. JILS-20T truck-mounted FWD.

Carl Bro

Carl Bro manufactures both a double-axle trailer-mounted FWD and a vehicle-mounted FWD.[15] The two loading plate options are a four-segmented 11.7-inch (300-mm)-diameter plate or a 17.55-inch (450-mm) plate. A single mass is used and controlled hydraulically. The minimum number of deflection sensors is 9, and the maximum is 18. One sensor is used to measure deflection through the center of the load plate, while the remaining sensors can be placed on the raise-lower bar oriented toward the tow vehicle or on the side or rear using a T-beam. The deflection sensors are velocity transducers, and their response is single integrated to determine the deflection. Figure 8 shows an example of a Carl Bro FWD.

Figure 8. Photo. Carl Bro FWD.

KUAB

KUAB has been manufacturing FWDs since 1976, and the first one was sent to the United States in 1988.[14] KUAB manufactures both trailer-mounted and vehicle-mounted FWDs that are either single- or dual-mass. Most KUAB FWDs use seismometers to measure deflections. Velocity transducers (geophones) are available as an option for some models. The overall number of deflection sensors is unlimited according to the specification, although the KUAB-50 model has seven sensors. The sensors can be aligned either toward the tow vehicle (see figure 9) or away from it. KUAB has the option of either a four-part segmented load plate with an 11.7-inch (300-mm) or 17.55-inch (450-mm) diameter, or it has a rigid load plate with a 5.85-inch (150-mm), 11.7-inch (300-mm), or 17.55-inch (450-mm) diameter. Figure 9 shows a KUAB FWD with geophone sensors.

Figure 9. Photo. KUAB FWD with sensors aligned toward the tow vehicle.

For the KUAB FWD with deflection sensors positioned to the rear of the load plate, positioning the FWD load plate close enough to the LVDT during the SHRP calibration procedure was difficult. This made it hard to trigger the data acquisition system and achieve the desired deflections during geophone reference calibration. About triggering, which is discussed in more detail in a later section, has reduced that issue.

Issues Encountered with the SHRP FWD Calibration Protocol

In addition to the FWD-specific issues cited above, several more general problems were encountered while using the old SHRP procedure and equipment. These included excessive beam movement, difficulty in triggering, and difficulty in getting sufficiently large deflections. Electrical problems included excessive noise in the signal and insufficient power from the battery charger. Also, data acquisition problems affected the speed and accuracy of FWD calibration.

Beam Movement Problems

Beam movement was measured using one of the deflection sensors from the FWD. Figure 10 shows the beam and block combination used in the SHRP protocol. After reference calibration of each deflection sensor, beam movement was determined from the FWD time histories. If beam movement was 0.12 mil (3 μm) or more when the sensor being calibrated peaked out, the calibration was repeated. This problem seemed to be aggravated by water in the soil beneath the test pad, making it a seasonal issue. This forced the FWD owner to return and attempt to calibrate at a later date. It also caused some of the calibration centers to shut down for periods of time (particularly in the spring).

Figure 10. Photo. FWD calibration beam and inertial block.

The SHRP calibration protocol required at least 16 mil (400 μm) of deflection at the 16,000-lbf (71.2-kN) load level during deflection sensor calibration. This meant that the load plate needed to be close to the end of the beam without touching it. Due to geometric constraints, it was difficult to achieve the necessary load plate proximity for several models of FWDs and HWDs.

Data Acquisition Problems

The most common data acquisition problems fell into the following two categories: FWD brand-specific problems and general data problems.

KUAB and JILS FWDs had triggering problems, especially at low load levels. The SHRP procedure used the response of the test pad to trigger the data acquisition system. When the calibration software detected the vibration in the test pad due to the release of the FWD mass, the system began to acquire data. Because of the nature of its mass release system, KUAB FWD did not cause a measurable vibration at the time of release. As a result, the data acquisition system often failed to begin acquiring data. Conversely, JILS produced a lot of vibration when the mass was released, and this often triggered data acquisition too early.

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Data transfer from the FWD was a problem with the old SHRP method because while the calibration system software collected and stored data from the reference calibration instrumentation, the data collected from the FWD had to be printed and typed into the calibration system. This increased the probability of transcription errors and took a considerable amount of time.

The software program *FWDCAL 4* was written to perform relative calibration data analysis using the SHRP method. Because the program could only read output from older Dynatest® FWDs, a spreadsheet with macros was written to work with additional data formats. However, the spreadsheet did not cover all FWD types and system configurations.

The lack of a common data file format was the main problem. Because each brand of FWD outputs data was in a different native format, calibration operators were required to be experts in reading FWD data. Differences in data file formats occasionally required manual calculations to convert FWD plate pressure to load units. Some but not all of the different brands of FWDs have the ability to directly produce the AASHTO standard PDDX data format.[7] All FWD manufacturers have promised to provide the PDDX output option. Some FWDs use a separate converter program to change their native data format into PDDX format. Unfortunately, the original AASHTO standard format did not provide all of the data needed for FWD calibration.

Other Known Problems

Legislative and financial restrictions limited some State transportation departments from sending people and equipment out of State to one of the FWD calibration centers, preventing them from getting their FWDs calibrated to the SHRP/ LTPP standard. Included in this group were FWDs from other countries such as Canada.

EQUIPMENT AND PROCEDURAL UPDATES

This section discusses the research that led to the development of the new FWD calibration protocol. The detailed procedure is included in appendix A. Specifications for each item of calibration equipment mentioned are provided in appendix E.

Data Acquisition

The Keithley KUSB-3108 DAQ replaces the Metrabyte model DAS-16G in the new protocol. The Keithley board offers the advantages of USB 2.0 connectivity, which is universally compatible with any computer with USB 1.0 or 2.0 ports and does not require the now obsolete ISA bus.

Initially, the possibility of using an internal peripheral component interconnect (PCI) card was explored. The PCI specification is slowly being phased out in favor of the faster PCI express slot; however, PCI cards are not backwards compatible with the new standard. An external device such as the KUSB-3108 can be easily installed by connecting it to the calibration computer via a standard USB cable. USB standards are backwards compatible and are a common feature of all modern computers.

A feature specific to the chosen model was the availability of drivers compatible with the Microsoft Visual Basic® language in which the *WinFWDCal* software was written, eliminating the need to develop custom drivers. Keithley supplies a driver set that is compatible with Microsoft Windows XP® and Windows Vista®. The software has been used successfully in both operating systems.

Protection of DAQ Cabling

One problem became evident as researchers began using the KUSB-3108 DAQ—the cables are attached to the box via a screw terminal system that leaves the wires vulnerable to being pulled out. Several calibration center operators reported having problems with the wires becoming loose.

An aluminum box was found to be well suited to provide some protection for the wiring (see figure 11). DAQ is held in the box with a strip of Velcro®. Holes are drilled in both ends for connections to the USB port and the input and output channels. The box has a lid, and it can be stored with the lid on. However, the lid should be removed during use so that the DAQ can render an accurate measure of ambient temperature. Details about the box and the related hardware are provided in table 39 of appendix E.
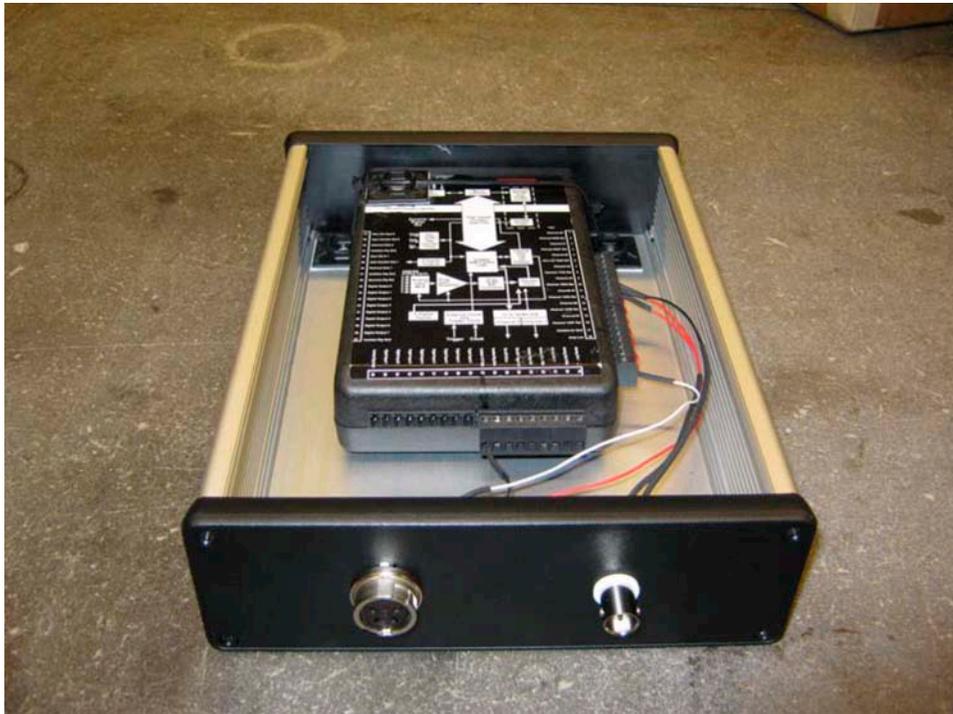
Figure 11. Photo. Box for DAQ wiring protection.

About Triggering

Modern data acquisition equipment allows the use of a technique called "about triggering" to determine when an event has occurred. Using buffers, about triggering allows the collection of data before and after a user-specified threshold value is reached. This means that the data are taken about or around the time when the trigger level is reached. The readings are continuously stored in buffers by *WinFWDCal*.

Currently, *WinFWDCal* uses 50 buffers with 300 readings per buffer. Data are collected at a speed of 15,000 readings per second. When each buffer is full, the data in it are scanned to determine if the threshold level (trigger) was exceeded. If it was, the data in the buffer, along with several preceding and following buffers, are saved to create the complete dataset. If not, the oldest data are discarded, and a new set of data is collected and reviewed.

One second of data is saved for analysis: one-third of 1 s before the trigger and two-thirds of 1 s after. With a reading rate of 15,000 Hz, this means 5,000 readings are taken before, and 10,000 readings are taken after the trigger point. This includes data from before the release of the mass to the several bounces after the first main pulse.

Incoming data are read as voltages. Converting the voltages to engineering units requires the sensors (the accelerometer and reference load cell) to be calibrated. The procedures for sensor calibration will be discussed in following sections.

About triggering has streamlined the data-taking process and eliminated the need to have separate hardware to detect the trigger point. It has also eliminated the triggering problem mentioned previously with the KUAB FWD load pulse.

For load calibration, the trigger level must be set high enough to avoid triggering by the preload force but low enough to trigger when the lowest drop level is used. When 10 consecutive readings exceed the trigger level, the about trigger point is set. Using 10 readings eliminates false triggers caused by voltage spikes.

In the case of a Dynatest® or Carl Bro FWD, the preload is about 1,000 lbf (4.5 kN). For a JILS FWD, the preload can be as high as 2,500 lbf (11 kN), while the KUAB preload level is very small. Setting the trigger level at 3,000 or 4,000 lbf (13 or 18 kN) is generally correct for load calibration since the smallest dynamic peak load is usually 6,000 lbf (26 kN).

Setting the appropriate acceleration trigger level requires finding an optimum between the pulse peak from the lowest and highest load levels. Research has shown that this must be tailored for each type of FWD. The pulse durations, and thus, the accelerations, differ from one type of FWD to another. The position of the FWD load plate face-to-face with the accelerometer in the calibration stand is variable. As a result, so are the peak accelerations. The response characteristics of the test pad can also vary from one day to another at the same location, so the trigger level must be determined immediately prior to each FWD calibration.

When the FWD is in place with the accelerometer on the deflection sensor calibration stand, one drop at the low drop height is analyzed to determine an appropriate trigger level for the accelerometer. *WinFWDCal* performs the analysis.

Drop Sequence

When the original SHRP FWD reference calibration procedure was developed, the specified drop sequence required five replicate drops at four load levels. Experience with the initial four and later eight Dynatest® FWDs used by SHRP showed that the drop sequence was well suited to check the linearity of the sensors, and 20 drops provided enough data to fit a regression with a good level of confidence.

However, it has been noted that some FWDs had a problem with this drop sequence. For example, JILS uses a heavier mass and a shorter drop distance, and the lowest load level (6,000 lbf (26 kN)), had a much shorter free-fall time than the Dynatest® FWD. Vibration associated with the release of the mass did not have enough time for damping before the mass struck the load plate. Calibration operators reported problems with excess noise messages at the low, and even the second, load level.

This issue was overcome by relying on the experience from performing hundreds of FWD calibrations over the past 15 years. Rather than working with a single fixed drop sequence, researchers were able to allow some flexibility depending on the daily response of the test pad. The solution involves a tradeoff between the number of load levels used and the number of replicate drops required to achieve the desired level of precision.

Either three or four load levels may be used, depending on the preference of the FWD owner or the recommendation of the manufacturer. *WinFWDCal* determines the required number of replicate drops per load level. The number of drops must be the same at each load level to simplify data collection and analysis. It is also recommend that the same drop sequence be used for both load and deflection sensor calibration.

The goal is for the standard error of the final calibration factors to be no more than 0.003 (i.e., 0.3 percent). Experience with all types of FWDs has shown that the expected random measurement error for one drop is seldom more than ±0.08 mil (±2 μm) deflection and ±20 lbf (±0.09 kN) load. Deflection is the more critical of the two to achieve the desired standard error, so it controls the number of replicate drops.

When the FWD is in place with the accelerometer on the deflection sensor calibration stand, one drop at the low drop height and one at the high drop are analyzed to determine the minimum number of drops needed to achieve the desired precision. *WinFWDCal* performs the analysis. A total of at least 18 drops is necessary to ensure the minimum statistical power. This requires a minimum of six replicate drops at three load levels or five replicates at four levels.

It was determined that 10 replicate drops per load level were a practical upper limit. If the required number of replicates exceeds 10, the FWD should be repositioned to obtain larger deflections. A larger range of deflections between the lowest and the highest drop height will result in fewer replicate drops needed. Therefore, switching from three to four load levels will usually reduce the required number of drops.

It is important that the drop sequence be determined for each FWD calibration. The routine accounts for the position of the FWD load plate with respect to the sensor stand, and the current

properties of the test pad are also factored. The dynamics of the FWD load pulse are considered to reduce the likelihood of excess noise messages. The ability of the software to determine the drop sequence based on the local daily conditions provides flexibility.

Recommended Peak Deflection

As noted in chapter 1, it is important that the peak deflection be sufficiently large to allow a clear distinction between the bias error and the random error. Research has shown that a peak deflection of 20 mil (500 μm) at a force of 16,000 lbf (71 kN) would adequately achieve that goal. Lesser deflections as little as 12 mil (300 μm) may suffice, but the required number of drops increases as peak deflection decreases.

It was found that a test area that is built with a 5-inch (125-mm) fiber-reinforced concrete surface, a 5.85-inch (150-mm) aggregate base, and a 120–200-inch (3–5-m) soft clay subgrade will achieve the target deflection level. The deflection profile near the edge of the test pad is variable, and deflections may initially go up before they go down near the edge of the pad. As a result, it is best to avoid placing the sensor stand too close to the edge of the test pad.

The calibration stand should be placed 11.7–17.55 inches (300–450 mm) from the edge of the test pad. It is important that the perimeter of the concrete is not bonded to the surrounding floor. To maintain a near-constant deflection over long periods of time, it is recommended to completely wrap the clay subgrade in neoprene or heavy polyethylene sheeting to resist drying of the material.

AASHTO R32-09 no longer requires a special test pad to be built to carry out the FWD calibration procedure.[1] Any good-quality concrete pavement that will provide a peak deflection that does not require more than 10 replicate drops per load level is sufficient. This makes the calibration procedure portable. The limit on the required number of drops, not the minimum amplitude of the peak deflection, determines whether a site can be used for FWD calibration. However, as a general rule, the optimal peak deflection is at the high load level of 16 mil (300 μm) or more.

WinFWDCal will also check each drop to ensure that the maximum acceleration does not exceed 5 *g*. If this limit is exceeded, the data are invalid.

Choosing and Using an Accelerometer in FWD Calibration

After reviewing many accelerometers, one was discovered with excellent frequency response and shock resistance. Peak accelerations experienced during the development phase showed that the accelerometer needed to have a range of at least 3 *g*. The Silicon Designs model 2220-005 ±5 *g* accelerometer was chosen (see figure 12). The device offers an optimum combination of low noise, high sensitivity, and excellent shock resistance. It is small in size and is housed inside a shielded aluminum box.
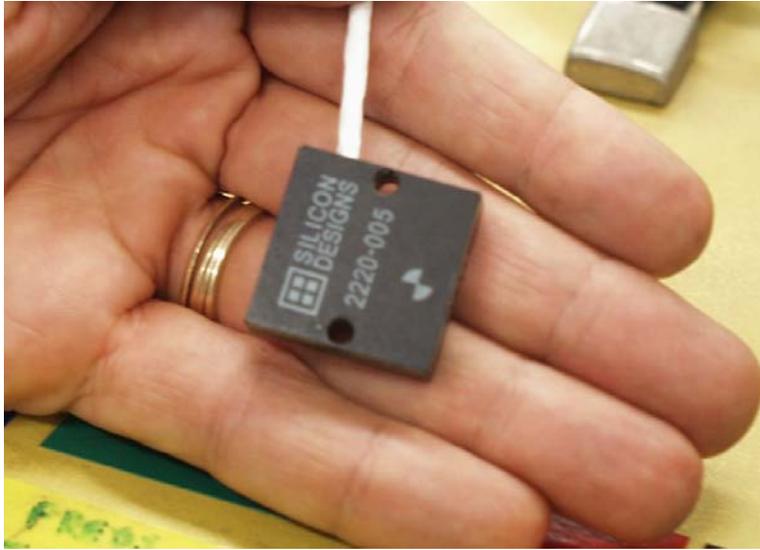
Figure 12. Photo. Silicon Designs model 2220 accelerometer.

Most accelerometers are not very shock resistant, and dropping them is usually fatal. Due to hydraulic damping, specifications for the Silicon Designs accelerometer indicate that the 5-*g* unit is resistant to a 2,000-*g* shock. During the research, an accelerometer box was unintentionally dropped onto a concrete floor from a height of 30 inches (760 mm), and it survived without any measurable effect on its calibration. Figure 13 shows an accelerometer box on a calibration platter.
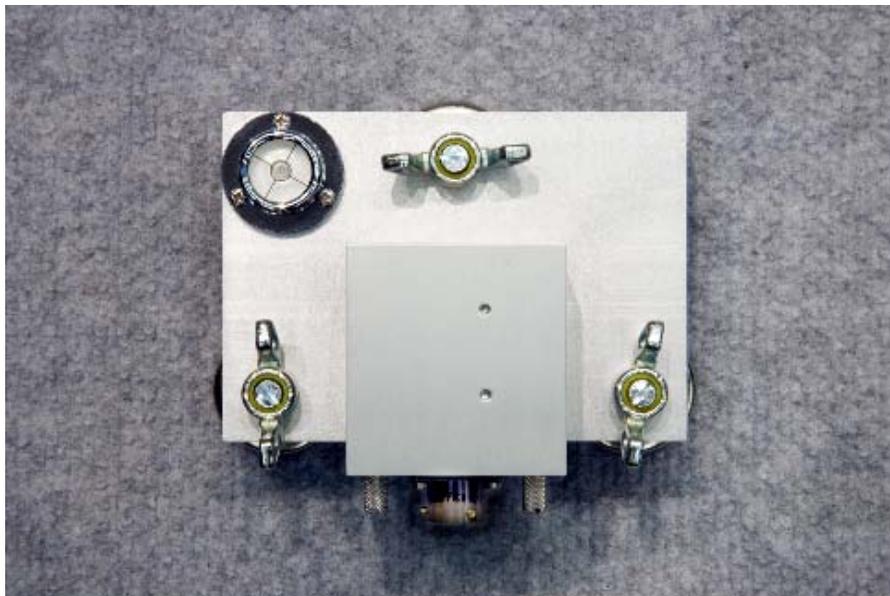
Figure 13. Photo. Accelerometer box on calibration platter.

The Silicon Designs accelerometer is a microelectromechanical systems (MEMS) device. As a result, it produces a signal due to the acceleration of Earth's gravity. This is termed the zero bias by the manufacturer. It is advantageous because it allows researchers to use Earth's gravity to calibrate the accelerometer.

A Vishay 2310 signal conditioner is used to power the accelerometer. The signal conditioner has a six-pole, low-pass Butterworth filter that is set at 1,000 Hz to protect against aliasing by removing unwanted high-frequency electrical noise. The same signal conditioner is also used with the reference load cell, thereby saving on hardware costs.

Calibration of the Accelerometer

The Silicon Designs accelerometer is a nonlinear device. The output is slightly nonlinear with respect to the acceleration. In order to overcome this, the manufacturer defines the following relationship:

$$g = b + a_1 V + a_2 V^2 + a_3 V^3$$

Figure 14. Equation. Nonlinear conversion of voltage to acceleration.

Where:

g = Measured acceleration in gravitational units.
V = Accelerometer output in volts.
a, b = Coefficients of polynomial from manufacturer's calibration at 50 Hz.

This relationship is used to convert the accelerometer response (in volts) to engineering units (in gravitational units). The second- and third-order terms contribute a relatively small amount to the conversion.

The accelerometer response is also slightly affected by ambient temperature. This only affects the zero bias, b, and the first order slope, a_1. Daily calibration of the accelerometer to a known acceleration (Earth's gravity) is used to calibrate the output and determine the bias and slope a_1 at ambient temperature.

Daily accelerometer calibration is straightforward. The accelerometer is calibrated on a flat and level plate that is also used to store the accelerometer when it is not being used (see figure 13). First, 1s of accelerometer readings (15,000 readings) is taken in a +1 g gravity field. This process is repeated 10 times. Next, the accelerometer (in its protective box) is inverted, and 10 more sets of readings are taken in a -1 g field. The accelerometer is immediately inverted back into the +1 g field, and 10 more sets are read to verify that the hysteresis effect (discussed later) did not cause a significant change in the resulting output.

The standard deviation of each second of data is examined to confirm that the accelerometer was being held steady during the test. Results are also compared to historical data for the accelerometer to ensure that the results are typical. Data from the calibration are used to determine a daily value for the zero bias, b, in gravitational units, and the slope, a_1, in gravitational units per volt. These results include the effect of the gain setting in the signal conditioner, temperature effects, hysteresis effects, aging of the accelerometer, and other factors.

Data Checks During Accelerometer Calibration

Several data checks are made during the daily calibration of the accelerometer. Some are performed to ensure that the device is working within normal parameters, and others are used to look for changes from one accelerometer calibration to the next. The data checks are as follows:

- **Time differential during data collection:** To minimize the hysteresis effect during accelerometer calibration, the maximum allowable time to turn over the box and take 10 s of readings in the -1 *g* position is 20 s. Generally, most operators can accomplish the flip in 6–8 s.

- **Change in slope:** The slope of voltage versus acceleration (the inverse of a_1) should be relatively constant over time even with temperature changes. Generally, a maximum of 0.25 percent change from one calibration to the next has been observed. A maximum change of 1.0 percent is currently being allowed in *WinFWDCal*.

- **Change in offset:** The change in the zero offset (bias) of the accelerometer is monitored. Currently, a maximum change of 0.02 percent is allowed from one calibration to the next.

- **Temperature change:** The KUSB DAQ has a temperature measurement system. The temperature at the time of accelerometer calibration is recorded, and the temperature thereafter is monitored. A temperature change less than 18 °F (10 °C) during calibration is allowed. Normally, the temperature is constant in an indoor calibration facility.

- **Overall temperature:** The behavior of the accelerometer was examined in a temperature sensitivity study. This occurred over a range of temperatures within the expected range in service and within the allowable range of the device from 5 to 131 °F (-15 to 55 °C).

Hysteresis of Silicon Designs Accelerometer

The Silicon Designs model 2220 accelerometer encounters problems with hysteresis. Every time the accelerometer is inverted in Earth's gravity, the zero bias changes. The magnitude of this change increases exponentially with time and occurs whether or not the accelerometer is powered; thus, it is a materials science problem rather than an electrical one. This accelerometer drift could present a biased nonrandom error. If it is not accounted for, hysteresis can lead to a calibration error in excess of 1 percent.

The magnitude of the error changes over time when the accelerometer is at rest in Earth's gravitation. To overcome this, the accelerometer needs to be kept upright in the +1 *g* gravity field as much as possible. It should only be flipped upside down during daily calibration. If the time for flip calibration is kept short, the effect on the overall daily calibration is small.

Hysteresis does not affect the dynamic response of the accelerometer during the FWD pulse because it stays in a +1 *g* overall gravity field. Since Earth's gravity (a static response) is used to calibrate the dynamic response of the sensor, hysteresis must be accounted for as part of the accelerometer calibration.

Figure 15 and figure 16 show the hysteresis effect measured for one accelerometer. An accelerometer was left in a +1 *g* condition overnight. Readings were taken for 15 min and were very stable (not shown). Next, the accelerometer was inverted to a -1 *g* condition, and the voltage output was recorded every second for 30 min. The accelerometer was then returned to a +1 *g* gravity field, and additional measurements were taken for 15 min (see figure 15).

Each figure shows an immediate change in one direction, with a signal change on the order of 1–1.5 mV. This is followed by a slower long-term change in the opposite direction. If inversion time (during daily flip calibration) is kept under 20 s, the effect on the accelerometer voltage is less than 0.035 percent (about 0.5 mV).

The rate of drift due to hysteresis diminishes with time. After 6 days at room temperature, the accelerometer is completely stable. If the accelerometer is stored upside down for a long period, it takes about 24 h to equilibrate it in the upright position to within 0.1 percent of the stable response. For this reason, the accelerometer should be stored in a +1 *g* field at all times.

As a general rule, if the accelerometer is inverted for a brief period of time, it should be left in the upright position for an equal length of time to re-equilibrate it. Note that in figure 16, the accelerometer was inverted from the orientation in figure 15, and the time scale was continued.
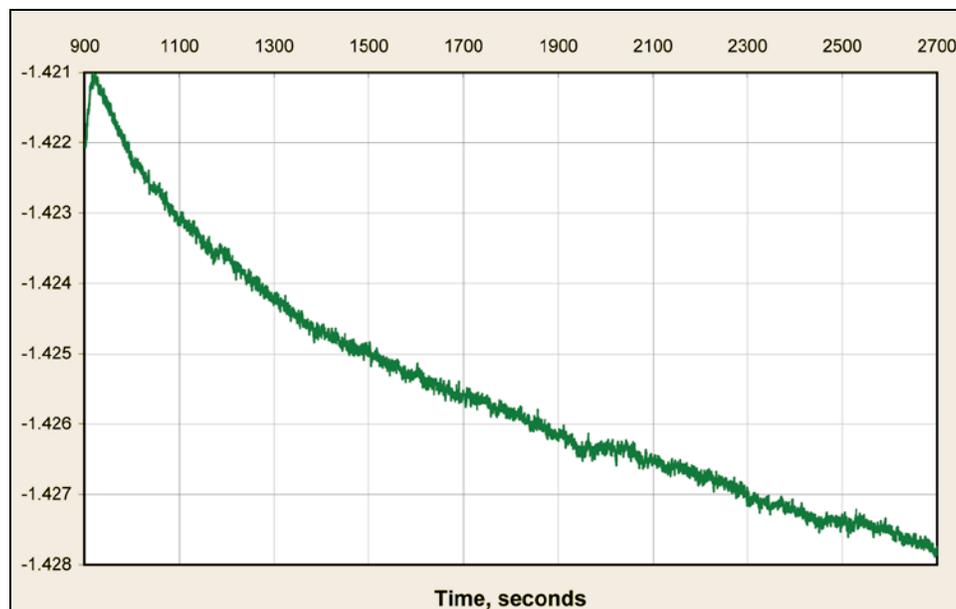
Figure 15. Graph. Hysteresis effect in a -1 *g* field.
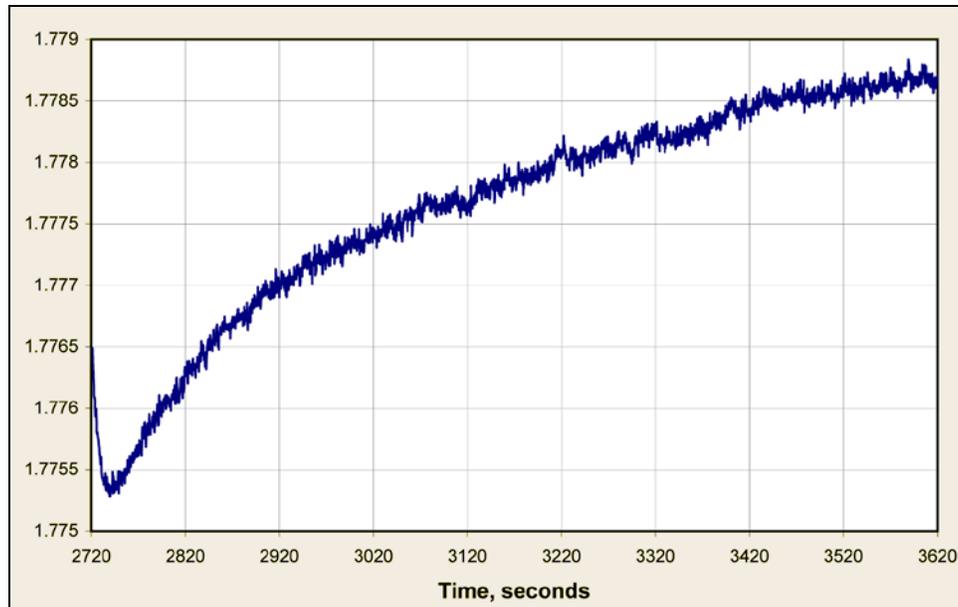
Figure 16. Graph. Hysteresis effect in a +1 *g* field.

Temperature and Electromagnetic Interference Sensitivity

The feasibility of using an accelerometer as a reference device for calibrating FWD deflection sensors depends in part on the effects of the environment. If the device is affected too much by temperature or by interference from electromagnetic fields, then the accelerometer could fall short of the ±0.3 percent accuracy required for deflection sensor calibration.

Silicon Designs specifies a scale factor (slope a_1) temperature shift between -250 and +150 ppm/°C for model 2220-005 (see figure 17). Two accelerometers (serial numbers 277 and 278) were calibrated over a range of temperatures, and the change in the output voltage was determined. Results show that if the maximum allowable error due to temperature change was 0.1 percent, the maximum acceptable temperature shift was 18 °F (10 °C).

Electromagnetic interference (EMI) has been shown to affect accelerometer measurements when the fields move with respect to the device. Aluminum and steel were tested for use as shielding materials. While a grounded steel box was able to completely defeat the effect of electromagnetic interference (EMI) on the accelerometer, an aluminum box had optimal results in fields above 1 G (0.0001 T) and was deemed sufficient. Even large magnetic fields had a limited effect on the accelerometer readings. A maximum change of 0.04 percent in the voltage output was observed when several high-powered magnets were placed next to the accelerometer. It should be noted that the aluminum box also helps insulate the accelerometer from temperature effects. Temperature measured at the DAQ can be expected to move more rapidly than inside the aluminum box, provided the box is not in direct sunlight.
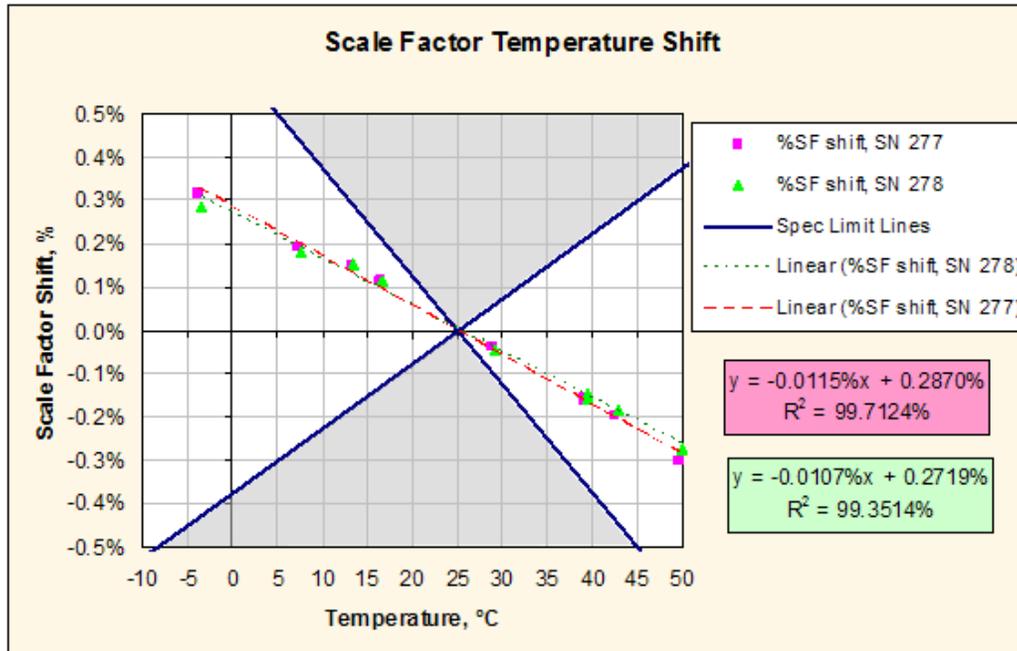
Figure 17. Graph. Scale factor temperature shift for accelerometer.

Double Integration of Accelerometer Signal

Using an accelerometer as a reference sensor in deflection measurement requires the output to be double integrated from the accelerometer to convert to displacement. This is a challenging problem in part because releasing the FWD mass before the mass strikes the load plate can leave a legacy of ongoing damped vibration in the pavement at the moment the mass strikes.

When considering integration for any purpose, it is necessary to remember that the first integral of a constant is a ramp. That is, $\int A \, dt = At + B$. The second integral of a constant is a parabola, $\int\int A \, dt = \frac{1}{2} At^2 + Bt + C$, where A, B, and C are constants, and t is time. In instrumentation engineering terminology, the ramp is the drift, and the parabola is the nonlinear drift.

Before performing the integration calculations, several boundary conditions and assumptions must be defined. Figure 18 shows the acceleration trace from a Dynatest® FWD impulse after converting from volts to gravitational units. The release of the mass occurs around 40 ms, and the strike of the mass on the load plate occurs just after 300 ms.

The baseline in figure 18 is on +1.0 *g* because the MEMS accelerometer responds to Earth's gravity. This zero bias can be measured by taking a burst of readings before the FWD mass is released. The readings are examined to ensure that no unwanted vibrations are occurring just before the drop. Subsequent acceleration data can be corrected to remove the zero bias before integration (additional details on this process are given in the next section). Figure 19 and figure 20 show the resulting integration of the accelerometer trace, first to velocity and then to displacement.

Figure 21 through figure 23 show a similar set of results for a JILS machine. The peak force for both examples was about 16,000 lbf (70 kN). It is evident that different types of FWDs have

different vibration characteristics both before and especially after the falling mass strikes the load plate, which is a challenge to accommodate in the integration routines. A small but acceptable amount of baseline drift can be seen in figure 20 and figure 23.
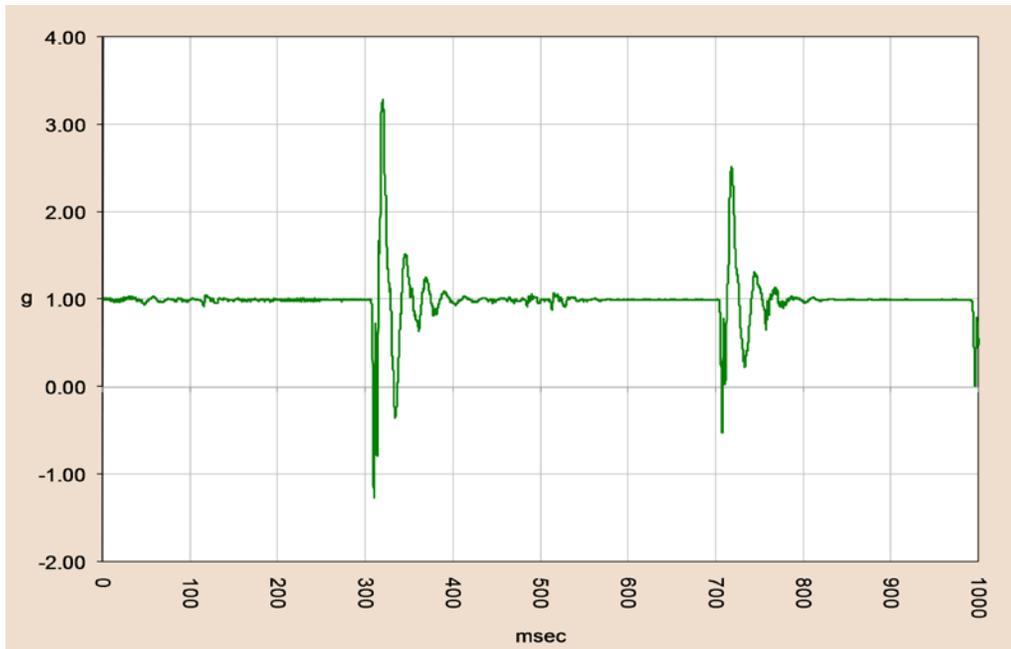
Figure 18. Graph. Raw accelerometer output from a Dynatest® FWD impulse.
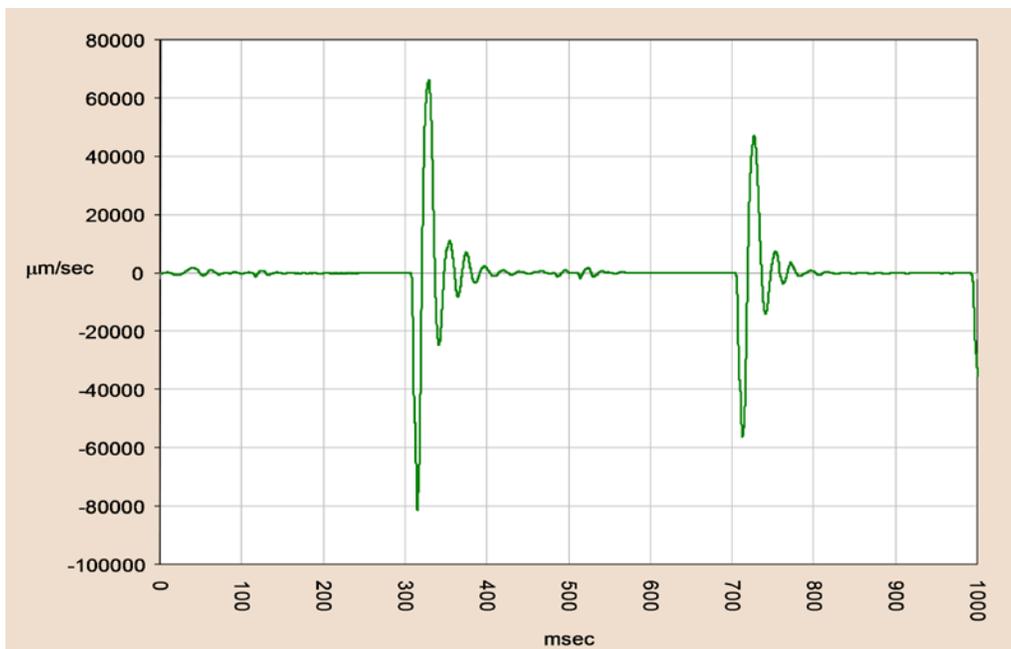
Figure 19. Graph. First integration (velocity) from a Dynatest® FWD impulse.
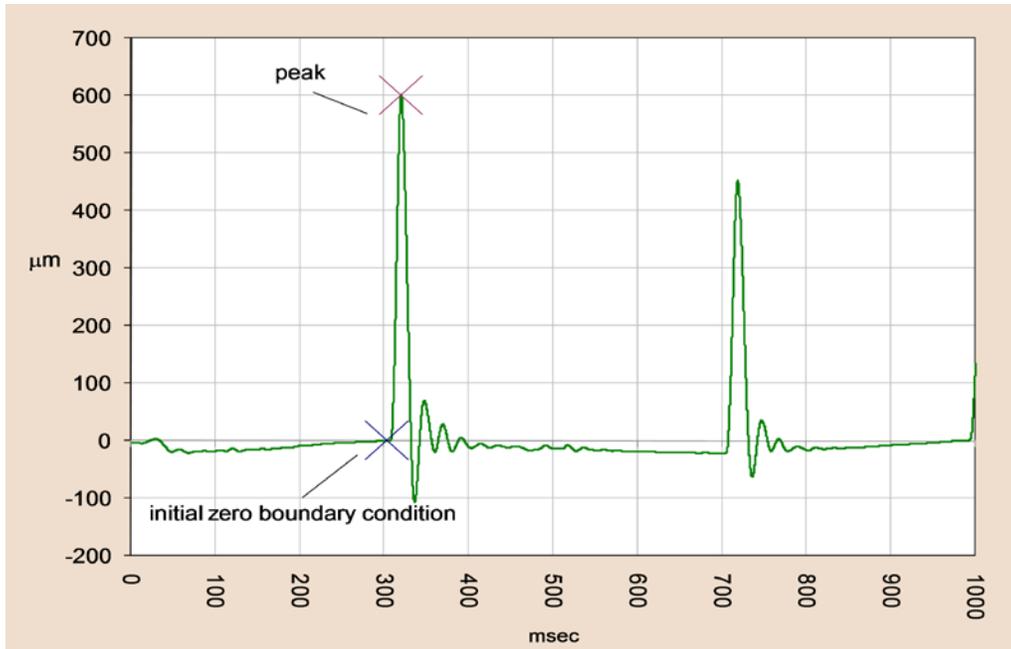
Figure 20. Graph. Second integration (deflection) from a Dynatest® FWD impulse.
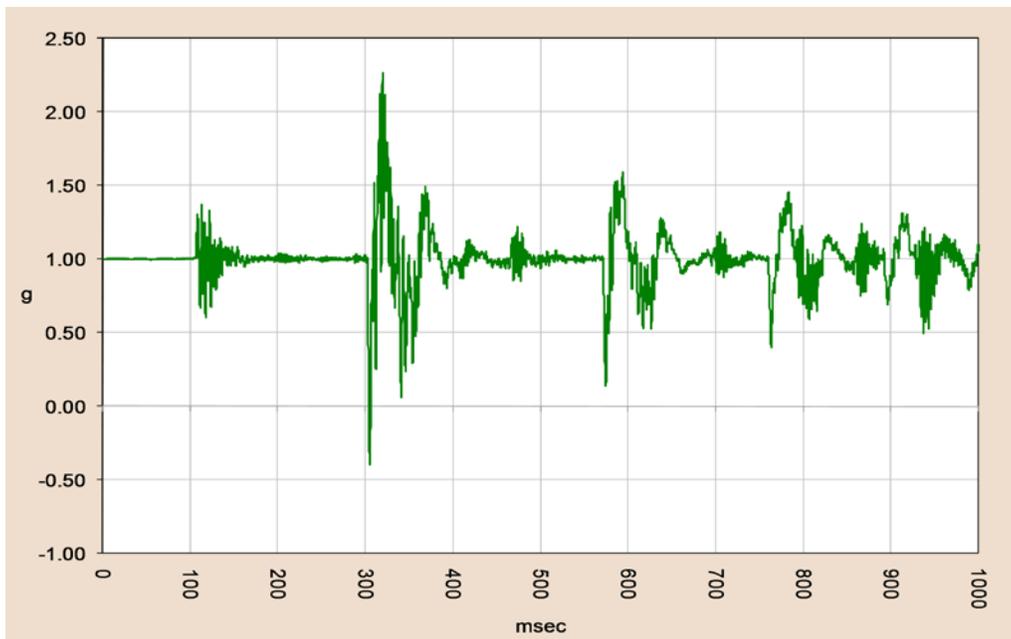
Figure 21. Graph. Raw accelerometer output from a JILS FWD impulse.

Figure 22. Graph. First integration (velocity) from a JILS FWD impulse.
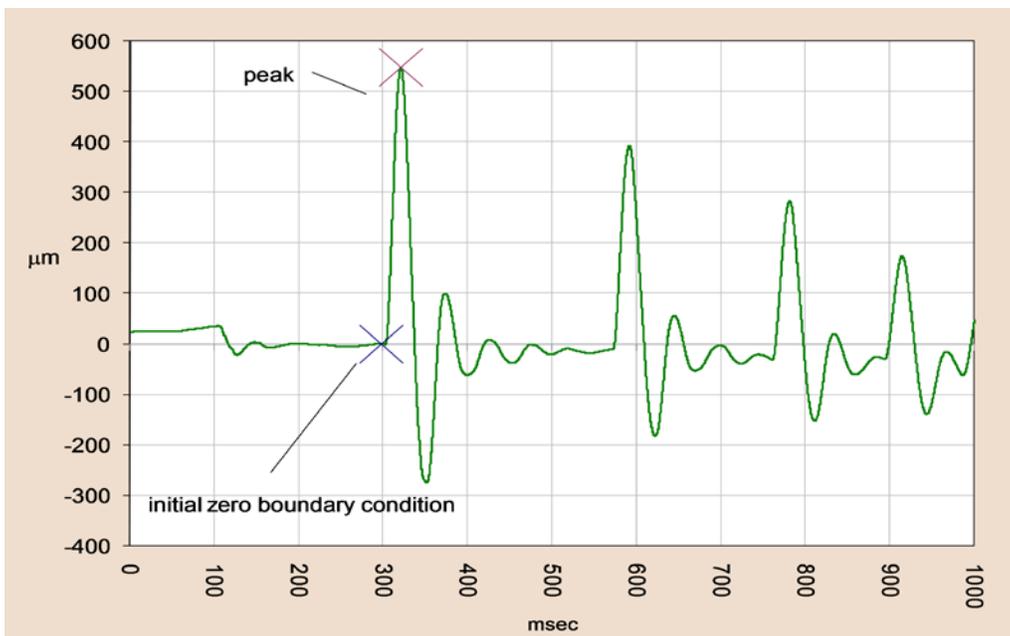
Figure 23. Graph. Second integration (deflection) from a JILS FWD impulse.

Integration Principles

The deflection sensor calibration stand experiences a unidirectional acceleration, $a(t)$, in the vertical (z-coordinate) direction. This is measured continuously using the accelerometer that is attached to the stand. The digitized data represent the vector sum of two accelerations: a constant acceleration, a_o, due to Earth's gravity and a variable acceleration, $a'(t)$, due to the impact of the falling mass.

The mass is released at time t_r, and the time of impact of the mass is t_i, which occurs after the release of the mass. Peak deflection z_{peak} is at t_{peak} (marked in figure 20 and figure 23), which occurs after the mass strikes the load plate. Thus, $t_r < t_i < t_{peak}$. The goal is to determine z_{peak} as accurately as possible.

When the mass goes into free fall, the force of the FWD load plate on the pavement is reduced by the weight of the mass. This causes the pavement to spring up slightly. The KUAB FWD has an outrigger system that supports the mass; hence, there is no change of force at the load plate. The JILS FWD uses a pair of air bags to apply a large preload on the load plate. It also uses a larger mass and a shorter free fall distance than the other types of FWDs, so the damping time between t_r and t_i is shorter (about 175 ms in figure 23).

If the extraneous vibrations due to the release of the mass are damped out before t_i, the combined acceleration after t_i is as follows:

$$a(t) = \frac{d^2z}{dt^2} = a_o + a'(t)$$

Figure 24. Equation. Acceleration due to gravity and the FWD load pulse.

Where:

$a(t)$ = Acceleration over time t.
a_o = Constant acceleration due to Earth's gravity.
$a'(t)$ = Acceleration due to the FWD mass strike at t_i.

The constant, a_o, is measured by averaging a burst of 3,000 readings taken immediately before the mass is released (at that time, $a'(t) = 0$). If the calibration stand is not exactly vertical or if the temperature has changed since the accelerometer was last calibrated, a_o will include these effects. Since a_o can be measured precisely and its value is subtracted from all subsequent accelerometer readings taken before and after the mass is released, this leaves a relative acceleration, $a'(t) = a(t) - a_o$. Thus, the equation in figure 24 becomes the following:

$$\frac{d^2z}{dt^2} = a'(t)$$

Figure 25. Equation. Relative acceleration after removing Earth's gravity.

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The relative acceleration in figure 25 can be integrated to find the velocity as a function of time, $v(t)$ (see figure 26).

$$v(t) = \frac{dz}{dt} = \int a'(t)\,dt = c_1 + \int_0^t a'(t)\,dt$$

Figure 26. Equation. Velocity as a function of time.

By examining the data, the starting point of the integration can be chosen on the interval $t_r < t_i$ so that $t = 0$ and $a'(0) = 0$. If $v(0) = 0$ (i.e., there is no initial velocity of the pavement at $t = 0$), then constant $c_1 = 0$. Hence, the deflection over time $z(t)$ becomes the following:

$$z(t) = \int v(t)\,dt = c_2 + \int_0^t v(t)\,dt$$

Figure 27. Equation. Deflection as a function of time.

Again, $t = 0$ is chosen so that $v(t) = 0$, and if $z(0) = 0$, then $c_2 = 0$. The starting point for integration in figure 26 and figure 27 will most likely not be at the same reading number in the data file. If there is also a time-variable acceleration $a_o(t)$ and/or a time-variable velocity $v_o(t)$ (e.g., residual vibration in the pavement caused by the decrease in force when the mass is released or due to the FWD vibrating after the release) at the start of integration, then figure 26 becomes the following:

$$v(t) = \frac{dz}{dt} = v_o(t) + \int a_o(t)\,dt + \int a'(t)\,dt = v_o(t) + c_3 + \int_0^t a_o(t)\,dt + c_1 + \int_0^t a'(t)\,dt$$

Figure 28. Equation. Velocity with initial vibration.

Where:

$v(t)$ = Velocity over time.
$v_o(t)$ = Initial time-variable pavement velocity (vibration).
$a_o(t)$ = Initial time-variable pavement acceleration (vibration).

The accelerometer measures the combined vector $a(t) = a_o + a_o(t) + a'(t)$. a_o can still be measured at a time when $a_o(t) + a'(t) = 0$. A starting point can also be chosen for the integration such that $a_o(0) + a'(0) = 0$. However, $v(0)$ is not likely to be zero at $t = 0$, and $v_o(t)$ and $a_o(t)$ are unknown functions, so it becomes difficult to solve the equation in figure 28. It is even more difficult to define $z(t)$.

If there is vibration present at t_i but it is still assumed that figure 26 and figure 27 are applicable, the constants will be nonzero. It is not possible to separate $a_o(t)$ and $a'(t)$ in the accelerometer data, and $v_o(t)$ is an undefined function. Thus, $z(t)$ will contain nonlinear drift.

The vibration functions $v_o(t)$ and $a_o(t)$ may be nearly fully damped at the starting point $t = 0$, in which case, the drift may be small, and the error of the peak deflection z_{peak} may also be small and possibly of random magnitude. However, if the vibrations are renewed and enhanced when the falling mass strikes the load plate at t_i, then $v_o(t)$ and $a_o(t)$ may be significantly nonzero, and the drift and the error in z_{peak} may become large.

The best approach is to only perform the double integration in an environment where the vibration due to the release of the FWD mass is essentially zero. Then, both $a_o(t)$ and $v_o(t)$ will be zero, or nearly so, and will contain little if any drift. To ensure that condition is met, the accelerometer signal can be analyzed during each drop for a short period before t_i and all drops that show excessive vibration can be rejected.

Research for this study has shown that it is important for the FWD to be level and seated squarely on the pavement to minimize undesired vibrations. Several seating drops (no data recorded) should be performed before data collection to establish good contact of the load plate. For the Dynatest® and Carl Bro FWDs, it is necessary to lubricate the load plate swivel, and it must be free to rotate. For the JILS FWD, which does not have a swivel, it is important to verify that the load plate is properly seated while the mass is in free fall. This can be accomplished using a sheet of paper, and the procedure for checking proper seating is explained in more detail in annex 3 of appendix A.

Implementation

WinFWDCal is used to implement data acquisition and double integration. It also provides several QC checks during data processing. An earlier section discussed setting the trigger level. The following steps are taken when the calibration operator initiates an FWD drop during reference calibration.

Measuring a_o

Before the computer screen turns green around the perimeter, which is a signal to the FWD operator to release the mass, the computer takes a burst of 3,000 readings at 15,000 Hz (200-ms read time) and computes the average (a_o) and standard deviation. If the standard deviation is larger than 0.005 V, a popup message alerts the user that the predrop vibration exceeds the acceptable level.

The readings are converted to gravitational units, and the vector is checked to ensure that all readings are between 0.98 and 1.02 g. According to NIST, the acceleration of gravity (1 g) equals approximately 32.2 ft/s^2 (9.80665 m/s^2).[16] In Minneapolis, MN, gravity is approximately 32.2 ft/s^2 (9.80585 m/s^2); in Denver, CO, it is approximately 32.1 ft/s^2 (9.79615 m/s^2); and in College Station, TX, it is approximately 32.1 ft/s^2 (9.79324 m/s^2). Gravity is not less than 0.9985 g in any of these locations. If the data are out of range, the accelerometer is not working correctly, and a popup message alerts the calibration operator. Data for the drops are saved in the time history file.

Finding the Trigger Point

Incoming readings from the accelerometer are continuously scanned for the trigger level. When 10 consecutive readings are over the trigger level, the trigger is satisfied. This process avoids a false trigger due to a voltage spike or other anomaly.

After the trigger is satisfied, at least 10,000 more readings are collected and saved in buffers. Accelerometer readings measured in volts are then transferred from buffers to a program array such that the trigger point is the 5,000th reading out of 15,000. Thus, 0.333 s of data are ahead of

the trigger, and 0.666 s are after the trigger. The raw data in volts, the absolute acceleration in gravitational units, and the relative acceleration in gravitational units are saved in the time history file for the drop.

Finding the Time of Impact, the Time of Peak, and the Pulse Rise Time

The time of impact, t_i, is determined by working backward in time from the trigger point. Researchers seek to find the transition point from where the deflection time history trace is steep to where it is level by examining the standard deviation of sets of 25 readings. In figure 23, t_i is located at the first X around 300 ms.

The standard deviation of the previous 25 readings is calculated and placed in an array. Moving back one point, the standard deviation of the next set of 25 readings is calculated. Similarly, the running standard deviation of consecutive sets of 25 points is tabulated.

When the standard deviation falls below 0.020 g, it indicates the time of impact. A secondary check is made to assure that the acceleration at that point is not less than -0.030 g. If it is not satisfied, researchers must continue to work backward until both criteria are satisfied.

The time of peak, t_{peak}, occurs at the first maximum reading after the trigger point. Pulse rise time can be calculated by subtracting t_i from t_{peak}. Rise time is reported on screen for each drop by *WinFWDCal*.

Finding the Starting Points for Integration

The starting point for integration of the acceleration data to velocity is determined by working backward from t_i. The first set of three consecutive readings where the acceleration is within ±0.0030 g is found. The starting point for acceleration integration is assigned as the middle reading of the three. The reading number is recorded in the time history file.

The starting point for integration of velocity data to deflection is accomplished in a similar manner using the velocity data array. Working back from t_i, the first set of three consecutive readings where the velocity is within ±30 μm/s is found. The starting point for velocity integration is assigned as the middle reading of the three. The reading number is recorded in the time history file.

Generally, the two starting points occur at different reading numbers. For both the acceleration and the velocity data arrays, if a starting point cannot be located within 50 ms ahead of t_i, a popup error message indicates excessive vibration before the strike of the mass. In this case, the data for the drop should be rejected, and the drop should be repeated.

Performing the Integration

Integration involves computing the area under a curve. Over a period of 1 s, 15,000 readings are taken, so the readings are 0.0667 ms apart. The digital integration is computed by averaging two adjacent readings and multiplying by the time interval. The running sum is computed by adding these areas forward and backward from the starting point. By definition, the sum at the starting point is zero.

Multiple Sensor Stand

The development of a multiple-sensor stand contributed to the project's goals of expediting the calibration process and creating a universally compatible procedure. The multiple-sensor stand can save time during calibration by eliminating the need to reference calibrate deflection sensors individually. The design of the stand allows it to be positioned close to the load plate for all brands and models of FWDs.

Under the new calibration protocol, the sensors only need be repositioned once during reference and relative calibration by performing a vertical inversion with respect to the location of the accelerometer. This ensures unbiased results from positions on the lower half of the stand to those at the top. In the case of a KUAB seismometer FWD, horizontal rotation of the stand removes the effect of the two columns of the stand.

Photos of the two stand designs are provided in figure 59 and figure 68 of appendix E. Details about installing and using the stands are provided in appendix F.

Column Design

After examining three different geometries of multiple-sensor stands, the vertical column or "ladder" design was found to be the best option. Its welded aluminum construction is lightweight, and it is stiff enough to ensure consistent deflections for all positions in the stand. Additionally, it is the least affected by the rolling motion of deflection waves.

For the new AASHTO R32-09 protocol, it was necessary to develop two different stands, one for geophones and another for the seismometers used by KUAB FWDs.[1] A total of 10 geophones or seismometers can be simultaneously calibrated using the new stands, and the same stand can be used for both reference and relative calibration.

Ball-Joint Anchor

To ensure accurate measurement with the columnar stand design, it is necessary to anchor the stand firmly to the test pad. Early tests on a variety of prototype stand designs involving an uncoupled anchor showed that testers could not provide enough downward force to keep the stand in contact with the test pad and produce consistent results. The graph in figure 29 shows the results of the tests.

Coupling the anchor to the floor is only an issue when performing the single inversion procedure. Monthly calibration with full rotation allows the use of an uncoupled stand since all sensors are in all positions in the stand, and the effects of position in the stand are accounted for.

Two methods of attaching the calibration stand to the floor were investigated. One approach was to bolt the stand directly to the pad with one or two anchors. The other method was to connect the stand through a ball-joint clamp bolted to the pad (see figure 53 in appendix E). The single-hole direct anchor was acceptable in terms of unattributed (or residual) error and range of deflections, as was the ball-joint anchor. The ball-joint anchor was selected over the direct anchor for the following reasons:

- The ball-joint makes it possible to keep the stand vertical during testing.

- Having a person hold the stand dampens the vibration. With the direct anchor and without a ball-joint, it is possible for the stand to be used without being held, which increased the variability of the results.

- Direct anchored stands would be more prone to damage if hit by the FWD trailer or truck.
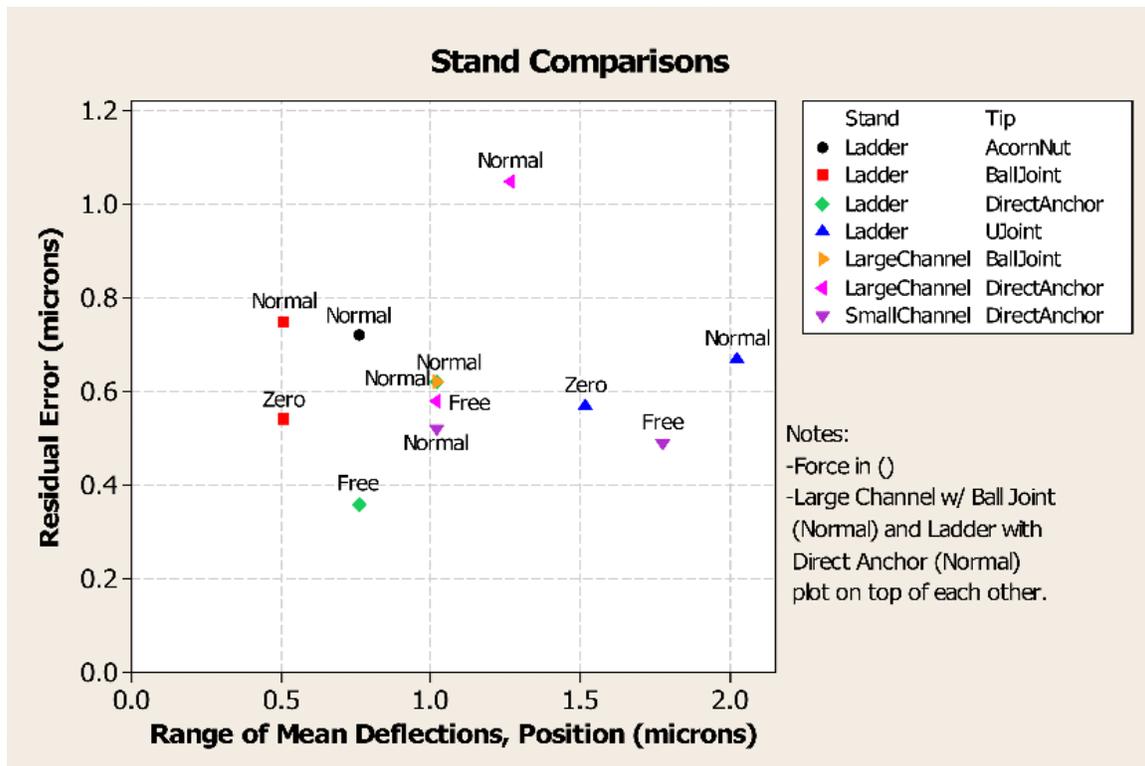
Figure 29. Graph. Comparison of sensor stand performance.

Reference Load Cell

The reference load cell has been modified in two ways. The thickness of the lid was increased from 0.625 to 1 inch (16 to 25.4 mm) to better resist bending and permanent deformation. The guide fingers were moved back slightly from an 11.7-inch (300-mm) diameter to an 11.89-inch (305-mm) diameter to accommodate the slightly larger load plate on JILS FWD.

When calibrating the reference load cell, the maximum load was increased from 20,000 lbf (89 kN) used in the SHRP protocol to 24,000 lbf (107 kN). This change was made to accommodate the higher preload pressure used by the JILS FWD. The calibration of the reference load cell should be performed by a qualified agency in accordance with AASHTO R33-03.[10]

A new design for the reference load cell with a significantly higher load capacity for use with HWDs was investigated. The design used an array of three commercially sold load cells with a combined load capacity of 90,000 lbf (400 kN). However, the concept was not successful because each of the three load cells had a slightly different sensitivity in terms of force per volt. When combined with slight variations in the flatness of the test pad and small eccentricities of loading from FWD, the resulting calibration factor was sensitive to the orientation of the reference load cell.

Overcoming this problem would require that each load cell have its own signal conditioner. The DAQ would read each channel, and the computer would sum the three loads. This made the endeavor prohibitively expensive and too complicated, so the project was abandoned.

Software Redevelopment

One task was to update the existing software to a modern Microsoft Windows®-based graphical user interface and eliminate the need for manual data entry. While there will always be ongoing updates to any software as complicated as *WinFWDCal*, the original goal was met.

The programming language for *WinFWDCal* is Microsoft Visual Basic 6.0®. It was chosen because it did not require a complete rewrite of the original code, which used Microsoft QuickBasic® language. Also, the KUSB data acquisition card had drivers for Microsoft Visual Basic 6.0®.

The update of the program started in June 2005 with the conversion of the *FWDREFCL* code to Microsoft Visual Basic 6.0®. By the time this was completed, the accelerometer and data acquisition systems had been chosen, and the proof of concept for the double integration method had been accomplished using LabVIEW in October 2005.

A draft Microsoft Visual Basic® program that performed some of the basic data acquisition functions and analysis was used during visits to the FWD calibration centers in April and May 2006. The objective of the visits was to test the software with all four types of FWDs. Comments by the calibration operators and other people who participated were incorporated into the program.

Results with *WinFWDCal* were checked using spreadsheets and Minitab® statistical software, as well as by hand to confirm their validity.[16]

The beta version of *WinFWDCal* was vetted at Cornell University prior to its release to the four regional calibration centers in late November and early December 2006. Periodic updates of *WinFWDCal* have been issued on a roughly quarterly basis. Version 2.0 of the software was released in December 2009. It incorporates some user-suggested improvements that make the

calibration setup easier to navigate. Version 2.0 also provides software support for monthly relative calibration using the manufacturer-provided calibration stands.

Electronic Data Transfer

A problem was encountered with transferring data from an FWD to *WinFWDCal*. Each type of FWD has a different native file format, and several manufacturers have many different formats. The AASHTO PDDX file standard was chosen as the preferred format for data transfer after discussion with the FWD manufacturers, calibration operators, and other FWD users.[7] This led to the development of a stand-alone program, *PDDXconvert*. *WinFWDCal* uses *PDDXconvert* as an intermediary for all data transfers.

A data file is copied in native format onto a USB flash drive or a floppy disk to transfer data from the FWD to the calibration computer. This eliminates the manual entry of data into the calibration software, which, in turn, saves time and reduces human error as a factor in the calibration procedure. *PDDXconvert* reads the file and converts it to a common format that *WinFWDCal* can read and use.

PDDXconvert does not solve all of the problems of electronic data entry to *WinFWDCal*. More data than just the sensor readings are needed for FWD calibration. Information such as the FWD model identification, FWD operator name, sensor serial numbers, current sensor gain factors, and last calibration date are needed for record keeping and for the certificate of calibration. A revised and more comprehensive standard is needed for the PDDX file format. A recommended new standard, based on experience working with various FWD native file formats and many user needs, is provided in appendix C.

Two FWD calibration data exchange file formats are described in appendix C. One format provides a suggested file name and contents for exchange of information from FWD that is needed by *WinFWDCal*. The other details the layout of an electronic file that is created by *WinFWDCal* that can transfer the calibration results to the FWD. The FWD manufacturers need to provide the means to create the first file and to read the second one.

Historical Database of FWD Calibrations

During the development of the new calibration protocol, each of the existing FWD calibration centers in the United States was asked to provide records of all calibrations performed there, and data were combined into a database of historical results. The data were reviewed to see if annual calibration is warranted. The results showed that changes in the sensor gains occur continuously, and annual calibration is needed to ensure that accurate data are collected by FWDs.[4]

The review found that some deflection sensors have gain settings outside the recommended range of 0.98 to 1.02 (which comes from the manufacturer's specifications). However, many of these sensors are stable from year to year. Since the calibration factors correct the measurement errors, there is no need to replace sensors that are stable.

Stability over time is more important than whether the gain factor falls between 0.98 and 1.02. Evaluation of the historical database showed that an individual gain factor does not change more than 1 percent from one calibration to the next (typically 1 year apart). This result is used as the first criterion in evaluating and accepting the results of an FWD calibration.

When data for a particular FWD are available for 4 years or more, the long-term data can also be used as part of the calibration acceptance criteria. From the historical database, it was found that an individual gain factor should change no more than 0.3 percent per year, provided that at least three calibrations were done in the 4-year period.

The long-term allowance for change (0.1 percent) is less than that for a single year (1 percent) because short-term change is usually more volatile than long-term change. Given that the random variability of two repeat calibrations is 0.3 percent, it makes sense that a long-term series of calibrations would show less variability.

In spite of the existence of the historic database, it will be difficult to implement the long-term acceptance criterion until the new AASHTO procedure has been in use for 4 years or longer for several reasons. Although the new calibration procedure is similar to the old SHRP procedure, there are many differences. Beam movement was a factor in the old procedure, and it has been eliminated in the new procedure. Additionally, there are only a small number of FWDs that have 4 years of calibration history, and essentially all of those machines were Dynatest® FWDs.

COMPARATIVE ACCURACY OF THE OLD AND NEW PROCEDURES

The objective of creating the new procedure was to make improvements without sacrificing the quality of the calibration. In order to compare the results of the old and new procedures, two large sets of replicate calibrations were collected—one using the older SHRP protocol and the other using the newly developed AASHTO R32-09 method.[1]

The same FWD was used for all of the calibrations. The data using the old procedure were taken in early 2006, and the new procedure was used in late 2006. The FWD sensor gain factors that were in place before the data collection began were left in place throughout all of the testing.

Influence on Deflection Sensor Gain Factors

Nine calibrations of the nine geophone sensors were completed using each protocol. The overall average gain obtained with the new AASHTO protocol was 0.26 percent higher than the average gain using the older SHRP protocol. The difference was statistically significant. The variance of the calibrations was the same for each protocol.

Figure 30 shows a comparison of the results for the two protocols. The upper half of the graph shows the final gain with the old SHRP protocol, and the lower half shows the results with the new AASHTO protocol.
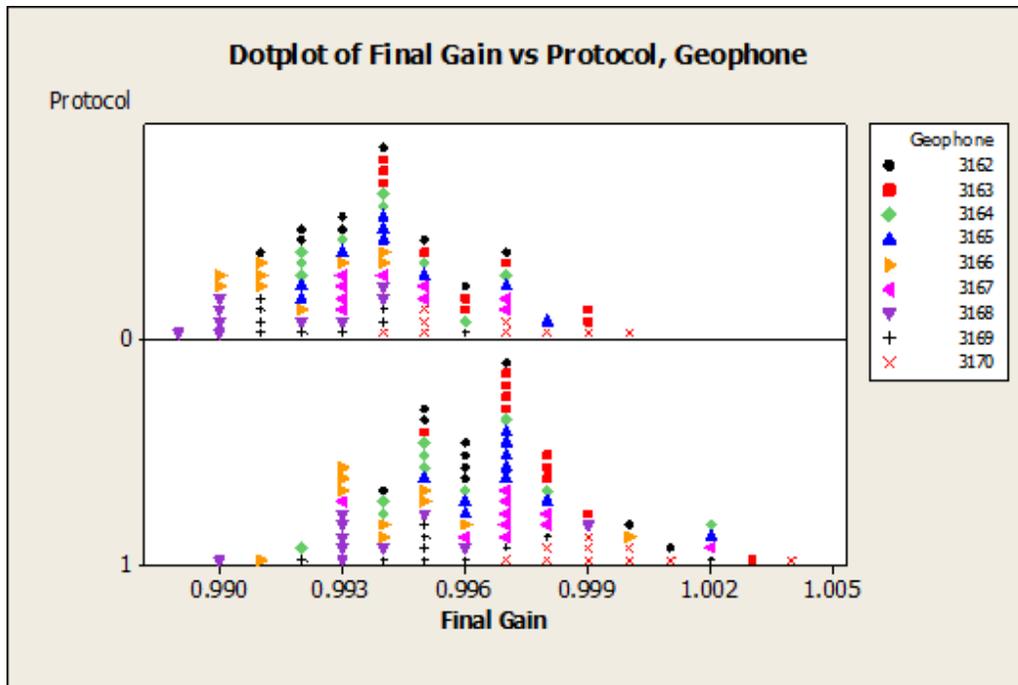
Figure 30. Graph. Deflection sensor final gain values produced with the old and new protocols.

Influence on Load Cell Gain Factors

In total, 20 load cell calibrations were completed with the old SHRP protocol, and 17 were completed with the new AASHTO procedure. Figure 31 shows the load cell final gains for the old and new protocols. The average final gain increased by 0.4 percent. The 95th percentile confidence interval on the difference in the final gain was 0.27 percent. Thus, the difference was statistically significant. The variance of the calibrations was the same for each protocol.

This difference was more than expected. Unlike the hardware and procedural changes that may have affected the deflection sensor gains, there was no significant change in the load cell calibration procedure in the new protocol. The long-term history of the load cell calibrations for the FWD was researched going back to 1994 to see if there was any explanation for the gain change by 0.4 percent.

The gain factor history is shown in figure 32. The year-to-year changes are much more volatile than the long-term trend, which is normal. The calculated trend line is essentially flat. The set of calibrations in early 2006 which used the old SHRP procedure tended to fall mostly below the trend line. The data for the new procedure tended to fall mainly above the trend line.

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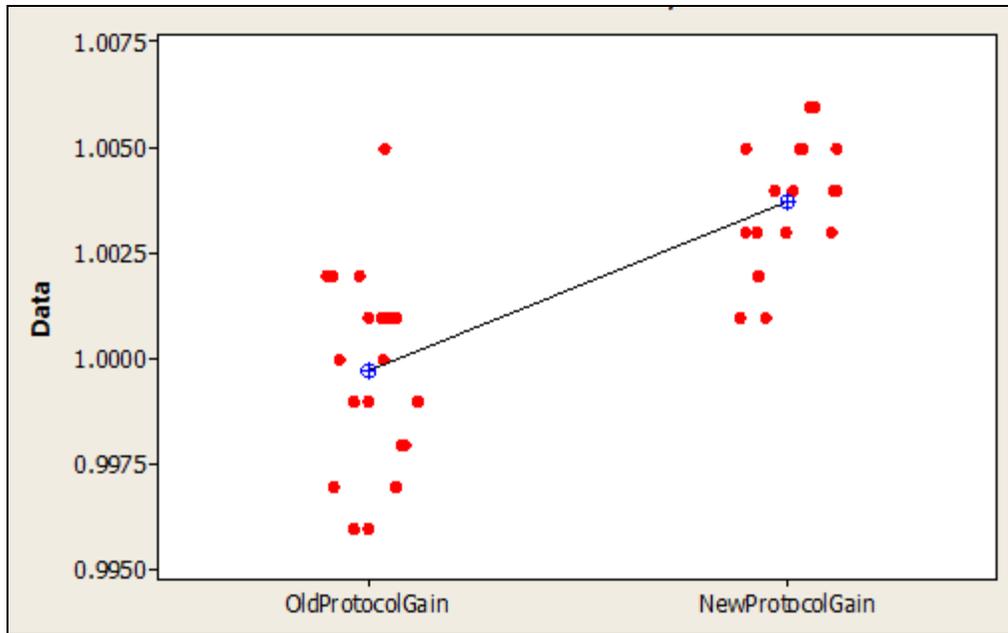
Figure 31. Graph. Individual value plot of load cell final gain values from the old and new protocols.
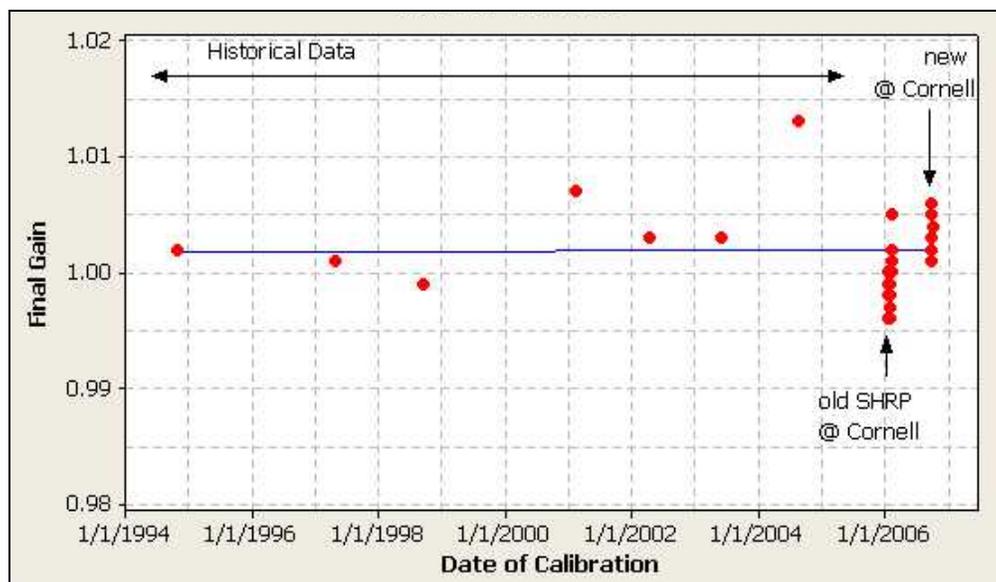
Figure 32. Graph. Load cell calibration history from 1994 to 2006.

Therefore, both protocols may have accurately reported the gain factors that were applicable at the time. It is believed that the response of the FWD load cell actually changed during the course of the year. The magnitude of the change found in 2006 was consistent with the changes that have been observed in earlier years. Other interpretations of the data are possible, but from a practical point of view, the results by the new procedure are credible.

Significance of the Differences

The differences in the calibration results using the two protocols were statistically significant. One conclusion from this may be that the new AASHTO protocol yields different results than the old SHRP protocol, but in practical terms, the differences are small. For example, for a deflection of 20 mil (500 μm), the average difference in the two protocols is only 0.05 mil (1.3μm). It is questionable whether such a small difference has practical meaning, even if the statistics indicate it is significant. Additional differences include the following:

- Beam movement up to 0.12 mil (3 μm) was tolerated using the old protocol.

- The new protocol completely eliminated that problem, which could account for the difference in the two protocols.

- The standard deviation for multiple calibrations is ±0.3 percent.

- Some real change in the sensor response could have occurred over the course of the year.

It is possible that the new procedure is more accurate than the old SHRP procedure. The differences are consistent with the expected standard deviation for multiple calibrations. It is also encouraging that the variances were the same by each method. From a practical perspective, the small differences are not a concern.

PRECISION AND BIAS STATEMENTS FOR FWD CALIBRATION

The pooled fund study focused on removing any possible bias error in the gain factors. Research found that no meaningful bias comes from either the load or deflection calibration procedures. The data cited in the previous section was used to formulate a precision and bias statement according to ASTM E-177.[17]

Using ASTM E-177 terminology, *repeatability* is defined as the overall variation expected at an individual FWD calibration center for all operators. *Reproducibility* is defined as the expected variation between single tests performed at multiple FWD calibration centers. Thus, repeatability was studied, but there is no information about reproducibility.

The series of calibration trials using the new procedure were used to define the precision and bias. The Dynatest® FWD was used for these tests. Multiple operators were involved to see if there was any difference between calibration operators. The calibrations were completed as quickly as possible (over a period of approximately 3 weeks) to minimize possible changes in the FWD.

Since this testing was on a single Dynatest® FWD at one location, the results should not be applied directly to all brands of FWDs or to multiple centers. However, the historical information about FWD calibration collected by Orr and Wallace and reviewed as part of this research shows that similar results can be expected for most other Dynatest® FWDs.[4]

Load Cell

In total, 17 load cell calibration trials were completed by 3 FWD calibration operators. No differences between operators were found. The overall standard deviation of the final calibration factor was 0.00152. The 95 percent repeatability using a student's *t*-test used a multiplier of 2.11.

Precision and Bias Statement for Dynatest® Load Calibration

The 95 percent repeatability of the final gain factor for Dynatest® load calibration is 0.321 percent. There is no bias expected in the final gain factor. No reproducibility statement is available at this time.

Geophone Calibration

Nine geophone calibration trials were completed by three calibration operators. No differences between operators were found. The overall pooled standard deviation of the final calibration factors for all nine geophones was 0.00245. By using the pooled standard deviation, the normal distribution multiplier of 1.96 may be used.

Precision and Bias Statement for Dynatest® Geophone Calibration

The 95 percent repeatability of the final gain factor for the Dynatest® geophone calibration is 0.480 percent. There is no bias expected in the final gain factor. No reproducibility statement is available at this time.

QA PROCEDURES AND OPERATOR CERTIFICATION

A key support function under this pooled fund study is the annual QA and certification reviews at each center. These visits help keep each operator informed about the changes in the protocol, equipment, and software. They also ensure that the calibration procedures are being carried out correctly. The annual visits also promote communication and feedback, helping identify needed improvements in the software and the protocol based on operator experience.

QA procedures were developed in the early 1990s beginning with SHRP to be used annually at the FWD calibration centers. The procedures were reviewed and updated as part of the support function of the pooled fund study. During March and April 2008, the first QA visits were conducted. A report for each separate visit was sent to the calibration center and copied to FHWA. Each calibration operator received a certificate of compliance, which was valid for the following year. The certificate conveys that the person performing the calibration is knowledgeable about the procedure.

Two checklists have been developed for use during the QA reviews. One is for reviewing the facilities and equipment, and the other is for reviewing the operator's performance. The findings are reviewed with the calibration operator, and they become part of the QA visit report. Details about the QA procedures and examples of the checklists are included in appendix D.

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The primary objectives of the pooled fund study have been achieved because the new protocol greatly increased the speed of FWD calibration without reducing the accuracy or ease of calibration. *WinFWDCal* is a Microsoft Windows®-based software program, and it guides all aspects of the new calibration procedure.

The overall philosophy for calibration of the load cell and deflection sensors has not changed from the old SHRP procedure. Reference calibration and relative calibration are still the foundation on which the new protocol was developed. The major changes include the use of the self-referencing accelerometer, the updated data acquisition system, the *WinFWDCal* computer program, and the new multisensor deflection sensor calibration stands.

A small but statistically significant shift in final calibration (gain) factors is evident when comparing results from the old SHRP procedure to the new AASHTO R32-09 procedure.[1] The average gain factor for the deflection sensors increased by less than 0.3 percent, while the average gain factor for the reference load cell increased by 0.4 percent.

It is not possible to determine which procedure is correct, but these results are close to the statistical repeatability of the procedure, and they should not be a cause for concern. The new AASHTO procedure eliminates the beam movement problem that was inherent in the SHRP procedure. As a result, it is likely to be more accurate.

The new procedure works well with all brands of FWDs. However, it is expected that there will continue to be a need for improvements as changes occur in FWDs, computer technology, and Microsoft Windows®. For example, the new Dynatest® truck-mounted FWD did not exist when the new AASHTO protocol was initially developed. In addition, access to the Carl Bro FWD was very limited during the development stage.

RECOMMENDATIONS

1. Review and update the calibration acceptance criteria.

   There are still a few instances in *WinFWDCal* where the internal QC criteria are not decisively defined. Using available data along with best judgment, initial tolerances were chosen to get the procedure into use. Over time, use of the new AASHTO R32-09 protocol has provided additional data to help refine the critical criteria. Release of *WinFWDCal* Version 2.0 includes changes that were created due to experience.

   The following criteria should be reexamined as additional data become available:

   - The allowable change for daily accelerometer calibration.

   - The allowable change in gain factors from one calibration year to the next.

- The allowable rate of change per year in gain factors for FWDs with at least 4 years of calibration history. (It will be mid2012 before sufficient data are available to allow reconsideration of this criterion.)

- The allowable noise in the accelerometer signal in the interval before the release of the FWD mass.

- The allowable noise in the accelerometer signal in the interval just preceding the impact of the falling mass.

Additional criteria may require review as researchers gain experience applying the *WinFWDCal* program. Feedback from the calibration center operators has been a great source of information.

2. Continue to provide support, QA, and operator certifications for the calibration centers.

   The calibration operators need ongoing support for several reasons. If they are experiencing issues calibrating an FWD, they need to communicate with people who can help them solve those problems. They need to know whether their equipment is working properly and if their results are believable. They also need a contact to offer suggestions for procedural improvements and help implement them.

   The annual QA reviews and operator certification are an important part of the center support. They provide a mechanism for two-way communication about changes in the protocol, equipment, and software. They also help identify problems that the centers are encountering.

   Since 2004, the pooled fund study has provided this support. Additionally, the SHRP calibration procedure was first introduced in 1992, and the Cornell Local Roads Program (CLRP) has provided general support to the centers ever since.

   In fall 2010, AMRL provided QA reviews and operator certifications. As a result, the basic support was assured. Careful coordination and communication between AMRL and CLRP is necessary to maintain the other aspects of general support.

3. Develop a means for interim certification of new calibration operators.

   The retirement and promotion of certified calibration operators seldom occurs just before a QA visit is due. Since the calibration operator must be certified in order to calibrate FWDs, this loss of personnel often requires a temporary shutdown of the center until the new operator can be trained and certified. It is costly and seldom possible to immediately arrange for new operator training and certification, which is a 3-day process.

   To avoid a prolonged closure period, a process whereby a certified operator can train and attest to the proficiency of the new operator should be developed. When the operator certifying agency (i.e., AMRL) receives notice, a temporary certificate should be issued covering the reminder of the pervious operator's certification period.

This process avoids a situation where the QA schedule gets out of sync. When the regularly scheduled time for the QA visit arrives, the temporary certificate can be replaced with a regular certificate, and the normal schedule is maintained. A similar procedure should be defined for new calibration operators in overseas centers.

4. Continue to upgrade *WinFWDCal* and *PDDXconvert* and release revised versions.

   Since the first public release of *WinFWDCal* in November 2006, several major releases of the software have gone out, and numerous small "bug fixes" have been made. While the rate of problem identification from the users has slowed down, programming support will be needed in the future.

   With any software package, there is a continual need for updates. Recommendations from the calibration centers and FWD owners need to be incorporated into the software as soon as possible to reduce the frustration of working with or around a bug.

5. Provide an electronic means to transfer the results (gain factors) of the calibration into the FWD computer.

   The new calibration procedure provides the means for electronic transfer of data from FWD to the calibration computer via a PDDX file format. The new procedure also outputs the calibration results electronically in the same file format. Electronic data transfer avoids the errors that come from manual entry. Currently, it is not possible to read the electronic output file and update the FWD operating system (field program) with the new calibration factors, calibration date, etc. This will require the assistance and cooperation of the FWD manufacturers.

6. Improve the electronic data transfer procedures.

   PDDXconvert only partially meets the needs for FWD calibration. Some of the necessary input data from FWD must still be entered manually or left out entirely. Also, several types of FWDs have their input data scattered among several different files.

   The manufacturers need to agree on and provide a standard output file format from the FWD operating system that would overcome the input/output problem. It would put all needed data in a single file and in a harmonized format. This will require the assistance and cooperation of FWD manufacturers.

APPENDIX A. FWD CALIBRATION PROTOCOL

INTRODUCTION

This appendix describes the new FWD calibration protocol. It is the basis of the current version of the AASHTO R32-09 procedure, *Standard Practice for Calibrating the Load Cell and Deflection Sensors for a Falling Weight Deflectometer.*[1] AASHTO R32-09 overrules any discrepancies with appendix A.

In May 2010, additional revisions to AASHTO R32-09 were submitted for review and approved by AASHTO. It is anticipated that the revised procedure will be published as AASHTO R32-11. This appendix is supplemental to the forthcoming AASHTO R32-11, and it provides additional background information about the FWD calibration procedures.

This protocol is written for use with the four types of FWDs currently manufactured or sold in the United States. It is not applicable to the calibration of lightweight deflectometers or cyclic loading pavement testing equipment. Due to differences in design of the four types of FWDs, there are some special considerations for each type, which are described in the annexes.

This protocol does not cover the calibration of other parts of FWDs including temperature probes and distance-measuring instruments. The manufacturers' recommended procedures should be used to calibrate those devices.

This protocol contains two procedures: annual calibration and monthly calibration. The deflection sensors must be removed from their holders on the FWD and installed in a calibration stand for either procedure.

Annual calibration can either be performed at a FWD calibration center or at a site where the FWD is located. The same equipment and procedures are used at both locations. A certified technician is required to perform the procedure. Annual calibration involves two steps: reference calibration and relative calibration. In reference calibration, the FWD's deflection and load transducers are calibrated against independently calibrated reference devices. In relative calibration, the deflection sensors are compared to each other.

In monthly calibration, only relative calibration of the deflection sensors is completed at any suitable location using the calibration stand supplied by the FWD manufacturer. A certified technician is not required. Monthly calibration is completed for verification of the accuracy of the deflection sensors and occasionally when a sensor must be replaced. The procedure used for monthly relative calibration is different than for annual relative calibration.

The annual and monthly procedures result in gain factors or dynamic calibration factors which are entered into the FWD software as multipliers. When the FWD raw measurements are multiplied by the gain factors, the result is a value which has been corrected to agree with the calibration instrumentation. It is necessary to have a place to enter the gain factors in the FWD operating system software (also known as the field program) provided by the manufacturer.

Frequency of Calibration

Annual calibration of the FWD load cell and deflection sensors should be performed at least once per year and as soon as possible after a sensor has been replaced.

Monthly calibration should be performed on the deflection sensors at least once per month and immediately after a deflection sensor has been replaced.

WinFWDCal

The calibration protocol as described herein has been automated in a software package named *WinFWDCal*. It can be used for both annual and monthly calibration. Use of the program is required to carry out the procedure.

ANNUAL CALIBRATION PROCEDURE

For annual calibration, the load cell and deflection sensors are calibrated with the goal of adjusting the accuracy (i.e., systematic error) of the devices to ±0.3 percent or better.

Personnel

Annual calibration requires two people to perform the procedure. One person is the FWD operator, who is responsible for assuring that the FWD is in proper working order for the calibration. During calibration, the operator controls the FWD and removes and replaces the sensors in their holders.

The other person is the calibration operator and is a certified technician. The calibration operator ensures that the calibration equipment is maintained and calibrated as needed. During calibration, this person is responsible for operating the calibration computer and the specialized software used in the calibration of the FWD. In addition, the calibration operator is responsible for providing the documentation of the calibration exercise.

Before beginning a calibration, the FWD operator should present a signed checklist documenting the steps taken in preparation for the calibration, indicating certain preferences concerning the way the calibration should be performed (see annex 1 of appendix A). The FWD operator is responsible for programming the FWD computer to carry out the requested procedure. The FWD operator should provide the history of past calibration results for the FWD.

During calibration, moving the sensors and operating the specialized equipment is a shared responsibility, with the calibration operator having primary control over the calibration equipment. The FWD operator is responsible for transferring the FWD data from the FWD computer to the calibration computer in a format that can be read electronically (including providing a means for the transfers).

After completion of the procedure, the calibration operator should provide the FWD operator with a certificate of calibration that lists the final gain factors for the load cell and each deflection sensor. The FWD operator should enter the final gain factors in the FWD computer and maintain a cumulative history of calibration results in the FWD computer as well as a history of calibration results for the FWD at the calibration center.

Equipment Preparation and Setup Before Calibration

During setup, FWD-specific information will need to be transferred from the FWD operating system (e.g., the FWD field program computer files) to the calibration computer. The annexes in this appendix describe the procedure for obtaining this information for each type of FWD.

FWD

The FWD needs to be in good operating condition prior to performing a calibration. A well-maintained FWD is easier to calibrate and less prone to mechanical and electrical problems during calibration and general use. A checklist to help the FWD operator prepare the FWD for calibration is provided in annex 1. It should be filled out in advance, and a signed copy of the completed checklist needs to be provided to the calibration operator.

Before beginning any calibration work and throughout the entire calibration period, there should not be any data filters turned on in the FWD operating system. The FWD operator is required to verify that all smoothing or filtering has been turned off.

Prior to calibration, the FWD should be warmed up using the standard operating procedure for the particular brand of FWD. After the FWD is moved into position for calibration, it is important that it is level to minimize unwanted vibrations. Trailer-mounted FWDs should also be level to avoid unwanted vibrations.

FWD Drop Sequence

The FWD mass and drop heights/load levels should be set up to produce loads within ±10 percent of the suggested loads shown in table 3. The FWD should be calibrated using three or four load levels. If only three load levels are used, the highest three load levels shown in table 3 should be used.

It is the FWD operator's prerogative to specify the load levels that will be used for reference calibration. Other load levels may be substituted for those suggested in table 3. The range of loads used should reflect that which FWD normally uses in daily operation. However, in no instance should the combination of static plate load plus maximum dynamic load exceed 24,000 lbf (106 kN). This limitation is required to protect the reference load cell and the concrete pavement used in the calibration procedure.

During setup, the minimum number of drops at each load level will be determined by *WinFWDCal* based on the deflection response of the concrete pavement or test pad. More than the minimum number of drops may be used without exceeding 10 drops per load level. The FWD operator should program the drop sequence in the FWD computer, progressing from the lowest to the highest load level. The same number of drops should be used at each load level, and the same drop sequence should be used for both load and deflection sensor calibration.

Table 3. Suggested dynamic load levels for reference calibration.

FWD Brand	Load Level 1	Load Level 2	Load Level 3	Load Level 4
Carl Bro	6,000 lbf (27 kN)	9,000 lbf (40 kN)	12,000 lbf (53 kN)	16,000 lbf (72 kN)
Dynatest$^®$	6,000 lbf (27 kN)	9,000 lbf (40 kN)	12,000 lbf (53 kN)	16,000 lbf (72 kN)
JILS	9,000 lbf (40 kN)	12,000 lbf (53 kN)	15,000 lbf (67 kN)	18,000 lbf (80 kN)
KUAB	6,000 lbf (27 kN)	9,000 lbf (40 kN)	12,000 lbf (53 kN)	16,000 lbf (72 kN)

Note: The metric and U.S. customary values in this table are not exactly the same. FWD should be calibrated in one unit system or the other. The values in the table are rounded with intervals that are approximately equally spaced.

The software may inform users that the deflections are either too large or too small to satisfy the precision requirements for reference calibration. The vertical accelerations are also checked to ensure that they do not exceed $±5$ *g*. If the deflection or the acceleration is too large, the FWD should be moved further away from the sensor stand. If the deflection is too small and if three load levels are used, users should try four load levels. If the deflection is still too small and the FWD cannot be moved closer to the sensor stand, users should try a sequence of higher load levels, if possible. If this does not solve the problem, users should find an alternative location to calibrate the deflection sensors.

FWD Calibration Equipment

Table 4 provides information on the equipment needed to perform the load cell and deflection sensor calibration. Detailed information for all components is found in appendix E of this report.

Both reference and relative calibration of all sensors should be performed on concrete pavement. The concrete floor area, or optional concrete test pad, should be in good condition with little or no cracking. The ball-joint base should be attached firmly to the concrete with two anchor bolts to hold the sensor stand in direct contact with the concrete. Additionally, the sensor stand should be clamped tightly in the base. Slippage, rocking, or vibration between the stand and the base or between the base and the concrete is not allowed. The ball-joint should rotate with slight friction.

Reference Load Cell Calibration

The reference load cell should be calibrated at least once per year in accordance with the AASHTO R33-03 procedure (see annex 7 of appendix A).[10]

Table 4. FWD calibration center equipment.

Equipment	Notes
Reference load cell with signal cable	30,000 lbf (133 kN) maximum capacity; calibrated annually to 24,000 lbf (106 kN) using AASHTO R33-03[10]
Reference accelerometer with signal cable	± 5 *g* maximum acceleration range, calibrated on the day of use
Vishay 2310 or 2310B signal conditioner with power cable	Amplifies the output from the reference devices before analog to digital conversion
Keithley KUSB-3108 data acquisition board with cables	Converts the analog output signal into a 16-bit digital value; connected to Vishay and calibration computer
Calibration computer and *WinFWDCal*	Stores the analog-to-digital (A/D) output and performs the calculations needed for the calibration
Accelerometer calibration platform	Performs daily calibration of the accelerometer. Also used to store accelerometer in a +1 *g* field
Geophone calibration stand and hardware sets	Designed to be used with Dynatest®, JILS, and Carl Bro geophones; also used with KUAB geophones
Seismometer calibration stand	Designed to be used with KUAB seismometers
Ball-joint base and anchor	Used with both the geophone and seismometer calibration stands
Protective shipping case	For storage and shipping of reference load cell, Vishay signal conditioner, Keithley DAQ, and related cables
Isolated concrete test pad	Designed to generate pavement deflections in the desired range; a test pad is recommended but not required

Accelerometer Calibration

The accelerometer is calibrated in Earth's gravity prior to use for relative calibration to determine the daily response of the accelerometer. This calibration should be repeated after 8 h have elapsed.

The accelerometer, mounted in an aluminum box, should be calibrated using the calibration platform. The platform should be carefully adjusted using the bubble level to assure that the accelerometer is aligned with Earth's gravity. The accelerometer needs to be calibrated in both ±1 *g* fields by inverting the box briefly. Care must be taken to avoid dropping the accelerometer during the calibration process because the shock may cause damage.

WinFWDCal will guide the calibration operator through the accelerometer calibration procedure to calculate the calibration coefficients. The accelerometer box should not be in the -1 *g* orientation for more than 30 s during the calibration process to minimize the effect of hysteresis on the readings. If it is inverted for a longer period of time, the accelerometer calibration process needs to be stopped. Next, the box should be placed upright in a +1 *g* field for at least twice as long as it was inverted (up to a maximum of 24 h) to return it to equilibrium. For example, if the box is upside down for 1 min, it should be allowed to equilibrate for at least 2 min before repeating the calibration of the accelerometer.

The accelerometer calibration is slightly temperature sensitive. As a result, it is important that the accelerometer is calibrated shortly before its use. Temperature is monitored continuously by *WinFWDCal*. The program will alert the calibration operator if the temperature changes by more than ±18 °F (±10 °C). If this occurs, the accelerometer needs to be recalibrated.

FWD Calibration Procedure

It is recommended to complete that deflection sensor calibration first, followed by the load cell calibration. *WinFWDCal* should be used to collect data and make the associated QA checks.

Table 5 shows the calibration data reporting requirements and the sources of the data. Most of the data are read electronically by the calibration computer from files copied from the FWD operating system. All of the data can be entered or updated manually using *WinFWDCal*.

Deflection Sensor Calibration

Deflection sensor reference calibration consists of two trials where all of the sensors are calibrated simultaneously in a special stand (see appendix F). The position of the sensors in the stand is inverted between the trials. This is followed by two relative calibration trials using the same stand, where the sensors are inverted once more. Spare deflection sensors should not be calibrated unless they have separate dedicated signal-conditioning channels in the FWD microprocessor.

For reference and relative calibration, the sensor stand should be manually held and kept vertical (as indicated by the bubble level) while data are being collected so the accelerometer box will be correctly aligned with Earth's gravity. The sensor stand should be supported by the rest stop between trials.

Reference Calibration

Deflection sensor reference calibration consists of performing at least two trials in which all of the sensors are calibrated simultaneously in the sensor stand. The position of the sensors in the stand is inverted between each trial. Spare deflection sensors should not be calibrated unless the FWD has separate dedicated signal-conditioning channels.

Table 5. FWD calibration data reporting requirements.

Data Item	Mode of Entry	Source
Center Information		
Calibration center location	Automatic	Center configuration file
Calibration operator name	Automatic	Center configuration file
Date and time of calibration	Automatic	Calibration computer
Temperature at calibration	Automatic	Data acquisition system
Reference load cell serial number	Automatic	Center configuration file
Reference load cell calibration constants	Automatic	Center configuration file
Reference load cell calibration date	Automatic	Center configuration file
FWD Information		
FWD owner	Manual	FWD operator
FWD operator name	PDDX file[1]	FWD computer
FWD Serial/ID number	PDDX file	FWD computer
FWD manufacturer	PDDX file	FWD computer
FWD load cell serial number	PDDX file	FWD computer or operator
FWD deflection sensor serial numbers	PDDX file	FWD computer or operator
Initial gain factor for FWD load cell	PDDX file	FWD computer
Initial gain factors for FWD deflection sensors	PDDX file	FWD computer
History of previous calibration results	History file	FWD computer
Calibration Data		
Unit system used in calibration	Manual	FWD operator
Number of load levels	Manual	FWD operator
Number of replicate drops	Computed	*WinFWDCal*
Reference load cell readings	Computed	*WinFWDCal*
FWD load cell readings	PDDX file	FWD computer
Reference accelerometer readings	Computed	*WinFWDCal*
FWD deflection readings	PDDX file	FWD computer
Interim gain factors from reference calibration	Computed	*WinFWDCal*
FWD relative calibration data	PDDX file	FWD computer
Adjustment factors from relative calibrations	Computed	*WinFWDCal*
Final gain factors	Computed	*WinFWDCal*

[1]Indicates that the PDDX file is created by *WinFWDCal* from FWD native output.

The deflection sensors should be placed in the sensor stand and centered on the reference accelerometer. *WinFWDCal* displays a diagram showing how to arrange the sensors in the stand (see table 8 and table 9 in appendix B).

The drop sequence for the first reference calibration trial should be performed. The operators should review and accept or reject the data for each drop. *WinFWDCal* will graphically display the deflection time history data after each drop.

Excessive drift from the baseline shown on the time history graph should be cause for rejection of a drop. The software will alert the user when drift is excessive.

At the conclusion of each trial, the user should transfer the data electronically from the FWD to the calibration computer and review the results. For each sensor, *WinFWDCal* will regress the FWD output (independent variable) versus the reference deflection sensor (dependent variable) forced through zero. The slope of the regression line for each sensor, when multiplied times the initial gain factor, gives the reference gain factor. The slope for an individual sensor is acceptable if its standard error does not exceed 0.0020. The trial is acceptable if the standard errors for all sensors do not exceed 0.0020.

If the first trial is acceptable, the user should continue with the second trial. The sensors in the stand should be inverted before the second trial according to the diagram displayed by *WinFWDCal*. If any trial is not acceptable, the data should be rejected and the trial is repeated. The user should investigate the reason why the standard error exceeded 0.0020 and correct it, if possible, before repeating the procedure. The user must verify that all sensors are held firmly in the stand.

Interim Gain Factor Acceptance Criteria

After two reference calibration trials have been accepted, *WinFWDCal* will calculate the average reference gain factor for each sensor and display the results as the interim gain factors (one gain factor for each deflection sensor).

WinFWDCal will calculate the difference in the reference gain factors for each sensor between the two trials. If the difference for each sensor is no more than 0.005, then the reference calibration test is complete. If any of the differences is greater than 0.005, two additional trials should be performed. The user should accept the results and continue but note if any of the differences is more than 0.005. The average of the reference gain factors for all trials for each sensor should be reported as the interim gain factors.

Relative Calibration

Relative calibration is followed by reference calibration and uses the same sensor stand. Two trials are performed. For each trial, 40 drops are applied from the highest drop height used in reference calibration. The sensors should not be repositioned in the sensor stand before the first trial.

WinFWDCal will adjust the FWD data collected in the relative calibration using the interim calibration factors internally. The user should not enter the interim factors in the FWD operating program before performing relative calibration.

To begin, the user should perform the drop sequence for the first relative calibration trial. At the conclusion of each trial, the data should be transferred electronically from the FWD to the

calibration computer, and the results should be reviewed. For each sensor, *WinFWDCal* will calculate the means ratio. The means ratio multiplied times the interim gain factor gives the relative gain factor.

WinFWDCal performs an ANOVA test for the data and reports the standard error. The trial is acceptable if the standard error is not more than 0.12 mil (3 μm) and there are no extreme outliers in the data.

WinFWDCal will display a plot of the data for the 40 drops. The graph should be scanned to detect extreme outliers (i.e., due to a loose sensor in the stand). An extreme outlier would appear substantially outside the normal range of the deflection data.

If the standard error is greater than 0.12 mil (3 μm) or if there are extreme outliers in the data, the first trial is not acceptable, the data should be rejected, and the trial should be repeated. Note that the sensors in the stand should not be repositioned. The reason why the data are unacceptable should be investigated and corrected, if possible, before the procedure is repeated. However, if the first trial is acceptable, the user should continue with the second trial. The sensors in the stand should be inverted before the second trial according to the diagram displayed by *WinFWDCal*. After two trials have been accepted, *WinFWDCal* will calculate the average relative gain factor for each sensor and report the results as the final gain factors, completing the deflection sensor calibration procedure.

Note that if two acceptable relative calibration trials cannot be obtained after performing four trials, no further effort should be made to calibrate the deflection sensors.

Load Cell Reference Calibration

If the reference load cell has not been calibrated within the past 12 months, it should be recalibrated in accordance with AASHTO R33-03.[10]

Reference load cell calibration consists of at least two trials. The FWD load plate should not be raised at any time during the procedure. To begin, users should perform the drop sequence for the first reference calibration trial. After, they should review and accept or reject the data for each drop. *WinFWDCal* will graphically display the deflection time data after each drop.

At the conclusion of each trial, the data should be transferred electronically from the FWD to the calibration computer, and the results should be reviewed. *WinFWDCal* will regress the FWD output (independent variable) versus the reference load cell (dependent variable) forced through zero. The slope of the regression line for each sensor, when multiplied times the initial gain factor, gives the reference gain factor. The slope for the trial is acceptable if its standard error is not more than 0.0020.

If the first trial is acceptable, the user should continue with the second trial. However, if the first trial is not acceptable, the data should be rejected, and the trial should be repeated. The user should investigate the reason why the standard error exceeded 0.0020 and should correct it, if possible, before repeating the procedure. The load cell should sit squarely under the FWD load plate and squarely on the concrete.

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Gain Factor Acceptance Criteria

After two trials have been accepted, *WinFWDCal* will calculate the average reference gain factor and report the results as the final gain factor. If the range of the two reference gain factors does not exceed 0.003, then the final gain factor should be accepted, completing the load cell calibration procedure.

However, if the results of the first two trials are outside the acceptable range, a third reference calibration trial should be performed. If the standard deviation of the gain factors for three acceptable trials does not exceed 0.003, then the results of the three trials should be averaged and reported as the final gain factor for the load cell, thus completing the load cell calibration procedure.

If the standard deviation of the three trials exceeds 0.003, the reference load cell calibration procedure should be repeated, yielding a fourth reference gain factor. If the standard deviation of all calibrations (four acceptable trials) does not exceed 0.003, the average of all four results should be reported as the final gain factor for the load cell, and the load cell calibration procedure is complete.

If acceptable results cannot be obtained after performing four trials, no further effort should be made to calibrate the load cell.

Evaluation and Acceptance of Final Results

WinFWDCal will perform the needed calculations. The data should be evaluated as follows.

1. The final gain factors from this calibration should be compared to the corresponding gain factors from the previous calibration (i.e., the initial gain factors). There should not be more than a 1 percent difference for each individual deflection sensor and for the load cell. If this criterion is satisfied, the final gain factor for the sensor is accepted. However, if this criterion is not satisfied for a sensor, it should be evaluated according to the next criterion.

2. The final gain factor for the sensor should fall within the range of 0.980 to 1.020. If this criterion is satisfied, the final gain factor for the sensor should be accepted. However, if this criterion is not satisfied for the sensor, it should be evaluated according to the next criterion.

3. If a historical record of previous calibrations according to this procedure is available for the sensor for 4 years or more and there are at least three previous calibration results over this time period, then the best fit time rate of change of the final gain factor for the sensor should not exceed 0.3 percent per year. If this criterion is satisfied, the final gain factor for the sensor is accepted.

Certificate of Calibration

If the final calibration results meet the acceptance criteria for all sensors according to one or more of the three criteria listed above, the calibration operator should provide the FWD operator with a certificate of calibration listing the final gain factors for the load cell and each deflection sensor. These factors should be entered into the FWD computer. An output file in PDDX format is provided by *WinFWDCal* to facilitate electronic data transfer.

Report and Retention of Data

The FWD operator should be provided with an electronic copy and a hardcopy of the calibration results. The FWD calibration report should consist of the following:

- The certificate of calibration or a summary page of the results if the calibration was not successful.

- An electronic copy of the complete record of the annual calibration including the data transferred from the FWD.

- A pre-calibration checklist.

- Any other records should be annotated with the FWD unit identification (e.g., manufacturer's serial number or agency ID) and the calibration date.

Calibration records should be retained by the calibration center for at least 5 years.

MONTHLY CALIBRATION PROCEDURE

Monthly calibration serves two purposes. First, it is a means to verify that the deflection sensors are functioning properly and consistently. Second, it can also be used to replace a damaged sensor, providing a short-term gain factor for the replacement sensor until an annual calibration can be performed.

Monthly calibration uses a calibration stand provided by the FWD manufacturer. The deflection sensors are stacked vertically in the stand so that all of the sensors are subjected to the same pavement deflection. Position in the stand may have an effect on the deflection readings. To compensate for this, the sensors are rotated through all positions in the stand. This rotation procedure is different from the relative calibration procedure performed for annual calibration.

Relative calibration relies on collecting a large amount of data that can be averaged to reduce the significance of random measurement errors. Deflections in excess of 20 mil (500 μm) are needed for the results to be accurate. *WinFWDCal* does the statistical data analysis to compute adjustment ratios and final gain factors from the data.

Since a large number of drops are involved, the properties of the pavement materials may change due to compaction or liquefaction during the procedure. However, all of the sensors are equally affected, and as long as the effect is not too extreme, the adjustment ratios are still accurate.

Some FWDs may have less than seven or more than nine active deflection sensors. If they do, these procedures should be modified to simultaneously calibrate the actual number of active sensors.

Equipment Preparation

FWD

The FWD should be in good operating condition prior to calibration. A well-maintained FWD is easier to calibrate and less prone to mechanical and electrical problems during calibration and during general use. A checklist to help the FWD operator prepare the FWD for calibration is provided in annex 1.

Before beginning any calibration work and throughout the entire calibration period, there should not be any data filters in operation in the FWD operating system. The FWD operator must verify that all smoothing or filtering has been turned off. Additionally, prior to calibration, the FWD should be warmed up using the standard operating procedure for the particular FWD brand.

Other Equipment

Additional calibration equipment includes the FWD calibration stand provided by the manufacturer.

Procedure Overview

Replicate deflection readings should be taken with the sensors assembled in the calibration stand. With the sensors in a particular position in the stand, two unrecorded seating drops followed by five recorded drops constitute a set. The deflection sensors should be rotated through the various positions in the calibration stand in a prescribed way. The rotation procedure is shown in table 6 for a nine-sensor system and table 7 for a seven-sensor system. The total number of sets of data is equal to the number of sensors on the FWD.

The test point (the location where the FWD load plate is positioned) should be "conditioned" before beginning the calibration procedure to reduce the significance of the set in the data analysis. The warm-up drops should be used for this purpose.

Monthly Calibration of the Deflection Sensors

Follow the *WinFWDCal* on-screen instructions for setup of the procedure as follows:

1. Remove all the deflection sensors from their holders on the FWD. For an FWD with *n* sensors, number the sensors from D1 to D*n* with respect to their normal position on the FWD. The center position is sensor number "1" on the Dynatest®, Carl Bro, and JILS FWDs and sensor number "0" on the KUAB FWD. In either case, the center sensor should be defined as D1 for this procedure.

2. Label the levels on the sensor stand from "A" to "G" or "I" as appropriate. The top level is labeled "A."

3. Position the deflection sensors in the stand for the first set as shown in table 6 or table 7.

4. Position the sensor stand vertically. Mark the location where it rests so that it can be relocated precisely on the same spot. This should be performed by gluing a washer to the pavement or by chipping a small divot in the pavement with a chisel or a screwdriver.

5. Select the FWD drop height and the distance from the loading plate to the sensor stand to yield deflections near 20 ±4 mil (500 ±100 μm). If deflections in this range cannot be achieved, choose another location. A concrete pavement on a relatively weak subgrade will usually yield the required deflection.

6. Lower the FWD loading plate. If the FWD operating system allows, do not raise the loading plate or move the FWD during relative calibration testing.

7. Make two seating drops (no data recorded) for each set followed by five replicate drops (for which data should be recorded).

8. Rotate the sensors in the stand at the end of each set as shown in table 6 and table 7. The general progression is for the sensors to move from the bottom toward the top of the stand.

   Note: The rotation must be performed as prescribed for the data analysis in *WinFWDCal* to work properly. If the direction of rotation is reversed, the calculations will be incorrect.

9. Record 45 drops for a 9-sensor FWD and 35 drops for a 7-sensor FWD.

Table 6. Monthly calibration sensor positions by set for a nine-sensor FWD.

Stand Position	Deflection Sensor Number in the Stand								
	1	2	3	4	5	6	7	8	9
A (top)	D1	D2	D3	D4	D5	D6	D7	D8	D9
B	D2	D3	D4	D5	D6	D7	D8	D9	D1
C	D3	D4	D5	D6	D7	D8	D9	D1	D2
D	D4	D5	D6	D7	D8	D9	D1	D2	D3
E	D5	D6	D7	D8	D9	D1	D2	D3	D4
F	D6	D7	D8	D9	D1	D2	D3	D4	D5
G	D7	D8	D9	D1	D2	D3	D4	D5	D6
H	D8	D9	D1	D2	D3	D4	D5	D6	D7
I (bottom)	D9	D1	D2	D3	D4	D5	D6	D7	D8

Table 7. Monthly calibration sensor positions by set for a seven-sensor FWD.

Stand Position	Deflection Sensor Number in the Stand						
	1	**2**	**3**	**4**	**5**	**6**	**7**
A (top)	D1	D2	D3	D4	D5	D6	D7
B	D2	D3	D4	D5	D6	D7	D1
C	D3	D4	D5	D6	D7	D1	D2
D	D4	D5	D6	D7	D1	D2	D3
E	D5	D6	D7	D1	D2	D3	D4
F	D6	D7	D1	D2	D3	D4	D5
G (bottom)	D7	D1	D2	D3	D4	D5	D6

Monthly Calibration Data Analysis

The data file should be transferred electronically from the FWD to *WinFWDCal* for analysis. Options provided in the software indicate whether a normal data analysis or a special analysis is required for sensor replacement.

Adjustment of Gain Factors—Normal Analysis

WinFWDCal will report the adjustment ratios and the gain factors for each deflection sensor. Since sensor replacement is not involved, the adjustment of the gain factors in the FWD operating system should be made only when those changes are both significant and verified to be necessary. The following guidelines should be used to evaluate the need to adjust the gain factors:

- If all of the adjustment ratios fall between 0.997 and 1.003, then they are not statistically significantly different from a ratio of 1.000. The calculated adjustments are trivial, the calibration test is complete, and no change of the gain factors should be made.

- When the adjustment ratios for one or more sensors fall outside of the range 0.997 to 1.003, a second relative calibration trial should be performed. If the gain factors for each sensor in both trials agree within 0.003, the need for the adjustment has been verified. The gains should be adjusted for all sensors. The gain factors for each sensor for the two trials should be averaged and entered in the FWD operating system, and the calibration test is complete.

- If the difference in the gains for the two trials for one or more sensors is greater than 0.003, two additional trials should be performed. If the second attempt also exceeds the allowable difference, the annual calibration procedure should be performed as soon as possible.

Adjustment of Gain Factors—Sensor Replacement

When replacing a damaged deflection sensor, the monthly calibration procedure should be used to determine a gain factor for the replacement sensor. The calculations are performed by *WinFWDCal*, and a gain factor is reported only for the replacement sensor.

Two relative calibration trials should be performed. If the two gain factors agree within 0.003, then the gain factors for the two trials should be averaged and entered in the FWD operating system, and the calibration test is complete. However, if the difference is greater than 0.003, two more relative calibration trials should be performed. *WinFWDCal* will report the average gain factor from the four trials and the standard deviation. If the standard deviation is not more than 0.003, then the average gain factor should be entered in the FWD operating system, and the calibration test is complete. If the standard deviation is more than 0.003, no further effort should be made to calibrate the replacement sensor, and the annual calibration procedure should be performed as soon as possible.

Report

The relative calibration report consists of all printouts from *WinFWDCal* annotated as necessary to explain any problems which may have occurred.

ANNEX 1. PRE-CALIBRATION CHECKLIST

Fill out and bring this checklist with you to the calibration center. Your signature below indicates that you have met all of the pre-calibration requirements.

FWD Operator: _____

FWD ID Numbers:
(serial and/or model
numbers) _____

FWD Manufacturer: _____

FWD Owner Agency: _____

☐ Inspect all connections, fittings, and cables and repair or replace those which are damaged. Damaged cables and bad connections can and will cause inaccuracies in deflection data.

☐ Assure that the load plate swivel is properly lubricated, if applicable, and that all bolts are tight. Refer to your owner's manual for instructions. Use the 12-inch or 300-mm diameter load plate during calibration.

☐ Remove the rear sensor extension bar if it is currently installed.

☐ Clean and inspect all sensors and signal cables. (Deflection sensors are removed from their holders during calibration.) Fine grained emery cloth is useful for cleaning the magnetic bases of Dynatest® sensors. Remove all stones embedded under the load plate.

☐ Provide a USB thumb drive or a formatted 3½" diskette for transfer of the FWD data to the calibration computer.

☐ Store your operating manuals in the FWD vehicle in case they are needed.

☐ Check the integrity of the batteries with a hydrometer or load tester. Clean the battery terminals and cables of corrosion.

☐ Check hydraulic fluid level(s) and assure that they are at the proper fill point. Inspect the hydraulic system for leaks. Replace the hoses if necessary.

☐ Select the system of units and the load levels to be used for calibration.

> Unit system: Target load levels:
>
> ☐ US Customary(lbf)   1. _____   2. _____
>
> ☐ Metric   3. _____   4. _____
>
> Adjust or calibrate the FWD to achieve the target levels within ±10 percent.

☐ Verify that the proper drop sequences are programmed into the FWD software for both reference and relative calibration. Name and save the setup files.

☐ Turn off filtering (smoothing) in the FWD operating system (if applicable).

☐ Have electronic data files or hardcopies from the previous calibration(s) available.

> Operator's signature: _____

ANNEX 2. SPECIAL PROCEDURES FOR CALIBRATING A DYNATEST® FWD

1. The FWD operating system (i.e., the field program) should be programmed to provide the output from the FWD in the F10, F20, or F25 format. All file extensions should be F*nn*, where *nn* is the version number of the FWD field program. This format is needed so that *PDDXconvert* can read the FWD file for *WinFWDCal*.

2. Save an F25 file in addition to the Microsoft Access® database file for use with *PDDXconvert* for FWDs using Dynatest®'s *FWDWin* as the operating system.

3. Warm up the FWD off the calibration test pad. Save the data in a file named "Warmup.Fnn," where *nn* is the version number of the FWD field program.

   Note: During the setup procedure in *WinFWDCal*, the Warmup.Fnn file will be read electronically to get information on sensor serial numbers, initial gains, etc.

4. Power the FWD with a battery charger. Without a charger, the FWD electrical system may not have enough power for a full calibration. Charging the FWD should be done in accordance with the manufacturer's recommendations. Some chargers may cause electrical noise on the time history signal during reference calibration.

5. Attach the trailer to the tow vehicle during calibration for trailer-mounted FWDs.

6. For the Dynatest® FWD, it is possible to be within the tolerance for the highest load and have the drop height set too high. Before placing the reference load cell under the load plate and with the mass positioned at drop height four (the highest position), users must verify that there will be no interference between the catch mechanism and the brace between the two columns that surround the cylinders that raise and lower the load plate. The reference load cell is nearly 3.875 inches (99 mm) high, so the catch mechanism will be that much higher during load calibration. If the clearance is too small, the target for the fourth drop height should be repositioned to provide the needed clearance.

7. Remove the removable masses to get the peak load from the highest drop height into the range of 16,000 lbf (71kN) ±10 percent for the Dynatest® HWD. This will avoid exceeding the capacity of the reference load cell and avoid damaging the test pad due to excessive deflections.

8. Clean out all stones that are embedded in the rubber pad under the load plate. The FWD operator should complete this cleaning before arrival at the calibration center.

9. Assemble the calibration stand hardware before FWD arrives. The knurled knob should be placed above the shelf in the calibration stand (see figure 33). The knurled knob should only be tightened by hand. Do not use a wrench to attach the hardware.

10. Clean the bottom of the geophones and remove any small particles that will interfere with proper contact of the magnetic mounts. Emery paper does a good job of this. The FWD operator should complete this cleaning before arrival at the calibration center.

11. Place a geophone on the knurled knob in the stand and try to rock it lightly back and forth. If there is any motion, reclean the bottom of the sensor. Each geophone must be securely fastened in the stand.

12. Place a wooden block under the FWD's raise-lower bar during load cell calibration to reduce the noise and vibration.

13. Ensure that the air in the large hydraulic cylinder has been bled out. Failure to bleed the air from the hydraulic system will result in vibration when the catch is released. This will delay the calibration due to excess noise messages. The FWD operator should perform the bleeding before arrival at the calibration center.

14. Verify that the new calibration gains have been entered correctly into the FWD field program by printing a summary of the relative gains. The relative gain is the value that is determined from the calibration. Do not change the reference gains because those are determined by the manufacturer.

Figure 33. Photo. Attachment of a Dynatest® geophone in the stand.

ANNEX 3. SPECIAL PROCEDURES FOR CALIBRATING A JILS FWD

1. The FWD operating system (i.e., the field program) should be programmed to provide output with DAT file extensions. This format is needed so that *PDDXconvert* can read the FWD file for the *WinFWDCal* software.

2. The JILS calibration operating system software will require the FWD operator to release each drop manually. It is used during reference calibration. JTEST is used during relative calibration.

3. Warm up the FWD off the calibration test pad. Save the data in a file named "WARMUP.DAT."

   Note: During the setup procedure in *WinFWDCal*, there are three files from the FWD computer that need to be read electronically in order to obtain information about the FWD sensor serial numbers and gains. The WARMUP.DAT file contains the deflection sensor serial numbers, the SETUP.PAR file contains the deflection sensor current gains, and the JILS.CFG file contains the load cell current gain.

4. Type the sensor gains or serial numbers manually into the *WinFWDCal* setup screen if the sensor gains or serial numbers cannot be read electronically.

5. Read the three configuration files and verify that each serial number is different. If they are not, rename the sensor numbers on the *WinFWDCal* setup screen with a number matching the sensor position on the FWD. For example, if all of the sensor serial numbers are "CHOP," rename them "CHOP*n*" where *n* is the number of the sensor starting at 1 for the center sensor at the load plate.

6. Attach the trailer to the tow vehicle during calibration for trailer-mounted FWDs.

7. Shim under the wheels as needed to assure both vehicles are level. The tongue wheel can also be used to help level the trailer. Both the tow vehicle and the trailer must be level when the FWD load plate is on the floor.

8. Check that the truck-mounted FWDs are level when the load plate is down. Check this on the chassis with a carpenter's level. Shim under the wheels if necessary to get the vehicle level.

9. Check that the load plate is squarely seated on the reference load cell and on the concrete test pad. The JILS load plate does not have a swivel, so the load plate may only be making partial contact. When good contact is achieved, it will not be possible to slide a piece of copy paper under the load plate more than a fraction of an inch (a few millimeters) at any point around the perimeter of the plate. Apply several seating drops (no data recorded) before making this check.

10. Remove the geophone sensor bar attached to the back of the FWD to allow the FWD to get close to the ball-joint anchor and the geophone stand.

11. Attach each geophone in the calibration stand with the knurled knob below the shelf as shown in figure 34. The knurled knob should only be tightened by hand. Do not use a wrench to attach the hardware.

12. Check that the quick connectors for the geophones are working properly. If they are not making good electrical contact, the FWD may provide intermittent noise or a sensor may fail to respond at all.

13. Power the FWD with a battery charger. Without a charger, the FWD electrical system may not have enough power for a full calibration. Charging the FWD should be performed in accordance with the manufacturer's recommendations. Some chargers may cause electrical noise on the time history signal during reference calibration.

14. Verify that the new calibration gains have been entered correctly into the FWD field program by printing a copy of the WARMUP.DAT, SETUP.PAR, and JILS.CFG files. The deflection sensor serial numbers are in the line that begins "Sensors:" near the top of the file. The geophone gains are in the SETUP.PAR file in the line below the text "# Sensor channels EU conversion factors:" The load cell gain is in the JILS.CFG file.
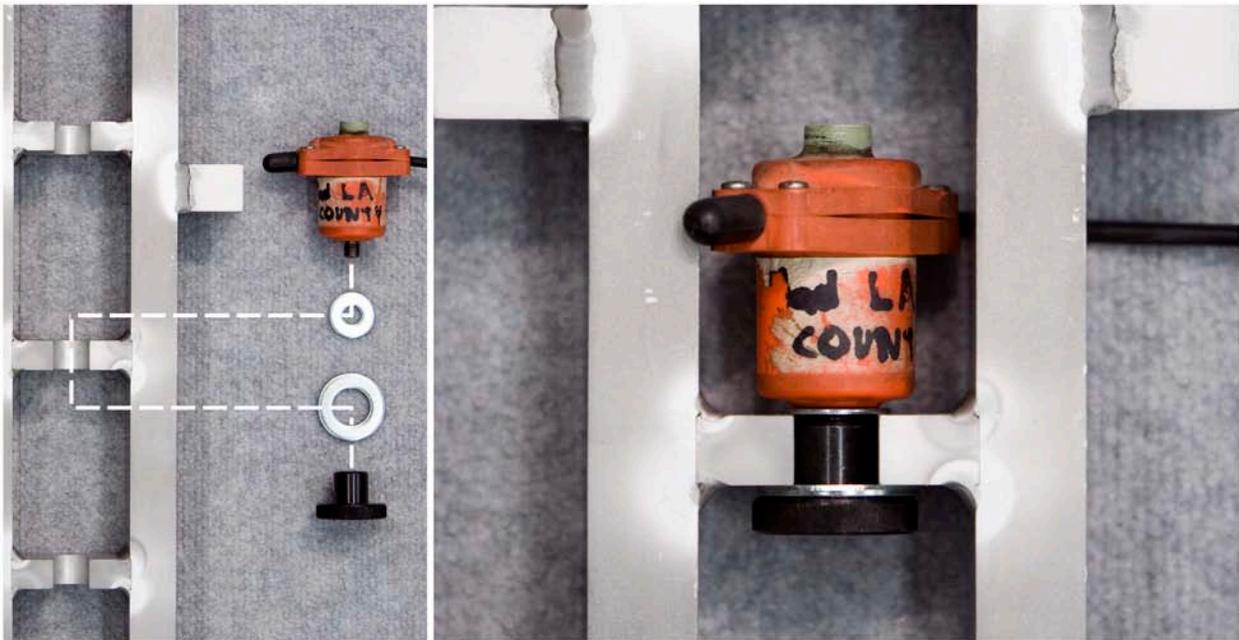
Figure 34. Photo. Attachment of a JILS geophone in the stand.

ANNEX 4. SPECIAL PROCEDURES FOR CALIBRATING A KUAB FWD

1. The FWD operating system (i.e., the field program) should be programmed to provide output of with FWD file extensions. This format is needed so that *PDDXconvert* can read the FWD file for the *WinFWDCal* software.

2. The FWD operating system software may require the FWD operator to release each drop manually. It may not be possible to program the desired drop sequence. In order to provide the pause needed after each drop during reference calibrations, the KUAB operating system software should be set up to perform manual drops.

3. During the setup procedure in *WinFWDCal*, the FVO.INI file from the FWD computer will be read electronically to get information on sensor serial numbers, initial gains, etc.

   Note: If the sensor initial gains or serial numbers cannot be read electronically, type the values into the *WinFWDCal* setup screen.

4. Power the FWD with a battery charger. Without a charger, the FWD electrical system may not have enough power for a full calibration. Charging the FWD should be done in accordance with the manufacturer's recommendations. Some chargers may cause electrical noise on the time history signal during reference calibration.

5. Attach the FWD trailer to the tow vehicle during calibration.

6. Conduct a static calibration of the seismometers before the reference calibration procedure is performed. The KUAB software will automatically file the static calibration factors.

7. It will only be possible to calibrate the 11.7-inch (300-mm) load cell on the KUAB. If the KUAB is outfitted with load cells with a diameter larger or smaller than 11.7 inches (300 mm), they should not be calibrated using the 11.7-inch (300-mm)-diameter reference load cell because the results would not be accurate.

8. Locate the FWD load plate as close as possible to the ball-joint anchor. This may require aligning the FWD beside the seismometer stand. Move the FWD into position before putting the seismometer stand in the ball-joint to avoid possible damage to the stand. The FWD should not touch the calibration stand during calibration.

9. Use the special two-column seismometer stand for deflection sensor calibration for KUAB FWDs with seismometers. The sensors are mounted on standoffs that are the same size as the ones on the FWD. After the set screw has been tightened, the seismometer should be firmly attached, and it should not wobble or rock on the standoff. Do not over tighten the set screw because the hole may be stripped. Place the geophones in the calibration stand as diagrammed by *WinFWDCal*.

   Note: The deflection sensor that is mounted through the load plate (i.e., the center sensor) is called sensor number zero on KUAB, but it is sensor number 1 as far as *WinFWDCal* is concerned.

10. Keep the stand aligned perpendicular to the load pulse from FWD during calibration of the seismometers. The easiest way to do this is to stand facing the load plate of FWD.

11. Attach each geophone in the calibration stand with the knurled knob below the shelf after removing the deflection sensors from the FWD as shown in figure 34. KUABs outfitted with geophones use the same one-column calibration stand used for Dynatest® geophones. The knurled knob should only be tightened by hand. Do not use a wrench to attach the hardware.

12. Place the geophones in the calibration stand as diagrammed by *WinFWDCal*. A magnetic collar holds the KUAB geophone to the calibration stand as shown in figure 35 and figure 36. A special magnetic cup holds the collar to the stand.

13. Enter the final gain factors for the deflection sensors in the *sharpcalfa* variable within the applicable [sensor#] section of the FVO.INI file. "#" refers to the sensor number with the numbering starting at zero.

14. Enter the final gain factor for the load cell in the *sharpcalfa* variable within the [loadplate] section of the FVO.INI file, if available. If this section is not in the file, the load cell testing should be considered to be calibration verification only.

15. Verify that the new calibration gains have been entered correctly into the FWD field program by printing a copy of the FVO.INI file.

**Figure 35. Photo. KUAB geophone parts.**

Figure 36. Photo. Attachment of a KUAB geophone in the stand.

ANNEX 5. SPECIAL PROCEDURES FOR CALIBRATING A CARL BRO FWD

1. The FWD operating system (i.e., the field program) should be programmed to provide output with FWD file extensions. This format is needed so that *PDDXconvert* can read the FWD file for *WinFWDCal*.

2. The FWD operating system software may require the FWD operator to release each drop manually. It may not be possible to program the desired drop sequence.

   In order to provide the pause needed after each drop during reference calibration, the operating system software can be set up to perform manual drops without raising the plate only after performing the seating drops (no data recorded) and at least one recorded drop. The FWD operator should prepare a list of the drops needed ahead of time and be prepared to reject the first drop after the seating drops.

3. In order to obtain the sensor serial numbers and the initial gains, use the RoSy$^®$ software from Carl Bro to create a text file containing these values. The file should be named "HW_INI.TXT."

   Note: During the setup procedure in *WinFWDCal*, the HW_INI.TXT file will be read electronically to get information on sensor serial numbers, initial gains, etc.

4. Type the values of the sensor initial gains or serial numbers into the *WinFWDCal* setup screen if they cannot be read electronically.

5. Attach the trailer to the tow vehicle during calibration for trailer-mounted FWDs.

6. The Carl Bro FWD uses a generator on the trailer to provide the electrical power for operations. If possible, warm up the FWD outside and fully charge the batteries prior to moving the FWD indoors. This will allow the calibration to proceed without turning on the generator any more than necessary.

7. Locate the FWD load plate as close as possible to the ball-joint anchor. This may require placing the geophone stand inside the rear of the FWD frame. Move the FWD into position before putting the geophone stand in the ball-joint to avoid possible damage to the stand. The FWD should not touch the calibration stand during calibration.

8. Remove the deflection sensors from the FWD and attach each geophone in the calibration stand with the metric knurled knob below the shelf as shown in figure 37. The knurled knob should only be tightened by hand. Do not use a wrench to attach the hardware.

9. The Carl Bro operating system software does not have a specific place for the new gain factors, so the final gain factors must be multiplied by hand and input into the FWD operational software in the correct place. Follow the manufacturer's recommendations for this step.

10. Verify that the new calibration gains have been entered correctly into the FWD field program by printing a copy of the updated HW_INI.TXT file. Use the RoSy® software from Carl Bro to create this text file.
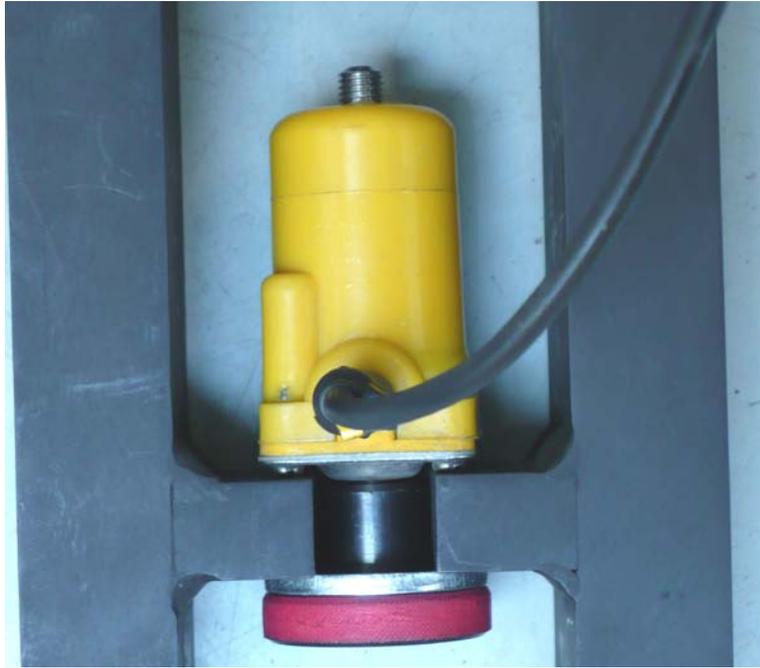
Figure 37. Photo. Attachment of a Carl Bro geophone in the stand.

ANNEX 6. SPECIAL PROCEDURES FOR ON-SITE CALIBRATIONS

The calibration protocol allows users to perform annual calibrations at locations other than a calibration center. The equipment is highly portable, and it may be advantageous to perform the calibration where the FWD is located rather than shipping the FWD to a center. This procedure is called on-site calibration because it is performed at a site preferred by the FWD owner.

The calibration procedure outlined in appendix A should be used without exception. It must be carried out by a certified calibration center operator as required in AASHTO R 32-09.[1]

A special test pad is not required to be constructed for on-site calibrations. In this regard, AASHTO R 32-09 indicates the following:[1]

> While an isolated test pad is recommended, it is not required, provided that all other facilities requirements, especially the minimum slab deflection requirement and sufficient slab damping, are achieved. The slab dimensions (4 by 5 m) are suggested, and other dimensions may be satisfactory … In general, a concrete pavement on a relatively weak subgrade will yield the required deflection amplitude.

As previously noted in this report, the recommended peak deflection is 20 mil (500 µm), and the minimum recommended deflection is 12 mil (300µm). Peak deflection is a useful way to identify suitable locations for performing calibrations. However, deflection is not the limiting criterion. *WinFWDCal* checks for the following two conditions:

- The maximum acceleration must not exceed 5 *g*.

- The maximum number of replicate drops must not exceed 10 drops at each load level.

The difficult part of on-site calibration is finding a suitable place to mount the ball-joint anchor and the calibration stand. Figure 38 shows a calibration being performed at the Hawaii Department of Transportation in a breezeway between two buildings. The concrete pavement at this location was relatively thin, and when the FWD was close to the calibration stand, the maximum acceleration exceeded 5 *g*. To overcome this problem, the FWD trailer was moved about 24 inches (600 mm) in front of the stand, thereby reducing both the peak deflections and maximum accelerations.

Figure 38. Photo. On-site FWD calibration at Hawaii Department of Transportation Materials Lab.

Note that the FWD must be level during the calibration. It is also important to have the calibration equipment protected from the weather at all times. To assess the suitability of a location for FWD calibration, it may be helpful to use the Facilities Review Form found in figure 45 in appendix D.

A procedure involving an FWD and one deflection sensor is used to find a place to install the ball-joint anchor. The sensor is removed from its holder and held in place by hand on the pavement. A firm downward pressure is required to keep the sensor in contact with the pavement. A concrete pavement works better than an asphalt pavement because it spreads the deflection basin over a wider area. The procedure is as follows:

1. Position the deflection sensor 3.9 inches (100 mm) from a joint in the concrete. Position the FWD so the rear of the load plate is 30 inches (750 mm) ahead of the deflection sensor (34 inches (850 mm) from the slab joint). If there is no pavement joint, draw a line across the pavement that can be used to measure from.

2. While manually holding the sensor on the, floor (see figure 39), perform one seating drop (no data recorded) at approximately 6,000 lbf (27 kN) followed by two drops at approximately 16,000 lbf (70 kN). Record the peaks for both drops, and refer to it as position #1.

   Note: If there is any concern that a 16,000-lbf (70-kN) load will damage the test pad, use a lesser load level and scale the measured deflection linearly to 16,000 lbf (70 kN).

3. Repeat the above procedure with the deflection sensor positioned at 7.8, 11.7, 17.55, and 23.4 inches (200, 300, 450, and 600 mm) from the rear of the test pad. Keep the spacing between the sensor and the rear of the FWD load plate constant at 29.25 inches (750 mm). Name the positions sequentially (#1, #2, #3, etc.).

4. Plot the peak deflection at 16,000 lbf (70 kN) versus distance from the joint or the line. Find the distance where the deflection is roughly 20 mil (500 µm). Install the two stainless steel inserts in the floor at that location as described in the Concrete Anchor Installation section in appendix E.

Care should be taken to avoid placing the ball-joint anchor too close to a joint or the edge of the pavement. It is often the case that the edge raises before it deflects downward. This can lead to vibration and excess noise problems in the data. Based on experience, a minimum distance of 11.7 inches (300 mm) is recommended between the anchor and the edge of the pavement.

After the ball-joint anchor and the calibration stand have been installed (see figure 39), go through the "Set Trigger" and "Determine Number of Drops" routines in *WinFWDCal*. Adjust the position of FWD either closer to the calibration stand or further away as needed to get a successful reference calibration.

Once a suitable place for on-site calibration has been found, it can be used repeatedly for future annual FWD calibrations. To protect the two stainless steel inserts from filling up with dirt, it is wise to put an Allen® head set screw in each anchor flush with the top of the holes.

Figure 39. Photo. Locating a place to install the ball-joint floor anchor.

ANNEX 7. REFERENCE LOAD CELL CALIBRATION PROCEDURE

INTRODUCTION

This appendix describes the new reference load cell calibration protocol in detail. It is the basis for the current version of the AASHTO R33-03 procedure.[10] AASHTO R33-03 overrules any discrepancies with this appendix.

The reference load cell is a custom-made precision instrument that is capable of measuring loads within ±0.3 percent or better. However, such a high degree of precision can only be attained if this calibration procedure is followed exactly. It is essential that the reference load cell is calibrated using a universal testing machine that is properly maintained and accurately calibrated.

The reference load cell and its signal cable, the associated signal conditioner, and DAQ should be considered a system of instruments that should be calibrated and used together. The load cell should be calibrated to a maximum load of 24,000 lbf (100 kN).

This procedure is written with both U.S. customary and metric units shown. The calibration operator should choose one unit system and follow the procedure using the values shown. The values are not meant to be a direct conversion. The values are chosen to provide regular steps and ranges with whole numbers where possible.

This procedure has been automated and is included in the *RefLCCal* computer program.[18]

FREQUENCY OF CALIBRATION

Calibration of the reference load cell should be performed at least once per year. It should also be performed immediately after any of the machine screws that attach the load measurement links to the upper or lower plates are loosened. Calibration may also be necessary if the load cell fails to pass the unbalanced zero test during FWD annual calibration.

EQUIPMENT

The following list provides information on the necessary equipment for reference load cell calibration:

- Universal testing machine.

  A static testing machine (hydraulic or screw-powered) with a load capacity of 100,000 lbf (500 kN) or more should be used. Although the reference load cell will only be calibrated to a capacity of 100 kN (24,000 lbf), the higher capacity of the testing machine assures that the test frame will be adequately rigid. The testing machine should have several load ranges, among them a zero–30,000 lbf (zero–130 kN) range. Slightly different ranges (i.e., zero–24,000 lbf (zero–100 kN)) would be acceptable as long as the entire range of the load cell can be calibrated on a single range of the universal testing machine. Care must be taken to avoid overloading the reference load cell during calibration.

Do not use a servo-controlled, closed-loop testing system for this purpose. In general, such equipment does not provide a high degree of accuracy that is required for this calibration.

- Special wood/aluminum bearing blocks for placement above and under the reference load cell.

- Custom manufactured load cell with its signal cable, associated signal conditioner, and DAQ. The load cell has three measurement links contained in aluminum housing.

- A Vishay 2310 signal conditioner, which should be the same signal conditioner that will be later used in the FWD calibration procedure.

- Keithley model KUSB-3108 DAQ, which should be the same A/D board that will be later used in the FWD calibration procedure.

- Pushbutton trigger for activating the data acquisition system.

Equipment Calibration

The universal testing machine should be calibrated annually by a certified technician according to ASTM E-74.[19] The calibrated machine should have a certified accuracy of 1 percent or better. The load indication system used for calibration should be traceable to NIST. The calibration certificate should be evaluated using a multinomial regression procedure to develop an adjustment algorithm (up to fifth order) that adjusts the indicated load on the universal testing machine to the corrected NIST traceable calibrated load. The load calculated by use of the adjustment algorithm is referred to herein as the adjusted load, while the load indicated on the testing machine dial is referred to as the indicated load.

The testing machine calibration coefficients and the date of calibration of the testing machine should be entered into the FWDCalCenterConfig.ini file used by *WinFWDCal* prior to calibrating a reference load cell.

The Vishay 2310 signal conditioner amplifier should be balanced according to the procedure described in the manufacturer's instruction manual. With the signal input terminals shorted together, at gain 100, the alternating current (a/c) noise on the ±10-V output terminals should be 1 mV or less.

Equipment Preparation

Load Cell Conditioning

A new load cell or one that has had the lid removed must be conditioned before being calibrated.

1. Use a torque wrench to tighten the machine screws on the top and the bottom of the load cell to 100 lbf-inch (11.3 N-m). Apply at least 100 conditioning drops on the load cell from the 16,000-lbf (72 kN) load level with the FWD. Remove the machine screws one at a time,

apply medium strength Loctite® to the threads, and torque to precisely 100 lbf-inches (11.3 N-m).

2. Apply another 100 conditioning drops on the load cell from the 16,000-lbf (72-kN) load level with the FWD. Record the unbalanced zero for the load cell after each 25 drops. It should change less than 1 mV during 25 load cycles. Continue applying additional load cycles until the unbalanced zero stabilizes, and apply at least 20 cycles of 24,000 lbf (100 kN) to the load cell with the universal testing machine. Apply additional cycles, if necessary, until the unbalanced zero stabilizes.

Equipment Inspection and Setup

1. Inspect the reference load cell carefully before calibration. Verify that the cable and the cable connectors fit and lock tightly and that there are no breaks in the wires. Verify that the machine screws on the load cell are tight.

2. Verify that one of the wood/aluminum bearing blocks has a ribbed rubber pad cemented to it. If the edges of the pads are loose, use automobile weatherstrip cement to reattach the pad.

3. Install a spherically seated bearing block in the cross head of the universal testing machine.

4. Make the following settings on the front panel of the Vishay 2310 signal conditioner:

   • Excitation switch ON.

   • Excitation voltage set to 10 V.

   • Filter set to 1,000 Hz.

   • AC IN button fully extended (e.g., out).

   • Set gain initially to 4.2 x 100.

     Note: If the reference load cell has been previously calibrated, the initial gain value may be different. If so, set the Vishay gain to the most recent value.

   • Auto balance switch off.

     Note: Verify that the tape playback switch on the rear panel of the signal conditioner is off. Position the signal conditioner and the computer several feet apart near the testing machine and attach them to the a/c line power.

5. The load cell and signal conditioner should be connected and powered for at least 30 min before performing the calibration procedure. This ensures the electronics are properly warmed up.

Calibration Procedure

Perform three calibration trials according to the following procedure. *WinFWDCal* must be used in conjunction with the following step-by-step procedure:

1. Hook up all cables and warm up the equipment for at least 30 min. Turn on the computer and initialize *WinFWDCal*. If a hydraulic universal testing machine is used, turn the pump on and allow the machine to warm up for at least 30 min.

2. Place a wood/aluminum bearing block with no rubber pad in the center of the testing machine platen.

3. Place the reference load cell on top of the bearing block with the support feet down (i.e., in contact with the top surface of the lower bearing block).

4. Place the second bearing block on top of the load cell with the cemented rubber pad down (i.e., in contact with the top surface of the load cell).

5. Carefully align the edges of the load cell and the two bearing blocks, and center the system under the spherical loading block of the testing machine.

6. Set the testing machine on a range equal to or slightly larger than 24,000 lbf (100 kN). Apply an indicated load of 24,000 lbf (100 kN) to the load cell three times. Apply the load at a rate of approximately 5,000–10,000 lbf (22–44 kN) per minute.

7. Temporarily remove the upper wood/aluminum bearing block. Set the auto balance switch on the Vishay 2310 signal conditioner to off. Read and record the unbalanced zero voltage using the pushbutton. If this voltage is in excess of ±5 V, the load cell may have been damaged by yielding, and it should be returned to the manufacturer for repair. If the load cell has been previously calibrated, verify that the difference in the unbalanced zero voltage is no more than 100 mV, or 5 percent of the previous value.

8. Briefly push down the auto balance switch on the signal conditioner to the reset position and release it to the on position. Adjust the trim knob until the KUSB board reads 0.0 V.

9. Replace and align the upper bearing block rubber pad down. Apply a load of 24,000 lb (100 kN), and check the output of the load cell is between 97 and 99 percent of full scale on the data acquisition system. In the case of the Keithley KUSB-3108, this will be between -9.7 and -9.9 V. Release the load, and record the gain setting.

10. If the voltage is not in the correct range, adjust the gain knob on the signal conditioner in 0.1 increments until the signal conditioner output is between 97 and 99 percent of full scale. (A gain of 4.20 x 100 is acceptable. A gain of 4.25 x 100 or 4.21 x 100 is not.) In no case should the output at 24,000 lb (100 kN) exceed 99 percent of full scale. The largest gain that does not produce an output above 99 percent of full scale should be used.

11. If the gain setting is changed, repeat steps 7–9.

Note: When the load is released, the indicted voltage will not read exactly zero because it was zeroed before the upper bearing block was put in place. Do not re-zero the signal conditioner at this point.

12. Carefully zero the universal testing machine. Use the push-button trigger to record the reading at the zero load level.

13. Apply load at a rate of 1,000 lbf (5 kN) per minute. Use the pushbutton trigger to record the readings at 1,000 lbf (5 kN) intervals up to a maximum indicated load of 24,000 lbf (100 kN). While releasing the load, record a reading at 12,000 lbf (50 kN) and at zero pound loads.

14. Remove the upper bearing block. Use the pushbutton to record the signal conditioner calibration voltages for +B and -B shunt values on the Vishay. Set the auto balance switch to off and again record the unbalanced zero voltage. This reading should be within 10 mV of the earlier reading. If it is not, repeat the calibration procedure.

Data Analysis

WinFWDCal will perform the data analysis for each trial. It will use a stepup regression utility to calculate a fifth degree polynomial of the form as follows:

$$Y = A_1 V + A_2 V^2 + A_3 V^3 + A_4 V^4 + A_5 V^5$$

Figure 40. Equation. Load cell calibration algorithm.

Where:

Y = The adjusted load calculated from the universal testing machine indicating load including the weight of the upper bearing block.
V = The load cell voltage.
A_i = Coefficients determined by the regression.

Evaluate the results according to the following acceptance criteria:

- The standard error of the regression should be less than ±20 lbf (±0.1 kN).

- Each of the coefficients should be statistically significant.

After completion of at least three acceptable trials, *WinFWDCal* will pool the data for all three trials and determine regression coefficients based on the combined data, and the calibration is complete.

The final set of calibration coefficients should be evaluated according to the above two criteria. In addition, the three sets of data should be random, neither steadily increasing nor steadily decreasing. This should be verified by reviewing a plot of the residuals versus the fitted values from the regression.

Entering the Coefficients in *WinFWDCal*

The load cell coefficients should be entered in the FWDCalCenterConfig.ini file. Any of the coefficients that are not found to be significant should be entered as 0.0.

When the regression coefficients are entered in the FWDCalCenterConfig.ini file, the unbalanced zero, the +B and -B calibration factors, and the load cell signal conditioner gain factor should also be entered. This information is used to validate the load cell during FWD calibration.

APPENDIX B. SUGGESTIONS FOR SUCCESSFUL ANNUAL CALIBRATIONS

The following suggestions are not a part of the formal protocol, but they have been found to be helpful in the success of the procedure.

1. The deflection sensor calibration procedure will work better if the deflections are 16 mil (400 μm) or more. It is not required that a special test pad be constructed, but if a regular concrete floor is used, locate the ball-joint base on a spot where the deflections are large enough.

2. Before doing any calibrations, verify that the FWD computer and the calibration computer are registering the correct date and time. Reconcile any issues before proceeding.

3. Locate the calibration data acquisition system as close as possible to the FWD computer so that the two system operators will be able to converse easily.

4. The signal conditioner and load cell should be connected and warmed up for at least 30 min before calibration. This will reduce the variability of the data during calibration. The signal conditioner and accelerometer only need to be warmed up an additional 5 min if the signal conditioner is already warm. If deflection sensor calibration is done first, the load cell can be warmed up while relative calibration is being performed.

5. Prior to calibration, the FWD should be warmed up using the standard operating procedure for the particular brand of FWD. This will reduce the variability of the data during calibration. Around 25 drops are needed for this purpose. More may be necessary if the FWD is colder than room temperature.

6. At the beginning of each programmed series of drops, add two seating drops (no data recorded) for which the data are not recorded. Seating drops are not required, but they will reduce the variability of the data during calibration. Seating drops are particularly needed after the deflection sensors have been moved in the calibration stand.

7. For load cell reference calibration, position the FWD so that the load plate is near the center of the calibration test pad. It is very important that the FWD is level when the calibration is performed. By doing load cell calibration on a different area of the test pad than the deflection sensor calibration, the life of the test pad is increased. It is acceptable to perform load cell calibration on an area of concrete floor that is away from the test pad provided that the FWD is level.

8. Position the reference load cell beneath the FWD load plate, ensuring that the three guides are properly aligned around the plate. Do not loosen or remove the alignment fingers on the reference load cell. Zero the signal conditioner with the load plate high so that there is no external load on the reference load cell.

   Note: For accurate results, it is important that the reference load cell be zeroed with the FWD load plate in the raised position. Also, the signal conditioner excitation and gain must

be set carefully to the levels at which the reference load cell was calibrated, as indicated in the *WinFWDCal* prerequisite information during setup.

9. Ensure that the FWD load plate is seated squarely on the reference load cell and on the concrete. To check this, perform a couple of seating drops and then try to slip a single sheet of copy paper under the load plate anywhere around the perimeter. It should not be possible to get the paper under the load plate or the three supports under the load cell any more than approximately 0.25 inches (6 mm). This will reduce the variability of the data during calibration.

10. For deflection sensor calibration, the mounting bolts for the ball-joint base and the bolts that clamp the stand to the base must be tight. Vibration will cause excessive variability of the readings, leading to an inability to pass the data acceptance criteria. The bolts holding the ball-joint in its socket should be tight enough to hold the stand upright but still allow the ball-joint to rotate freely.

11. The sensor stand connector pin (see figure 125) should be tightly attached to the stand. Apply Loctite® to the threads to assure that the pin will not turn. This will reduce the variability of the data during calibration

12. Verify that the deflection sensors are held firmly on the shelves of the sensor stands. This will reduce the variability of the data during calibration.

13. Attach the reference accelerometer box on the center shelf in the stand using two thumb screws. Press down on the box while tightening the screws to ensure that the box is seated firmly on the shelf. Try to keep the accelerometer aligned vertically in Earth's gravity field at all times to avoid hysteresis in the accelerometer readings.

14. Place the geophones in the single-column calibration stand as shown in table 8. If only seven sensors are being calibrated, then the top two positions (A and B) should be empty in trial 1, and the bottom two positions (I and J) should be empty in trial 2. An on-screen figure in *WinFWDCal,* similar to table 8, will show how the sensors should be placed in the stand.

    Note: The goal is to have the sensors centered on the accelerometer and to invert them uniformly in the second trial. If additional calibration trials are needed, they should be performed in sets of two using the positioning shown in the table.

15. Place the KUAB seismometers in the double-column calibration stand as shown in table 9. If nine sensors are being calibrated, put them in the top two positions. For trial 2, rotate the stand 180 degrees. Do not invert the sensors in the stand. The wide axis of the stand should be perpendicular to the wave coming from the FWD load plate. An on-screen figure in *WinFWDCal,* similar to table 9 will show how the sensors should be placed in the stand.

    Note: For trial 1, stand behind the stand facing the FWD load plate with sensors D1, D3, etc., in the left column. For trial 2, rotate the stand vertically on the ball swivel so the column with sensors D1, D3, etc., is on the right.

Table 8. Geophone positions in single-column stand (nine sensors).

Stand Position	Trial 1	Trial 2
A (top)	Empty	D9
B	D1	D8
C	D2	D7
D	D3	D6
E	D4	D5
Accelerometer Shelf	Accelerometer	Accelerometer
F	D5	D4
G	D6	D3
H	D7	D2
I	D8	D1
J (bottom)	D9	Empty

Table 9. KUAB seismometer positions in double column stand (seven sensors).

Stand Position	Trial 1		Trial 2	
A (top)	Empty	Empty	Empty	Empty
B	D1	D2	D2	D1
C (accelerometer)	D3	D4	D4	D3
D	D5	D6	D6	D5
E (bottom)	D7	Empty	Empty	D7

16. The accelerometer calibration is slightly temperature sensitive. Temperature is monitored continuously by *WinFWDCal*; however, the measurement point is at the KUSB DAQ. It is important to keep the DAQ and the accelerometer box out of direct sunlight to avoid measurement errors or false warnings.

17. Use a gentle downward pressure on the handles of the calibration stand while the reference and relative calibration data are being collected. At least half of the bubble on the level should be inside the black circle on the sight glass while data are being collected. Holding the stand consistently for each drop will reduce the standard error in the calibration trial.

18. For load or deflection reference calibration, if either of the following conditions occurs, the calibration testing should be repeated after identifying the source of the following problems and correcting them:

- Excessive noise at load levels of 9,000 lbf (40 kN) or more. The noise, due to electrical noise or mechanical vibrations, is of concern only if it results in an erroneous baseline value or an erroneous peak reading. The time history graphs provided by *WinFWDCal* should be reviewed to determine if the noise is a concern before rejecting the data for a drop.

- Standard deviations at any load levels that differ by more than a factor of three between the reference system data set and the FWD dataset.

- Standard deviations less than 25 lbf (0.11 kN) for the load cell and 0.16 mil (4 μm) for the deflection sensors are acceptable regardless of the ratio. *WinFWDCal* will check the ratios and post an error message, if applicable.

19. When not in use, the load cell, accelerometer, signal conditioner, and other calibration equipment should be stored in a protected location. The accelerometer should be stored in a +1 *g* gravity field to eliminate hysteresis. To accomplish this, attach the accelerometer box to the calibration platform using the two thumb screws. Use the bubble level to adjust the platform on the storage shelf.

20. In the event that the accelerometer is found to not be level after a period of storage, it will take at least 24 h at room temperature to eliminate most of the internal hysteresis. Full recovery can take 3–6 days, and the time period is longer at cold temperatures. This is true whether or not the accelerometer is powered by the signal conditioner.

APPENDIX C. PDDX STANDARD VERSION 2.0

INTRODUCTION

The purpose of the AASHTO PDDX standard is to foster a uniform file format for output from all types of pavement deflection devices, including FWDs. A harmonized file format allows programmers to develop deflection data analysis programs without the need to provide file readers for the many different native file formats that have been promulgated by equipment manufacturers over time.

While the purpose of this specification is to define a harmonized data format, it is not intended to replace the native file formats of the various manufacturers. Both formats can be provided if the manufacturer chooses. Equipment owners have the option to choose the desired output file format. The PDDX format can be used for static, steady-state vibratory, and dynamic pulse-loading devices, although the primary focus of the Version 2.0 standard is for pulse-loading devices (i.e., FWDs).

The PDDX format puts related data items into sections with descriptive names. It is similar to the .INI format used in Windows®-based configuration files. Each line in the file can either be a section heading or a data entry field with one or more values.

PDDX VERSION 2.0 OVERVIEW

Version 2.0 of the PDDX standard incorporates a few changes from Version 1.0. It reconciles the minor differences that have evolved between the PDDX standard and the input data needs of the AASHTO *DARWin* pavement design program. *DARWin* can read PDDX Version 2.0 files. The new version also adds a few data items that were inadvertently left out of Version 1.0. It was necessary to change the name of some data items from Version 1.0, which may require updating PDDX file readers.

The following three types of file formats are described in detail below:

- PDDX file format.

- FWD calibration history file format.

- FWD calibration data exchange file formats.

The PDDX file format is used for reporting the results of routine FWD testing of roads and airfields. This format provides data that is collected at multiple test points in a line or a grid pattern.

The FWD calibration record file format contains a historical record of the last calibration that was performed on the FWD. This may be an annual calibration possibly supplemented by monthly calibrations. The file contains information on the date and location where the calibration was performed. It also identifies the special equipment that was used in the calibration. Some sections from the PDDX file format are included in the calibration history file.

Two FWD calibration data exchange file formats are provided. One file is created by the FWD computer and provides information that is needed to begin performing an annual calibration. The data are transferred electronically from the FWD computer to the calibration center computer.

The second file contains the results of the calibration that can be transferred electronically from the calibration center computer to the FWD computer. Both of these files require the cooperation of the FWD manufacturers to provide a means for writing the first file and reading the second one.

Description of Each Data Section and Data Entry Lines

As discussed previously, the data format has a modular structure. Data elements of similar characteristics are grouped together in individual sections. The first line is the section descriptor contained in brackets. Each module contains a number of data items with its associated value or values. Both the added data items and the renamed data items have been identified in the descriptions in bold type.

STANDARD PDDX FILE FORMAT

Pavement Deflection Data Exchange File Section

This should be the initial section in the file. It identifies information related to the PDDX format or version that is being used.

Section
Descriptor   [Pavement Deflection Data Exchange File]

PDDX Version Number
Syntax: PDDXVersionNumber = *number*
Description: This entry denotes the current PDDX format version. Depending on the nature and scope of future revisions, the version number of PDDX may change. This is provided to allow for possible changes in the PDDX Standard in the future.
Example: PDDXVersionNumber = 2.0

Delimiter Symbol
Syntax: DelimiterSymbol = *string*
Description: A single American Standard Code for Information Interchange (ASCII) printable non-white space character denoting the delimiter symbol. The recommended delimiter symbols include the comma (ASCII character 44), exclamation mark (ASCII character 33), and concatenation symbol (ASCII character 124).
Example: DelimiterSymbol = ,
Note: The delimiter symbol and the decimal symbol entries must be mutually exclusive. In the United States, the usual delimiter is the comma, and the usual decimal symbol is the period.

Decimal Symbol
Syntax: DecimalSymbol = *string*
Description: A single ASCII printable non-white space character denoting the decimal symbol.
                 The internationally accepted decimal symbols include ASCII characters 44
                 (comma) and 46 (period).
Example: Decimal Symbol = .
Note: The decimal symbol and the delimiter symbol entries must be mutually exclusive.
                 In the United States, the usual delimiter is the comma, and the usual decimal
                 symbol is the period.

Operations Information Section

This section contains general information recorded once for informational purposes. These data
are not used in the analysis of the deflection data; however, they may aid engineers with respect
to data analysis by recording time of day and other pertinent information.

Section
 Descriptor   [Operations Information]

File Name
Syntax: FileName = *string*
Description: This entry identifies the directory location and filename of the PDDX file where
                 the deflection testing data are stored.
Example: FileName = C:\FWD\DATA\SAMPLE.DDX

Software Version
Syntax: SoftwareVersion = *string*
Description: This entry identifies the software version of the FWD operational software.
Example: SoftwareVersion = 18.9
Note: This is used by the LTPP database to identify which version of the field program
                 is used to collect the data from FWD. This data field is not in the PDDX standard
                 Version 1.0.

Start Date
Syntax: StartDate = *date*
Description: Date at onset of testing in dd-mmm-yyyy date format.
Example: StartDate = 28-Apr-2009

Start Time
Syntax: StartTime = *time*
Description: Time at the onset of testing in hour:minute:second in 24-h clock format.
Example: StartTime = 07:41:18

End Date
Syntax: EndDate = *date*
Description: Date at completion of testing in dd-mmm-yyyy date format.
Example: EndDate = 29-Apr-2009

End Time
Syntax: EndTime = *time*
Description: Time at completion of testing in hour:minute:second 24-h clock format.
Example: EndTime = 15:24:12

Operator Name
Syntax: OperatorName = *string*
Description: Name of deflection device operator.
Example: OperatorName = Joe Smith

Weather Condition
Syntax: WeatherCondition = *string*
Description: General description of weather conditions at testing site (e.g., sunny, cloudy, raining).
Example: WeatherCondition = sunny

Units Section

This section contains information regarding the units system. All units applicable to the PDDX file format are described in this section. Some units that are unique to FWD calibration are listed in the other file formats.

Note that all units are listed in singular format. English and metric units for applicable data are summarized in table 10. All units used in one PDDX file must be of the same system of units. Thus, a file must use only metric or English measurements. Also, only one unit identifier per data element is allowed for each entry. All permissible unit identifiers are defined below and are case-insensitive.

Table 10. Unit systems for English and metric PDDX files.[1]

Parameter	English System Units	Metric System Units
Length	Mil	Micron
	Inch	Millimeter
	Foot	Centimeter
	Yard	Meter
	Mile	Kilometer
Mass	Pound	Kilogram
Time	Second	Second
Force	Pound-force	KiloNewton
	Kilopound-force	Kilogram-force
Pressure	Pound-force per square inch	KiloPascal
Temperature	Fahrenheit	Celsius
Frequency	Hertz	Hertz
Angle	Degree-minute-second	Degree-minute-second

[1]Some of the strings in the table are modified slightly from Version 1.0.

Section
 Descriptor   [Units]

Load Plate Radius Units
Syntax: LoadPlateRadiusUnits = *string*
Description: The units to be used to identify the radius of the load plate on an impulse load
                 deflection device. The common units of measurement are inches and millimeters.
Example: LoadPlateRadiusUnits = inch

Load Units
Syntax: LoadUnits = *string*
Description: Units used to measure the magnitude of the applied load (force or pressure) in
                 pound-force, Newton, kiloPascal, or pound-force per square inch. Data with a
                 different unit than the one chosen during calibration setup is converted based
                 upon this data field.
Example: LoadUnits = pound-force

Deflection Units
Syntax: DeflectionUnits = *string*
Description: Unit used to measure the magnitude of the pavement surface deflection. All
                 deflection sensors must use the deflection unit specified by this entry. The typical
                 units of measurement are mils or microns. Data with a different unit than the one
                 chosen during calibration setup is converted based upon this data field.
Example: DeflectionUnits = mil

Temperature Units
Syntax: TemperatureUnits = *string*
Description: Unit used to measure temperature data. All temperature sensors must use the
                 temperature unit specified by this entry.
Example: TemperatureUnits = Fahrenheit

Sensors Location Units
Syntax: SensorsLocationUnits = *string*
Description: Units used to measure the longitudinal and transverse coordinates of deflection
                 sensors with respect to the center of the load plate.
Example: SensorsLocationUnits = inch

GPS Units
Syntax: GPSUnits = *string*, *string*, *string*
Description: Units used to measure global position using a global positioning system (GPS)
                 device. Each GPS unit should be separated by the delimiter symbol.
Example: GPSUnits = degree-minute-second, degree-minute-second, foot

Test Location Units
Syntax: TestLocationUnits = *string*, *string*, *string*
Description: Units used to measure test location distances in an x, y, z coordinate system, with z denoting elevation. Common units are mile, foot, kilometer, and meter. Each test location unit should be separated by the delimiter symbol.
Example: TestLocationUnits = mile, foot, foot

Nominal Test Spacing Units
Syntax: NominalTestSpacingUnits = *string*
Description: Units used to measure the nominal spacing between test points.
Example: NominalTestSpacingUnits = foot

Load Frequency Units
Syntax: LoadFrequencyUnits = *string*
Description: Units used to measure the loading frequency of vibratory loading devices.
Example: LoadFrequencyUnits = Hertz

Drop History Data Frequency Units
Syntax: DropHistoryDataFrequencyUnits = *string*
Description: Units used to measure the drop history data sampling rate.
Example: DropHistoryDataFrequencyUnits = Hertz

Joint Crack Width Units
Syntax: JointCrackWidthUnits = *string*
Description: Units used to measure the width of a joint or a crack.
Example: JointCrackWidthUnits = millimeter
Note: This data field is not in the PDDX standard Version 1.0.

Device Information Section

This section contains information regarding the deflection device type, name, and model. Other entries include serial numbers for the overall device, the load plate, and the deflection sensors.

Section
 Descriptor   [Device Information]

Device Designation Name
Syntax: DeviceDesignationName = *string*
Description: The name of the deflection device being used for testing.
Example: DeviceDesignationName = KUAB 2m-FWD

Device Model Number
Syntax: DeviceModelNumber = *string*
Description: The model designation for the deflection device being used for testing.
Example: DeviceModelNumber = 8714

Device Serial Number
Syntax: DeviceSerialNumber = *string*
Description: The serial number of the deflection device being used for testing.
Example: DeviceSerialNumber = 245

Load Cell Serial Number
Syntax: LoadCellSerialNumber = *string*
Description: The serial number of the load cell being used for testing.
Example: LoadCellSerialNumber = LC132

Sensor Serial Numbers
Syntax: SensorSerialNumbers = *string(s)*
Description: The serial numbers of each of the deflection sensors being used for testing listed
                     in the same order as the x-axis distances defined in the device configuration
                     section. Each serial number should be separated by the delimiter symbol.
Example: SensorSerialNumbers = 30829, 30830, 30831, 30890, 30832, 30796, 30864

Device Load Type
Syntax: DeviceLoadType = *string*
Description: The type of loading device being used for testing (static, vibratory, impulse,
                     or rolling).
Example: DeviceLoadType = Impulse

Device Configuration Section

This section contains information regarding the exact configuration of the deflection device at
the time of testing. Figure 41 provides an illustration of a typical load cell and deflection
 sensor configuration.
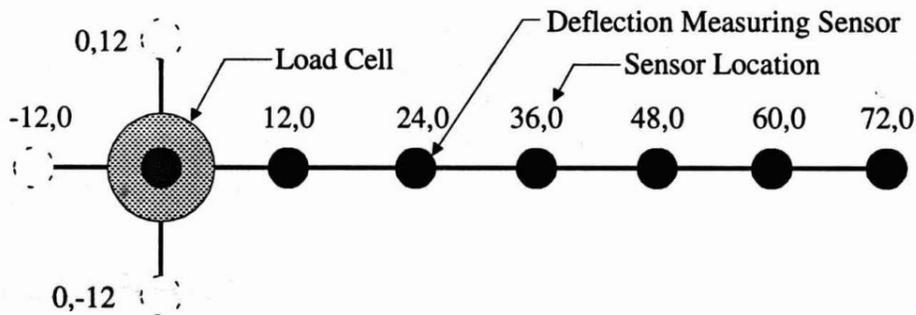
Figure 41. Illustration. Typical load cell and deflection sensor configuration.

Section
  Descriptor   [Device Configuration]

Load Plate Radius

Syntax: LoadPlateRadius = *number*
Description: Radius of the load plate used during testing. Enter the radius in the units that have
                    been previously specified.
Example: LoadPlateRadius = 5.91

Number of Deflection Sensors

Syntax: NumberOfDeflectionSensors = *number*
Description: This entry denotes the number of deflection measuring sensors that are being used
                    for collection of deflection data.
Example: NumberOfDeflectionSensors = 9

Deflection Sensor X-Axis Distances

Syntax: DeflectionSensorXAxisDistances = *number(s)*
Description: This entry denotes the x-coordinate of each deflection sensor with respect to the
                    center of the load plate. The x-direction is typically measured in the direction
                    in which the deflection device is traveling. Negative distances are behind the
                    load plate.
Example: DeflectionSensorXAxisDistances = 0, 12, 24, 36, 48, 60, 72, -12, 0
Note: Generally, FWD collects data in the order of the data acquisition channels.
                    Therefore, the x and y distances should correspond to the arrangement in which
                    the deflection sensors are connected to the data acquisition channels. Thus, if
                    channel 1 corresponds to the sensor in position (0,0) and channel 2 corresponds to
                    position (12,0), they should be listed in that order.

Deflection Sensor Y-Axis Distances

Syntax: DeflectionSensorYAxisDistances = *number(s)*
Description: This entry denotes the y-coordinate of each deflection sensor with respect to the
                    center of the load plate. The y-direction is typically perpendicular to the direction
                    in which the deflection device is traveling. Negative distances are to the right of
                    the load plate.
Example: DeflectionSensorYAxisDistances = 0, 0, 0, 0, 0, 0, 0, 0, -12
Note: Generally, FWD collects data in the order of the data acquisition channels.
                    Therefore, the x and y distances should correspond to the arrangement in which
                    the deflection sensors are connected to the data acquisition channels. Thus, if
                    channel 1 corresponds to the sensor in position (0,0) and channel 2 corresponds to
                    position (12,0), they should be listed in that order.

Number of Temperature Sensors

Syntax: NumberOtTemperatureSensors = *number*
Description: Number of sensors used to collect temperature data.
Example: NumberOtTemperatureSensors = 3

Temperature Sensor Use

Syntax: TemperatureSensorUse = *string(s)*

Description: Description of the item for which each temperature sensor is recording the temperature at the time of testing. Options for the item description include air, pavement surface, pavement middepth, and pavement bottom.

Example: TemperatureSensorUse = air, surface, middepth

Load Frequency

Syntax: LoadFrequency = *number*

Description: The loading frequency used for vibratory testing devices. Note that the frequency value should correspond with the previously entered load frequency unit.

Example: LoadFrequency = 25

Device Calibration Section

This section contains information regarding the equipment manufacturer's calibration of the deflection device as well as the results of the most recent annual calibration and monthly calibration. Annual calibration is conducted on FWDs for the load cell and deflection sensors to ensure that all readings are accurate within specified limits.

Section
 Descriptor   [Device Calibration]

Load Cell Manufacturer Calibration Date

Syntax: LoadCellManufacturerCalibrationDate = *date*

Description: Date of the most recent load cell calibration in dd-mmm-yyyy date format.

Example: LoadCellManufacturerCalibrationDate = 27-Sep-1991

Note: This calibration date is the FWD manufacturer's load cell calibration. Usually done only upon delivery or major work on the machine, it is not the annual calibration date. This field is named load cell calibration date in Version 1.0.

Load Cell Manufacturer Calibration Factor

Syntax: LoadCellManufacturerCalibrationFactor = *number*

Description: Calibration factor obtained from the most recent calibration of the load plate load cell.

Example: LoadCellManufacturerCalibrationFactor = 10956

Note: This calibration factor is the FWD manufacturer's calibration. Usually done only upon delivery or major work on the machine, it is not an annual calibration gain factor. This field is named load cell calibration factor in Version 1.0.

Load Cell Manufacturer Calibration Intercept

Syntax: LoadCellManufacturerCalibrationIntercept = *number*
Description: The y-intercept of the linear relationship developed for calibration of the load cell.
Example: LoadCellManufacturerCalibrationIntercept = 174
Note: This calibration intercept is the FWD manufacturer's calibration. Usually done only upon delivery or major work on the machine, it is not the annual calibration factor. This field is named load cell calibration intercept in Version 1.0.

Load Cell Annual Calibration Date

Syntax: LoadCellAnnualCalibrationDate = *date*
Description: Date of the most recent reference calibration of the FWD load cell in dd-mmm-yyyy date format.
Example: LoadCellAnnualCalibrationDate = 27-Sep-2009
Note: This is the date of the most recent annual calibration of the load cell. This data field is not in the PDDX standard Version 1.0.

Load Cell Annual Calibration Gain

Syntax: LoadCellAnnualCalibrationGain = *number*
Description: The multiplier that adjusts the measured values from FWD to match the output from the reference load cell.
Example: LoadCellAnnualCalibrationGain = 1.003
Note: This is the final gain factor for the FWD load cell determined by using the annual calibration procedure. This data field is not in the PDDX standard Version 1.0.

Sensor Static Calibration Date

Syntax: SensorStaticCalibrationDate = *date*
Description: Date of most recent deflection sensors static calibration in dd-mmm-yyyy date format.
Example: SensorStaticCalibrationDate = 27-Apr-1992
Note: The static calibrations are only done with a KUAB FWD. The static calibration of seismometers is performed through the use of a built-in micrometer on the top of each sensor.

Sensor Static Calibration Factors

Syntax: SensorStaticCalibrationFactors = *number(s)*
Description: Static calibration is conducted for deflection devices utilizing seismic displacement transducers (seismometers) for deflection measurement under a static condition (no pavement loading).
Example: SensorStaticCalibrationFactors = 0.573, 0.553, 0.420, 0.300
Note: The static calibrations are only done with a KUAB FWD. The static calibration of seismometers is performed through the use of a built-in micrometer on the top of each sensor.

Sensor Manufacturer Calibration Date

Syntax: SensorManufacturerCalibrationDate = *date*

Description: Date of most recent deflection sensors dynamic calibration in dd-mmm-yyyy date format.

Example: SensorManufacturerCalibrationDate = 27-Apr-1992

Note: This is the manufacturer's deflection sensor calibration date. This field is named sensor dynamic calibration date in Version 1.0.

Sensor Manufacturer Calibration Factors

Syntax: SensorManufacturerCalibrationFactors = *number(s)*

Description: Dynamic calibration is conducted for deflection devices with seismometers to relate the sensor's dynamic to static behavior.

Example: SensorManufacturerCalibrationFactors = 1.050, 1.050, 1.050, 1.050

Note: This is the FWD manufacturer's deflection sensor calibration factor. For example, in the Dynatest® FWD, this is labeled the absolute gain factor. This field is named sensor dynamic calibration factor in Version 1.0.

Sensor Annual Calibration Date

Syntax: SensorAnnualCalibrationDate = *date*

Description: Date of most recent deflection sensor annual calibration in dd-mmm-yyyy date format.

Example: SensorAnnualCalibrationDate = 27-Apr-2009

Note: This is the date that the deflection sensors were most recently calibrated using the annual calibration procedure. This field is named sensor reference calibration date in Version 1.0.

Sensor Monthly Calibration Date

Syntax: SensorMonthlyCalibrationDate = *date*

Description: Date of most recent deflection sensor annual calibration in dd-mmm-yyyy date format.

Example: SensorMonthlyCalibrationDate = 27-May-2009

Note: This is the date that the deflection sensors were most recently calibrated using the monthly calibration procedure. This field is named sensor relative calibration date in Version 1.0.

Sensor Calibration Gains

Syntax: SensorCalibrationGains = *number(s)*

Description: The multiplier that adjusts the measured values from FWD to match the output from the reference accelerometer.

Example: SensorCalibrationGain = 1.006, 1.003, 1.011, 0.998, 1.018, 0.999, 1.001

Note: These are the final gain factors for the deflection sensors using the annual calibration procedure or the most recent monthly calibration procedure. This field is named sensor reference calibration gain in Version 1.0.

DMI Device Calibration Date

Syntax:	DMIDeviceCalibrationDate = *date*
Description:	Date of the most recent distance measuring instrument (DMI) device calibration in dd-mmm-yyyy date format.
Example:	DMIDeviceCalibrationDate = 27-Sep-2009

DMI Device Calibration Factor

Syntax:	DMIDeviceCalibrationFactor = *number*
Description:	Calibration factor obtained for the DMI device.
Example:	DMIDeviceCalibrationFactor = 2694.3

Location Identification Section

This section contains information regarding the location and nature of the test site. Basic components of the test site are included such as the geographic location, client, and pavement feature section.

Section Descriptor   [Location Identification]

Site Name

Syntax:	SiteName = *string*
Description:	Location of the project site. For highway testing, provide the name of the State, county, township, or city in which the project is located. On airport projects, provide the name of the airport.
Examples:	SiteName = VA, Fairfax County
	SiteName = O'Hare International Airport

Facility Name

Syntax:	FacilityName = *string*
Description:	Name of pavement facility or system being tested.
Example:	FacilityName = Interstate 95
	FacilityName = Runway 9L-27R
Note:	A facility is a collection of sections that have the same use (e.g., a single runway, street, or parking lot).

Section Name

Syntax:	SectionName = *string*
Description:	Name of the pavement section where deflection testing is conducted.
Example:	SectionName = Lorton Road to Newington Interchange
	SectionName = Section Al
Note:	A section is a pavement that has similar cross section, construction history, traffic level, and use that can be treated as a single unit for analysis purposes.

Direction of Travel

Syntax:	DirectionOfTravel = *string*
Description:	Indicates the direction of travel during testing.
Example:	DirectionOfTravel = Northbound
Note:	This is a user-defined entry that may be a compass direction, but it does not need be. Any designation, such as a runway end or street name, may be used to indicate direction of travel.

Pavement Type

Syntax:	PavementType = *string*
Description:	Type of pavement being tested (e.g., asphalt concrete (AC), Portland cement concrete (PCC), AC/PCC, flexible, rigid, composite).
Example:	PavementType = PCC

Data Configuration Section

This section describes total test points on the project, their spacing, details of the measurements collected at each test point, and other data specific to each test point.

**Section
 Descriptor**   [Deflection Data]

Number of Test Locations

Syntax:	NumberOfTestLocations = *number*
Description:	The number of test locations that are included in the current file.
Example:	NumberOfTestLocations = 10

Nominal Test Pattern

Syntax:	NominalTestPattern = *string*
Description:	The typical test pattern being used for testing—linear for highways and runways or grid for parking lots and aircraft parking aprons.
Example:	NorninalTestPattern = linear

Nominal Test Spacing

Syntax:	NorninalTestSpacing = *number*
Description:	The typical test spacing being used for testing; a typical test spacing exists in feet, meters, etc.
Example:	NorninalTestSpacing = 500

Drop History Data Frequency

Syntax:	DropHistoryDataFrequency = *number*
Description:	The rate at which readings are recorded for each sensor being sampled by the DAQ.
Example:	DropHistoryDataFrequency = 10,000

Number of Drop History Data Samples
Syntax: NumberOfDropHistoryDataSamples = *number*
Description: Total number of readings obtained for each sensor during the recording of each
                    time history.
Example: NumberOfDropHistoryDataSamples = 300

Test Location Section

The test location section indicates the number of current test points where "locationcounter" is an
integer starting at 1 and ascending for each test point in the current file. Figure 42 provides an
example of a typical test location.
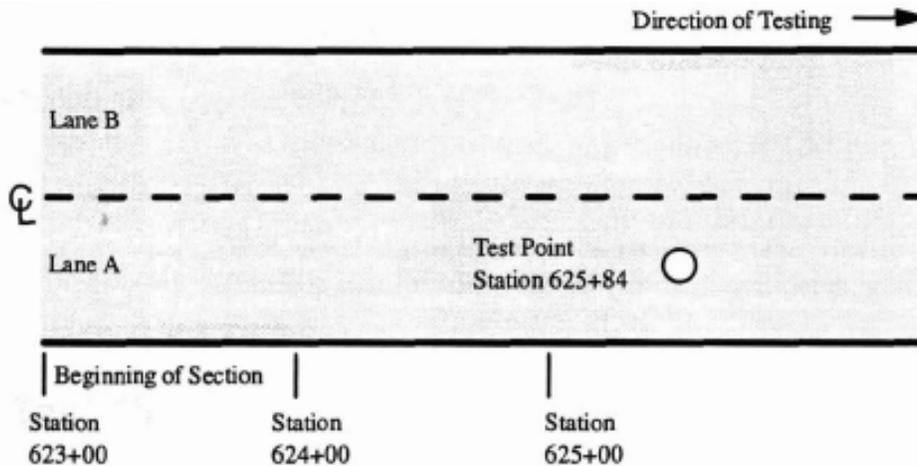
Figure 42. Illustration. Example of a typical test location.

Section
 Descriptor   [Test Location *locationcounter*]
Example: [Test Location 1]
Note: The maximum number for *locationcounter* is NumberOfTestLocations. This
                    section will be repeated sequentially for each test location.

Test Location
Syntax: TestLocation = *number*, *number*, *number*
Description: Location of the test point in an x, y, z coordinate system with respect to a
                    beginning reference point, where z is an elevation. On a roadway, the x-parameter
                    may be the stationing or an electronic distance meter reading.
Example: TestLocation = 62584, 0, 0

GPS Location
Syntax: GPSLocation = *number*, *number*, *number*
Description: Global location of the test point in an x, y, z coordinate system.
Example: GPSLocation = 28.345, 74.345, 0

Test Lane

Syntax:	TestLane = *string*
Description:	Designation of the lane being tested. Test lane layouts are designated at the discretion of the engineer or FWD operator.
Example:	TestLane = outside lane, inner wheelpath

Test Type

Syntax:	TestType = *string*
Description:	Type of test being performed (e.g., basin, center, edge, corner). The latter three designations would mainly be used on concrete pavements.
Example:	TestType = basin

Drop History Type

Syntax:	DropHistoryType = *string*
Description:	The type of drop history recorded at the test location (e.g., load only, deflections only, or load and deflections).
Example:	DropHistoryType = load and deflections

Test Temperatures

Syntax:	TestTemperatures = *number(s)*
Description:	The temperatures measured for the current test point.
Example:	TestTemperatures = 60.7, 94.2, 80.5
Note:	The measured temperatures are described in the [Device Configuration] section (e.g., air, surface, mid-depth, gradient average).

Test Date

Syntax:	TestDate = *date*
Description:	Date at onset of testing in dd-mmm-yyyy date format.
Example:	TestDate = 12-Apr-2009

Test Time

Syntax:	TestTime = *time*
Description:	Time at the beginning of testing for the current test point in hour:minute:second 24-h clock format.
Example:	TestTime = 07:41:18

Test Comment

Syntax:	TestComment = *string*
Description:	Any comment regarding the current test point entered manually by the operator.
Example:	TestComment = Longitudinal crack

Number of Drops

Syntax:	NumberOfDrops = *number*
Description:	The number of load drops made at each test point.
Example:	NumberOfDrops = 12

Drop Data

Syntax: DropData_*dropcounter = number(s)*
Description: The measured peak load and deflections for the current drop, where *dropcounter*
                    is the number of the drop in the sequence.
Example: DropData_1 = 9194, 4.93, 4.14, 4.01, 3.65, 3.10, 2.50, 2.15
Note: The maximum number for *dropcounter* is NumberOfDrops.

Drop History Data

Syntax: DropHistoryData_dropcounter_samplecounter = number(s)
Description: The time history load and deflections data for each drop, numbered sequentially
                    as *dropcounter_samplecounter*. Each entry contains information similar in format
                    to DropData_counterdrop when load and deflection are recorded.
Example: DropHistoryData_1_5 = 1248, 1.15, 1.02, 0.98, 0.87, 0.79, 0.70, 0.62
Note: The maximum number for *samplecounter* is NumberOfDropHistoryDataSamples.

SPECIAL FORMAT FOR FWD CALIBRATION RECORD FILES

At the conclusion of each FWD calibration, *WinFWDCal* creates a permanent electronic record
of the calibration results in DDX file format. The file is named FWDCalibrationRecorddd-mmm-
yyyy.DDX (where dd is the date, mmm is the month abbreviation, and yyyy is the year (e.g., 12-
Feb-2009)).

The file includes the following sections from the PDDX file format as defined above:

- Pavement Deflection Data Exchange File Section.

- Operations Information Section.

- Units Section.

- Device Information Section.

- Device Configuration Section.

- Device Calibration Section.

- A FWD Calibration Center Information Section, as defined below, is appended.

The same file is created for both annual and monthly calibration. When retained together with
the FWD and reference system data files, a complete record of the calibration is formed that
allows the calibration results to be recreated and reviewed at any time using *WinFWDCal*.

FWD Calibration Center Information Section

This section includes information about the FWD calibration center personnel and equipment. It is created only for record keeping associated with FWD calibration. This section would not normally be included in the PDDX file format that is used for road and airfield data exchange. In order to be self-contained, some additional units of measurement are defined in this file.

Section
  Descriptor   [FWD Calibration Center Information]

Calibration Center
Syntax: CalibrationCenter = *string*
Description: The name of the FWD calibration center.
Example: CalibrationCenter = Colorado Department of Transportation

Calibration Center ID Code
Syntax: CalCenterIDCode = *number*
Description: An ID code assigned to each FWD calibration center based upon the order of
                       installation.
Example: CalCenterIDCode = 21

Calibration Center Operator
Syntax: CalibrationCenterOperator = *string*
Description: Name of the FWD calibration center operator.
Example: CalibrationCenterOperator = Edward Trujillo

Calibration Center Operator Certification Date
Syntax: CalibrationCenterOperatorCertificationDate = *date*
Description: Date of last FWD calibration center operator certification and QA/QC visit. The
                       certification is valid for 15 months after this date, and recertification must be
                       scheduled within 12 months of this date.
Example: CalibrationCenterOperator = 27-Aug-08

***WinFWDCal* Version Number**
Syntax: *WinFWDCal*VersionNumber = *string*
Description: Version number of *WinFWDCal* software along with the release date.
Example: *WinFWDCal*VersionNumber = 1.2.702 21 April 2008

Type of Calibration
Syntax: TypeOfCalibration = *string*
Description: Denotes the type of procedure that was used for the FWD Calibration
                       (e.g., annual, monthly, or sensor replacement).
Example: TypeOfCalibration = Annual

Signal Conditioner Serial Number
Syntax: SignalConditionerSerialNumber = *string*
Description: Serial number of signal conditioner used in FWD calibration at a calibration
                     center.
Example: SignalConditionerSerialNumber = 095889

A to D Board Serial Number
Syntax: AtoDBoardSerialNumber = *string*
Description: Serial number of KUSB A/D board used in FWD calibration at a calibration
                     center.
Example: AtoDBoardSerialNumber = 1142589

Universal Test Machine Name
Syntax: UniversalTestMachineName = *string*
Description: Name of universal calibration machine used to calibrate the reference load cell.
Example: UniversalTestMachineName = Baldwin Universal Testing Machine
                     UniversalTestMachineSerialNumber = 040-1663

Universal Test Machine Calibration Date
Syntax: UniversalTestMachineCalibrationDate = *date*
Description: Date of NIST traceable calibration of universal testing machine in dd-mmm-yyyy
                     format.
Example: UniversalTestMachineCalibrationDate = 09-Sept-2008

Reference Load Cell Name
Syntax: ReferenceLoadCellName = *string*
Description: Name assigned to reference load cell used in FWD calibration.
Example: ReferenceLoadCellName = CLRP001

Reference Load Cell Calibration Date
Syntax: ReferenceLoadCellCalibrationDate = *date*
Description: Date of last calibration of reference load cell used in FWD calibration.
Example: ReferenceLoadCellCalibrationDate = 04-August-2004

Reference Load Cell Excitation Volts
Syntax: ReferenceLoadCellExcitationVolts = *number*
Description: Excitation value in volts for reference load cell used in FWD calibration.
Example: ReferenceLoadCellExcitationVolts = 10.000

Reference Load Cell Signal Conditioner Gain
Syntax: ReferenceLoadCellSignalConditionerGain = *string*
Description: Gain setting on signal conditioner used with reference load cell for FWD
                     calibration.
Example: ReferenceLoadCellGain = 5.3 X 100
Note: The first number is the setting on the knob of the signal conditioner. It is
                     followed by the gain multiplier (pushbutton).

Reference Load Cell Unbalanced Zero
Syntax: ReferenceLoadCellUnbalancedZero = *number*
Description: The reading in volts with the load cell in an unbalanced condition.
Example: ReferenceLoadCellUnbalancedZero = 0.283
Note: By comparing this value to the daily value, the unbalanced zero reading is used to ensure the load cell is undamaged and working properly.

Reference Load Cell +B Voltage
Syntax: ReferenceLoadCell+BVoltage = *number*
Description: The reading in volts with the load cell balanced first when a shunt resistance is used to produce a positive voltage on the balancing circuit.
Example: ReferenceLoadCell+BVoltage = 1.772
Note: By comparing this value to the daily value, the +B and -B readings are used to ensure the signal conditioner gain setting is correct. A load cell with a very large gain may need to use the +A and -A shunts on the signal conditioner. In these cases, the field names will have an A instead of a B in the field names.

Reference Load Cell -B Voltage
Syntax: ReferenceLoadCell-BVoltage = *number*
Description: The reading in volts with the load cell balanced first when a shunt resistance is used to produce a negative voltage on the balancing circuit.
Example: ReferenceLoadCell-BVoltage = -1.772
Note: By comparing this value to the daily value, the +B and -B readings are used to ensure the signal conditioner gain setting is correct. A load cell with a very large gain may need to use the +A and -A shunts on the signal conditioner. In these cases, the field names will have an A instead of a B in the field names.

Reference Load Cell Calibration Units
Syntax: ReferenceLoadCellCalibrationUnits = *string*
Description: The units used in the calibration of the reference load cell (kiloNewton or pound-force).
Example: ReferenceLoadCellCalibrationUnits = pound-force

Reference Load Cell Calibration Coefficients
Syntax: ReferenceLoadCellCalibrationCoefficients = *number(s)*
Description: Polynomial coefficients used to convert volts into load in units listed under ReferenceLoadCellCalibrationUnits.
Example: ReferenceLoadCellCalibrationCoefficients = -98.2421e-01, 27.1714e-05, 61.1421e-09, 00.0000e+00, 00.0000e+00

Reference Load Cell Trigger Level
Syntax: ReferenceLoadCellTriggerLevel = *number*
Description: The load level in ReferenceLoadCellCalibrationUnits that is used to start auto-triggering and collection of data during FWD calibration.
Example: ReferenceLoadCellTriggerLevel = 1,000

Reference Load Cell Daily Unbalanced Zero

Syntax: ReferenceLoadCellDailyUnbalancedZero = *number*
Description: The daily reading in volts with the load cell in an unbalanced condition taken as
                    part of the prerequisites of calibration.
Example: ReferenceLoadCellDailyUnbalancedZero = 0.283
Note: The unbalanced zero reading is used to ensure the load cell is undamaged and
                    working properly.

Reference Load Cell Daily +B Voltage

Syntax: ReferenceLoadCellDailyPBVoltage = *number*
Description: The daily +B voltage reading taken as part of the prerequisites of calibration.
                    Together with the -B reading, these data are used to account for variations in the
                    setting of the gain by the FWD calibration center operator.
Example: ReferenceLoadCellDailyPBVoltage = 1.773

Reference Load Cell Daily -B Voltage

Syntax: ReferenceLoadCellDailyMBVoltage = *number*
Description: The daily -B voltage reading taken as part of the prerequisites of calibration.
                    Together with the +B reading, these data are used to account for variations in the
                    setting of the gain by the FWD calibration center operator.
Example: ReferenceLoadCellDailyMBVoltage = -1.773

Accelerometer Model Number

Syntax: AccelerometerModelNumber = *string*
Description: Manufacturer's model number of accelerometer used in FWD deflection sensor
                    calibration.
Example: AccelerometerModelNumber = 2220-005

Accelerometer Serial Number

Syntax: AccelerometerSerialNumber = *string*
Description: Manufacturer's serial number of accelerometer used in FWD deflection sensor
                    calibration.
Example: AccelerometerSerialNumber = 278

Accelerometer Reference Calibration Date

Syntax: AccelReferenceCalibrationDate = *date*
Description: Date of calibration of reference accelerometer provided by manufacturer.
Example: AccelReferenceCalibrationDate = 07-Sep-2004

Accelerometer Reference +1G DC

Syntax: AccelRef+1GDC = *number*
Description: Reading of accelerometer in a +1G field (volts) provided by manufacturer.
Example: AccelRef+1GDC = 0.825

Accelerometer Reference -1G DC
Syntax: AccelRef-1GDC = *number*
Description: Reading of accelerometer in a -1G field (volts) provided by manufacturer.
Example: AccelerometerRef-1GDC = -0.777

Accelerometer Reference Calibration Coefficients
Syntax: AccelRefCalibrationCoefficients = *number(s)*
Description: Polynomial coefficients to convert output in volts into acceleration in *g* provided
                by manufacturer where the first coefficient listed is co.
Example: AccelRefCalibrationCoefficients = -4.52e-02, 1.241e + 00, 1.048e-03, -1.369e-04
Notes: The form of the equation is acceleration (g) = co + Σ(ci volts).

Accelerometer Daily Calibration Date
Syntax: AccelDailyCalibrationDate = *date*
Description: Date of the last daily flip calibration in dd-mmm-yyyy format.
Example: AccelDailyCalibrationDate = 03-Aug-2005

Accelerometer Daily Calibration Time
Syntax: AccelDailyCalibrationTime = *time*
Description: The time of the last daily flip calibration of the accelerometer in hour:minute
                24-h clock format.
Example: AccelDailyCalibrationTime = 16:17

Accelerometer Daily Calibration Temperature Unit
Syntax: AccelDailyCalibrationTemperatureUnit = *string*
Description: Units of temperature used when performing the last daily flip calibration of the
                accelerometer (Fahrenheit or Celsius).
Example: AccelDailyCalibrationTemperatureUnit = Fahrenheit

Accelerometer Daily Calibration Temp
Syntax: AccelDailyCalibrationTemp = *number*
Description: Temperature recorded during the last daily flip calibration of the accelerometer in
                units of AccelDailyCalibrationTemperatureUnit.
Example: AccelDailyCalibrationTemp = 67.5

Accelerometer Excitation Volts
Syntax: AccelExcitationVolts = *number*
Description: Excitation voltage for the reference accelerometer.
Example: AccelExcitationVolts = 10

Accelerometer Signal Conditioner Gain
Syntax: AccelSignalConditionerGain = *string*
Description: Gain setting on signal conditioner used with for the reference accelerometer.
Example: AccelSignalConditionerGain = 2.0 X 1
Note: The first number is the setting on the knob of the signal conditioner. It is
                followed by the gain multiplier (pushbutton).

Accelerometer Daily Slope Factor
Syntax: AccelDailySlopeFactor = *number*
Description: Calculated relative difference in voltage between the reference calibration and the last daily flip calibrations.
Example: AccelDailySlopeFactor = -0.50486
Note: This value is multiplied by the output voltage to generate a relative voltage that can be used directly with the calibration factors from the accelerometer certificate (AccelerometerRefCalibrationCoefficients).

Accelerometer Historical Slope Factor Dates
Syntax: AccelHistoricalSlopeFactor = *date, date, date, date*
Description: Dates of the four accelerometer historical slope factors in dd-mmm-yyyy format.
Example: AccelHistoricalSlopeFactorDates = 12-Jan-2009, 02-Feb-2009, 27-Feb-2009, 18-Mar-2009

Accelerometer Historical Slope Factors
Syntax: AccelHistoricalSlopeFactor = *number, number, number, number*
Description: Historical listing of the previous four accelerometer slope factors.
Example: AccelHistoricalSlopeFactor = -0 49856, -0 49857, -0 49853, -0 49850
Note: These values are compared to the accelerometer daily slope factor during the FWD calibration to ensure the device is working properly.

Accelerometer Daily Calibration +1G Voltage
Syntax: AccelDailyCalibration+1GVoltage = *number*
Description: Recorded voltage in a +1-G field during the last flip calibration of the accelerometer.
Example: AccelDailyCalibration+1GVoltage = 1.7598

Accelerometer Daily Calibration -1G Voltage
Syntax: AccelDailyCalibration-1GVoltage = *number*
Description: Recorded voltage in a -1-G field during the last flip calibration of the accelerometer.
Example: AccelDailyCalibration-1GVoltage = -1.7598

Accelerometer Daily Calibration +1G Flip Voltage
Syntax: AccelDailyCalibration+1GFlipVoltage = *number*
Description: Recorded voltage in a +1-G field after the -1 *g* reading during the last flip calibration of the accelerometer.
Example: AccelDailyCalibration+1GFlipVoltage = 1.7698
Note: The daily calibration readings are used to confirm that the hysteresis of the accelerometer is not significant and will not adversely affect the FWD calibration.

Accelerometer Trigger Level

Syntax: AccelTriggerLevel = *number*

Description: The acceleration level in *g* units that is used to start auto-triggering and collection of data during FWD calibration.

Example: AccelTriggerLevel = 0.50

SPECIAL FORMAT FOR FWD CALIBRATION DATA EXCHANGE FILES

The information in this section will assist FWD manufacturers to adapt their FWD operating systems (field programs) to be more compatible with the FWD annual and monthly calibration processes. This section defines the format for a minimum subset of the many data items listed in the previous sections that is needed to facilitate calibration.

Electronic methods are used to transfer data between the FWD computer and the calibration computer. Some of this information is required just for record-keeping purposes, while other data items are used in the calibration calculations. Electronic data transfer helps reduce transcription errors and expedite FWD calibration.

At the beginning of a calibration, the FWD computer needs to provide some information about the load cell, deflection sensor serial numbers, the current gain factors, the FWD operator's name, etc. The FWD operating program (field program) should be able to produce a file named FWDCalibrationInput dd-mmm-yyyy.DDX (where dd is the date, mmm is the month abbreviation, and yyyy is the year (e.g., 12-Nov-2009)). The contents of this file are defined below.

After an annual or monthly calibration is complete, the FWD operating program needs to be able to locate and read the results from a file named FWDCalibrationOutputdd-mmm-yyyy.DDX. The results should then be used to update the calibration data in the FWD computer.

Input Data Requirements for *WinFWDCal*

The following is an example of the contents of FWDCalibrationInput dd-mmm-yyyy.DDX. Only the data sections and data items are listed here. A complete description of each item is provided in the previous sections.

[Pavement Deflection Data Exchange File]
PDDXVersionNumber = 2.0
DelimiterSymbol = ,
DecimalSymbol = .

[Operations Information]
FileName =D:\WINFWD\Temp\FWDCalibrationInput 20-Feb-2009.ddx
EndDate = 02-20-2009
EndTime = 15:43
OperatorName = Daniel Atkins

[Units]
LoadUnits = pound
DeflectionUnits = mil

[Device Information]
DeviceDesignationName = Dynatest® FWD
DeviceModelNumber = 8001
DeviceSerialNumber = 8001-001
LoadCellSerialNumber = 0331
SensorSerialNumbers = 3170, 3162, 3163, 3164, 3165, 3166, 3167, 3168, 3169

[Device Configuration]
NumberOfDeflectionSensors = 9

[Device Calibration]
LoadCellAnnualCalibrationDate = 20-Feb-2008
LoadCellAnnualCalibrationGain = 1.0006
SensorAnnualCalibrationDate = 20-Feb-2008
SensorCalibrationGains = 1.001, 0.999, 1.001, 0.999, 0.999, 0.998, 1, 0.996, 0.999

Output Data from *WinFWDCal*

The following is an example of the contents of FWDCalibrationOutput dd-mmm-yyyy.DDX. Only the data sections and data items are listed. A complete description of each item is provided in the previous sections.

[Pavement Deflection Data Exchange File]
PDDXVersionNumber = 1.0
DelimiterSymbol = ,
DecimalSymbol = .

[Operations Information]
FileName = C:\WinFWDCal\InterimDropData\FWDCalibrationOutput 21-Feb-2009.ddx
EndDate = 21-Feb-2009
EndTime = 15:43
OperatorName = Daniel Atkins

[Device Information]
DeviceDesignationName = Dynatest® FWD
DeviceModelNumber = 8001
DeviceSerialNumber = 8001-001
LoadCellSerialNumber = 0331
SensorSerialNumbers = 3170, 3162, 3163, 3164, 3165, 3166, 3167, 3168, 3169

[Device Configuration]
NumberOfDeflectionSensors = 9

[Device Calibration]
LoadCellAnnualCalibrationDate = 21-Feb-2009
LoadCellAnnualCalibrationGain = 1.0005
SensorAnnualCalibrationDate = 21-Feb-2009
SensorCalibrationGains = 1.002, 1.002, 1.003, 1.000, 1.000, 0.999, 1.002, 0.997, 1.001

[FWD Calibration Center Information]
CalibrationCenter = Cornell Local Roads
CalCenterIDCode = 21
CalibrationCenterOperator = David Orr
CalibrationCenterOperatorCertificationDate = 18-Nov-2008
WinFWDCalVersionNumber = Version 1.4.18 22 December 2008
TypeOfCalibration = Annual

APPENDIX D. QA REVIEWS

The purpose of a QA review is to achieve consistency of calibrations among centers. When the protocol is done correctly, the final gain factors for an FWD will be accurate within ±0.3 percent regardless of which center performs the calibration. QA reviews should be performed annually to ensure that the center is achieving the quality standards. In addition, the QA review provides the center with the most current information about the protocol.

Three people are needed to perform a QA review: the FWD calibration operator, an FWD operator, and the independent QA reviewer. Table 11 lists the roles and responsibilities for each person involved in the review.

Table 11. Roles and responsibilities during QA review.

Personnel	Role Definition
FWD calibration operator	Independently performs an FWD calibration in accordance with the most recent calibration protocol.
FWD operator	Runs the FWD during the calibration.
QA reviewer	Observes the FWD calibration and assesses the proficiency of the calibration operator.

This appendix assumes a single FWD calibration operator is being reviewed, but multiple people may be certified in a single QA review. One day should be scheduled for each FWD calibration operator. While training is not part of the QA review, if a new operator needs to be trained during the same visit, up to an additional 2 days should be scheduled for that.

Prior to the review, the calibration operator is provided with a pre-QA review questionnaire to assure a smooth and efficient review (see figure 43). An operator review form (see figure 44) and a facilities review form (see figure 45) are used during the review. Copies of these forms should also be sent out before the review. The purpose of each document is as follows:

- **Pre-Trip Memorandum**: Provides an overview and schedule for the review process.

- **Transmits checklists**: Provides any specific details not covered by the other documents.

- **Pre-QA Review Questionnaire**: Gathers data about the number and types calibrations performed since the last review. This is a useful way to know if the center has been able to perform calibrations and may be used to help solve problems the FWD calibration center is having.

- **Operator Checklist**: Defines key points that the QA reviewer will be looking for concerning the calibration operator's implementation of the calibration protocol and use of the equipment and software.

- **Facility Checklist**: Defines key points that the QA reviewer will be looking for concerning the calibration facility and equipment.

In order for the QA review to be efficient, it is important that the FWD is in good working condition. It is not required that the FWD passes the calibration in order for the calibration center operator to demonstrate his/her proficiency and be certified. However, if the FWD is not working properly, it may not be possible to complete the review process.

REVIEW PROCESS

At the beginning of the review, the calibration operator, FWD operator, and QA reviewer meet to discuss the anticipated flow of the review process. This provides an opportunity to ask questions about the review, the calibration protocol, or the software and equipment. Problems or questions that have come up during the previous year can be reviewed and discussed. During this meeting, the QA reviewer should provide information about changes in the protocol or the software since the last review.

As part of the review, the QA reviewer will copy the last year of FWD calibration results from the calibration computer to a CD, a thumb drive, or a portable hard drive. This semiautomated process takes 15–45 min once it is started depending on how many files need to be copied. It can be done while the QA review meeting is taking place. After the files are copied, the QA reviewer will update the FWD calibration software and provide a backup copy of the updated software for the calibration operator.

Facility Review

A review of the facility and the equipment determines compliance with the FWD calibration protocol. This assures that the equipment conforms to the protocol and that it is in good working condition.

The QA reviewer checks that the equipment being used is compliant with the calibration protocol, the serial numbered equipment are correct, the reference devices are up to date on their calibrations, and the facility is able to perform FWD calibrations without electromagnetic interference or significant temperature changes during a typical FWD calibration. A checklist assists the reviewer by providing information on the important observation points. It is used as a record of the items reviewed.

Operator Review

The calibration operator is reviewed to assure that the protocol is being performed correctly. The calibration operator demonstrates proficiency with the protocol by calibrating an FWD. Three levels of operator compliance have been defined in table 12.

A checklist guides the QA reviewer through the important observation points. This includes the setup procedure in the *WinFWDCal* software, deflection sensor calibration, load cell calibration, and documentation and certification of the FWD calibration.

Table 12. Calibration operator compliance levels for QA review.

Compliance Level	Definition
Fully compliant	Operator fully understands and demonstrates sound implementation of the calibration protocol and uses the calibration equipment and software appropriately.
Partially compliant	Operator fully understands the calibration protocol. Some necessary changes in equipment, software use, and/or implementation of the calibration protocol may be required.
Noncompliant	Operator does not demonstrate an adequate understanding of the calibration protocol or its implementation.

Upon completion of the FWD calibration, the calibration operator and QA reviewer meet to discuss the review process and communicate any needed modifications. The FWD operator should be included in the meeting if the QA reviewer feels that this would improve the quality of future calibrations. During the meeting, the QA reviewer informs the calibration operator of the compliance level. When the review is passed, the operator is issued a certificate of compliance. A sample certificate is provided in figure 46.

A written report documenting the QA visit should be created as soon as possible after the visit, preferably within 2 weeks. The certificate of compliance is valid for 15 months, but the next QA visit must be scheduled within 12 months. This allows some flexibility in scheduling but ensures communication within 1 year.

Because AMRL took over responsibility for the QA visits in late 2010, it can be expected that some changes in procedures and checklists will occur.

Pre-QA Review Questionnaire
Agency Name
Date

To expedite the quality assurance process, please provide the following information.

Calibration Center Name:
Calibration Center Operator:

Please fill out the following table about the <u>number</u> of FWDs calibrated at this center for the time frame stated:

Time Frame:				
FWD Brand	Dynatest	Carl Bro	JILS	KUAB
Trailer Mounted				
Truck Mounted				
HWD				
Other				
Brand Totals				
			Overall Total	

Briefly describe any difficulties you have experienced with the calibration software, hardware, and procedure. We will further discuss any difficulties during the QA Review.

Have you had problems with any FWD being calibrated? If so, please describe the problems and how you were able to overcome them.

Please use this space to provide any comments and/or suggestions that you may have regarding FWD Calibration.

Do you need any replacement parts, such as concrete anchors, washers, etc?

Figure 43. Illustration. Pre-QA review questionnaire.

FWD Calibration Quality Assurance Review

FWD Calibration Center Name: _____

Center Operator Name: _____

Phone: _____

Fax: _____

Email: _____

Overall Compliance: Operator

Review Area	Yes	No	Comments
Facilities & FWD Set-up:			
Calibration Set-up:			
Deflection Sensor Calibration:			
Load Cell Calibration:			
Documentation & Certification:			

Software	Version	Date
WinFWDCal.exe:		
PDDXConvert.exe:		
FWD Calibration History.mdb:		

Required Changes & Improvement Recommendations

_____

_____

_____

_____

Reviewed By: _____

Date: _____

Signature: _____

Title: _____

Agency: _____

Phone: _____

Email: _____

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Figure 44. Illustration. Calibration operator QA review form.

FWD Calibration Quality Assurance Review

Calibration Protocol & FWD Setup Check List

Review Item	Yes	No	Comments
1. Is a copy of the most recent protocol available?			
2. Is the center using the most current version of WinFWDCal?			
3. Are the data in the Calibration Center INI file correct?			
4. Did the center operator check that all of the hardware was in good condition and properly connected?			
5. Was the FWD properly warmed up prior to the calibration?			
6. Have all FWD data filters been turned off before and during any calibration work?			
7. Did the center operator ask the FWD operator for the pre-calibration checklist and FWD configuration file(s)?			
8. Did the operator check that the sensors are properly labeled with respect to their position on the FWD?			

General Notes:

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_____
_____
_____
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Figure 44 (continued). Illustration. Calibration operator QA review form.

FWD Calibration Quality Assurance Review

Calibration Set up Check List (includes accelerometer calibration)

Review Item	Yes	No	Comments
1. Did the operator setup *WinFWDCal* and enter the FWD configuration data correctly?			
2. Did the operator properly perform the flip calibration of the accelerometer?			
3. Did the operator successfully determine the accelerometer trigger level (sensitivity)?			
4. Did the operator successfully determine the minimum number of drops for the number of load levels?			
5. Did the center operator work with the FWD operator to set-up the proper drop sequences for reference and relative calibration?			

General Notes:

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Figure 44 (continued). Illustration. Calibration operator QA review form.

FWD Calibration Quality Assurance Review

FWD Deflection Sensor Calibration Check List

Review Item	Yes	No	Comments
1. Is the ball joint anchor properly attached to the floor with the bolts tightened?			
2. Is the calibration stand properly clamped in the ball joint anchor?			
3. Is the friction in the ball joint properly adjusted?			
4. Have all of the prerequisites been properly followed?			
5. Are the sensors placed into the proper positions for all reference and relative trials?			
6. Were time history plots reviewed to assure mechanical noise is not causing an error in double integration?			
7. Is the stand held properly (vertically and with slight down pressure) during calibration?			
8. Have the **reference** calibration trials been properly reviewed and accepted?			
9. Have the **relative** calibration trials been properly reviewed and accepted?			

General Notes:

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Figure 44 (continued). Illustration. Calibration operator QA review form.

FWD Calibration Quality Assurance Review

FWD Load Cell Calibration Check List

Review Item	Yes	No	Comments
1. Is the reference load cell properly and accurately aligned with the FWD load plate?			
2. Have all of the prerequisites been properly followed?			
3. Were time history plots reviewed to assure that the load amplitude is correctly registered?			
4. Were the load cell calibration data properly reviewed and accepted?			

General Notes:

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Documentation and Certification Check List

Review Item	Yes	No	Comments
1. Has the calibration center operator reviewed the acceptance criteria for load and deflection sensor calibration and correctly determined whether to issue a certificate?			
2. Were all concerns about the results and trends of the calibrations reviewed with the FWD operator?			
3. Has a certificate and FWD calibration file been prepared and provided to the FWD operator?			
4. Have the final calibration factors been correctly entered into the FWD operating system (i.e., field program)?			

General Notes:

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Figure 44 (continued). Illustration. Calibration operator QA review form.

FWD Calibration Quality Assurance Review

FWD Calibration Center Name: _____

Address: _____

Address: _____

City, State/Country Code: _____

Phone: _____

Fax: _____

Overall Compliance: Facility & Equipment

Review Area	Yes	No	Comments
Facility			
Equipment			

Serialized Equipment	S/N	Date
MicroMeasurements Model 2310 signal conditioner:		
Keithley KUSB-3108 DAQ Board:		
Silicon Designs $\pm$5g Accelerometer:		
Reference Load Cell:		

Required Changes & Improvement Recommendations

_____

_____

_____

_____

Reviewed By: _____

Date(s): _____

Signature: _____

Title: _____

Agency: _____

Phone: _____

Email: _____

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Figure 45. Illustration. Center facilities QA review form.

FWD Calibration Quality Assurance Review

Facility Check List

Review Item	Yes	No	Comments
1. Is the calibration test area clean and in good condition?			
2. Is there easy access for the FWD and towing vehicle?			
3. Does the FWD sit level inside the facility while testing?			
4. Are the trailer & tow vehicle attached together during calibration? (if applicable)			
5. Was the center computer set up so both system operators can converse easily?			
6. Can the facility can be kept at a constant temperature between 10 and 30° C (50 and 86° F)?			
7. Is it possible to successfully conduct a calibration on all types of FWD at this facility?			
8. Is the building electrical supply adequate and free of line noise?			
9. Is the area free of electromagnetic interference and radio frequency interference?			
10. Has adequate security has been provided for the calibration equipment?			

General Notes:

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Figure 45 (continued). Illustration. Center facilities QA review form.

FWD Calibration Quality Assurance Review

Equipment Check List

Review Item	Yes	No	Comments
1. Are all of the cables in good shape and working properly?			
2. Are the signal conditioner and data acquisition (DAQ) board those specified in the protocol?			
3. Are the signal conditioner and DAQ board in good condition and working properly?			
4. Has the reference load cell been calibrated in accordance with the protocol?			
5. Is the reference load cell in good condition and working properly?			
6. Is the reference accelerometer box in good condition and working properly?			
7. Is the reference accelerometer stored in a +1g field?			
8. Is the geophone calibration stand in good condition and working properly?			
9. Are all of the geophone holders in good condition and stored properly?			
10. Is the seismometer stand in good condition and stored properly?			
11. Is the ball joint anchor in good condition and working properly?			
12. Are the miscellaneous parts kept organized and stored properly?			
13. Is the calibration computer adequate to perform FWD calibration?			
14. Is the means of data transfer from the FWD to the Calibration Center computer adequate?			
15. Are the calibration data being zipped and backed up in a separate location?			
16. Is there a means for printing the calibration certificate and documentation?			

General Notes:

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Figure 45 (continued). Illustration. Center facilities QA review form.
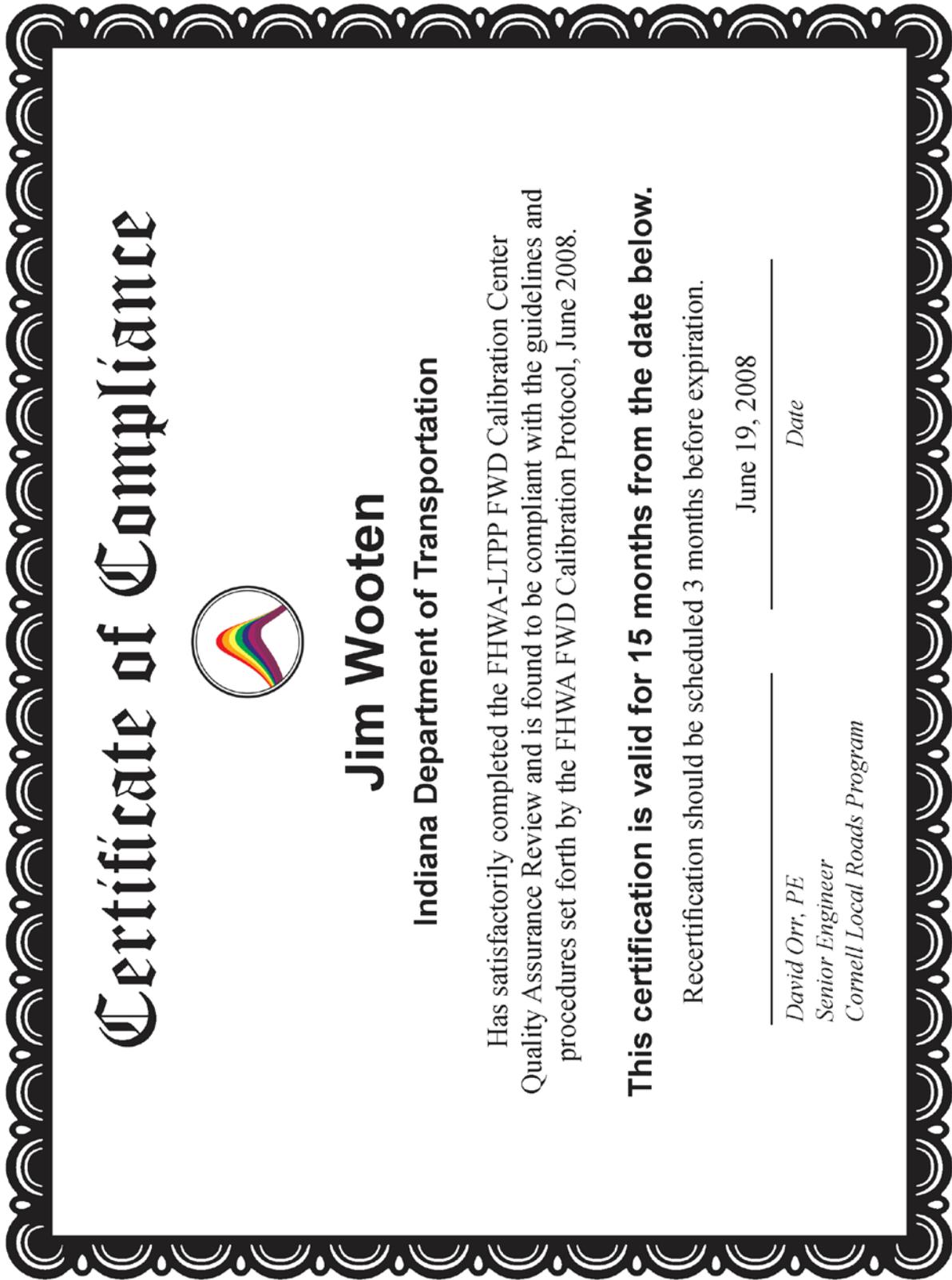
Figure 46. Illustration. Center operator certificate of compliance.

APPENDIX E. SPECIFICATIONS AND DRAWINGS

SPECIFICATIONS

1. General specifications

1.1 Description

The FWD calibration hardware set includes one accelerometer box assembly, one geophone calibration stand assembly, one seismometer calibration stand assembly, one reference load cell assembly, and one ball-joint anchor assembly. In some cases, only one of the stands is ordered for a hardware set. Drawings of each item are included by reference as part of this specification. Table 13 shows a list of drawings for each assembly.

Table 13. Parts required for one hardware set.

Assembly	Drawing Number
Accelerometer box assembly	CLRP-AB01
Ball-joint anchor assembly	CLRP-BJ01
Geophone stand assembly[1]	CLRP-GCS01
Seismometer stand assembly[1]	CLRP-SCS01
Geophone adapters assembly	CLRP-GA01
Reference load cell assembly	CLRP-LC01

[1]Indicates that in some cases, only one stand is ordered for a hardware set.

1.2 Materials

The required materials are described in the referenced drawings (see table 13).

1.3 Manufacturing Requirements/Conflicts

The contractor should provide all materials needed to manufacture one complete hardware set unless otherwise noted.

Additional manufacturing requirements are listed with the specifications for each individual part or subassembly. If there is a conflict between the drawings and the specifications, the specifications should govern.

1.4 Surface Smoothness

An industrial quality surface finish is desired. All machined surfaces should have a smoothness of 63 μ-inches (0.0016 mm) or less.

1.5. Mill Surface Finish

The mill surface finish on aluminum extrusions should be inspected for nicks, cuts, and dings, and a reasonable effort should be made to smooth out the defects before anodizing. Avoid removal of excessive amounts of material in this process.

1.6 Anodizing

Where anodizing is required on aluminum parts, all parts should be thoroughly cleaned and anodized according to MIL-A-8625F Type 2 Class 2 (Black). All parts should have a cosmetically homogeneous appearance after being anodized.

If for any reason parts must be stripped to remove the anodizing, a phosphoric chromic solution should be used, followed by surface polishing to remove pitting and achieve a 63-μ-inch (0.0016-mm) smoothness.

1.7 Loctite®

Where Loctite® is required, medium strength #242 Loctite® should be used.

1.8 Delivery/Acceptance

The contractor should provide a guaranteed delivery time. All parts should be assembled and delivered to the address provided by the purchasing agency.

The purchasing agency should have 7 days after delivery to check parts for proper alignment and fit as well as finish, as required. If the part or parts are not acceptable, the contractor should replace them at no additional charge.

1.9 Method of Payment

Payment should be authorized upon acceptance of the complete order.

2.0 Accelerometer Box Assembly Specifications (Drawing CLRP-AB01)

2.1 Description

The accelerometer box assembly is designed to house a Silicon Designs Model 2220 accelerometer as well as to provide some EMI shielding and additional physical protection. The box assembly mounts on the calibration platter, the geophone calibration stand, and the seismometer calibration stand by means of two #10-24 knurled head thumbscrews through the lip on the box.

2.2 Materials

All of the materials for the accelerometer box assembly are described in the referenced drawing and the bill of materials.

2.3 Manufacturing Requirements

The accelerometer box top and bottom, the box assembly, and calibration platter should be assembled together to ensure proper alignment prior to delivery to the customer. The accelerometer box top and bottom should also be fitted into the geophone calibration stand and the seismometer calibration stand, and the fit should be a firm coupling to both stands without any gaps or interference between mating surfaces.

Each aluminum part should be cleaned and then anodized in accordance with section 1.5. Upon delivery, the customer should finish assembly of the box by mounting the accelerometer and the Amphenol receptacle, mating the box top and bottom, mounting the bubble level, and attaching the leveling screws to the calibration platter.

3.0 Ball-joint Anchor Assembly Specifications (Drawing CLRP-BJ01)

3.1 Description

The ball-joint anchor assembly is the means by which the calibration stands are coupled to the test pad during FWD calibration. The clamp provides a solid mechanical connection to the calibration stand, and the Techno/Sommer KG60 ball-joint provides some rotational freedom, making the stands easier to use as well as providing for some moment compensation.

3.2 Materials

All of the materials for the ball-joint anchor assembly are described in the referenced drawing and the bill of materials.

3.3 Manufacturing Requirements

Upon delivery, the customer should finish assembly of the anchor by attaching the base bar and the clamp base to the ball-joint. The clamp should be attached to the clamp base, and the rest stop should be mounted to the anchor assembly

4.0 Geophone Calibration Stand Assembly Specifications (Drawing CLRP-GCS01)

4.1 Description

The geophone calibration stand assembly is designed to hold up to 10 geophones from the Dynatest®, Carl Bro, KUAB, or JILS FWD. The accelerometer box (see section 2.0) mounts to the middle shelf in the stand. The stand is attached to the ball-joint anchor (see section 3.0) during the calibration procedure.

4.2 Materials

All of the materials for the geophone calibration stand are described in the referenced drawing and the bill of materials.

4.3 Manufacturing Requirements

Prior to welding the stand, the parts should be cleaned and dry fitted together. A qualified Tungsten inert gas (TIG) welder should perform all of the welding. After welding, the stand should be cleaned and then anodized in accordance with section 1.5.

After delivery, the customer should finish assembly by adding handles and bubble levels as needed and use Loctite® to keep the connector pin in place.

5.0 Seismometer Calibration Stand Assembly (Drawing CLRP-SCS01)

5.1 Description

The seismometer calibration stand assembly is designed to hold up to 10 KUAB seismometers in a 2-column configuration. Additionally, the accelerometer box (see section 2.0) mounts to the middle shelf in the stand. The stand is attached to the ball-joint anchor (see section 3.0) during the calibration procedure.

5.2 Materials

All materials for the seismometer calibration stand assembly are described in the referenced drawing and the bill of materials.

5.3 Manufacturing Requirements

Prior to welding the stand, the parts should be cleaned and dry fitted together. A qualified TIG welder should perform all of the welding. After welding, the stand should be cleaned and anodized in accordance with section 1.5.

After delivery, the customer should finish assembly by adding handles and bubble levels as needed and use Loctite® to keep the connector pin in place.

6.0 Geophone Adapter Specifications

6.1 Description

The geophone adapters are used to couple three different types of geophones to the geophone calibration stand (see section 4.0) and allow for ease of movement of the geophones within the stand.

6.2 Materials

All materials for the geophone adapters are described in the referenced drawing and the bill of materials.

6.3 Manufacturing Requirements

The geophone adapters should be dry fitted into the geophone calibration stand sensor shelves to ensure a loose sliding fit in the slotted hole on each shelf.

7.0 Reference Load Cell Assembly (Drawing CLRP-LC01)

7.1 Description

The reference load cell is a custom load cell designed specifically for FWD calibration. The load cell allows all brands of FWD to be calibrated with a 11.7-inch (300-mm) load plate.

7.2 Materials

All materials for the reference load cell assembly are described in the referenced drawings and bill of materials.

7.3 Manufacturing Requirements

Prior to welding the base to the body, the parts should be cleaned and dry fitted together. A certified TIG welder should perform all of the welding. After welding, the load cell parts should be cleaned and anodized in accordance with section 1.5, with the exception of the measuring links (Drawing CLRP-LC04), which should not be anodized.

After delivery, the customer should have the measuring links gauged by a qualified strain gauge installer. Then, the load cell should be fully assembled, conditioned, and calibrated according to AASHTO R33-03.[10]

COMPLETE DRAWING LIST

Table 14 provides a complete drawing list for the accelerometer box, ball-joint anchor, geophone calibration stand, seismometer calibration stand, geophone adapters, reference load cell, and data acquisition cables. The drawings follow in the same order in this appendix.

Table 14. Complete drawing list.

Drawing Number	Part Name
CLRP-AB01	Accelerometer box assembly
CLRP-AB02	Accelerometer box bottom
CLRP-AB03	Accelerometer box top
CLRP-AB04	Calibration platter
CLRP-AB05	Accelerometer wiring
CLRP-BJ01	Ball-joint anchor assembly
CLRP-BJ02	Clamp
CLRP-BJ03	Clamp base
CLRP-BJ04	Base bar
CLRP-BJ05	Rest stop
CLRP-GCS01	Geophone stand assembly
CLRP-GCS02	Geophone stand side rail
CLRP-GCS03	Geophone stand top shelf
CLRP-GCS04	Geophone stand bottom shelf
CLRP-GCS05	Geophone stand sensor shelf
CLRP-GCS06	Geophone stand accelerometer shelf
CLRP-GCS07	Geophone stand handle holder
CLRP-GCS08	Geophone stand connector pin
CLRP-SCS01	Seismometer stand assembly
CLRP-SCS02	Seismometer stand side rail
CLRP-SCS03	Seismometer stand top shelf
CLRP-SCS04	Seismometer stand sensor shelf
CLRP-SCS05	Seismometer stand standoff
CLRP-SCS06	Seismometer stand bottom shelf
CLRP-SCS07	Seismometer stand handle holder
CLRP-SCS08	Seismometer stand connector pin
CLRP-SCS09	Seismometer stand shelf subassembly
CLRP-SCS10	Seismometer stand accelerometer shelf
CLRP-SCS11	Seismometer stand accelerometer shelf subassembly
CLRP-GA01	Geophone adapter assemblies
CLRP-GA02	Carl Bro adapter
CLRP-GA03	JILS adapter
CLRP-GA04	KUAB adapter
CLRP-LC01	Load cell assembly
CLRP-LC02	Load cell body
CLRP-LC03	Base plate
CLRP-LC04	Measuring link
CLRP-LC05	Cover plate
CLRP-LC06	Foot
CLRP-LC07	Guide fingers
CLRP-LC08	Interior connector wiring

Drawing Number	Part Name
CLRP-LC09	Strain gauge layout
CLRP-LC10	Bridge wiring
CLRP-DAQ01	Vishay to DAQ cable
CLRP-DAQ01A	Vishay 2310B BNC to DAQ cable
CLRP-DAQ01B	Vishay 2310B BNC to DAQ cable—stock parts
CLRP-DAQ02	Vishay to load cell DAQ cable
CLRP-DAQ03	Accelerometer signal cable
CLRP-DAQ04	Pushbutton to KUSB DAQ cable
CLRP-DAQ06	KUSB protection wiring
CLRP-DAQ07	KUSB enclosure rear panel
CLRP-DAQ08	KUSB enclosure front panel

ACCELEROMETER BOX
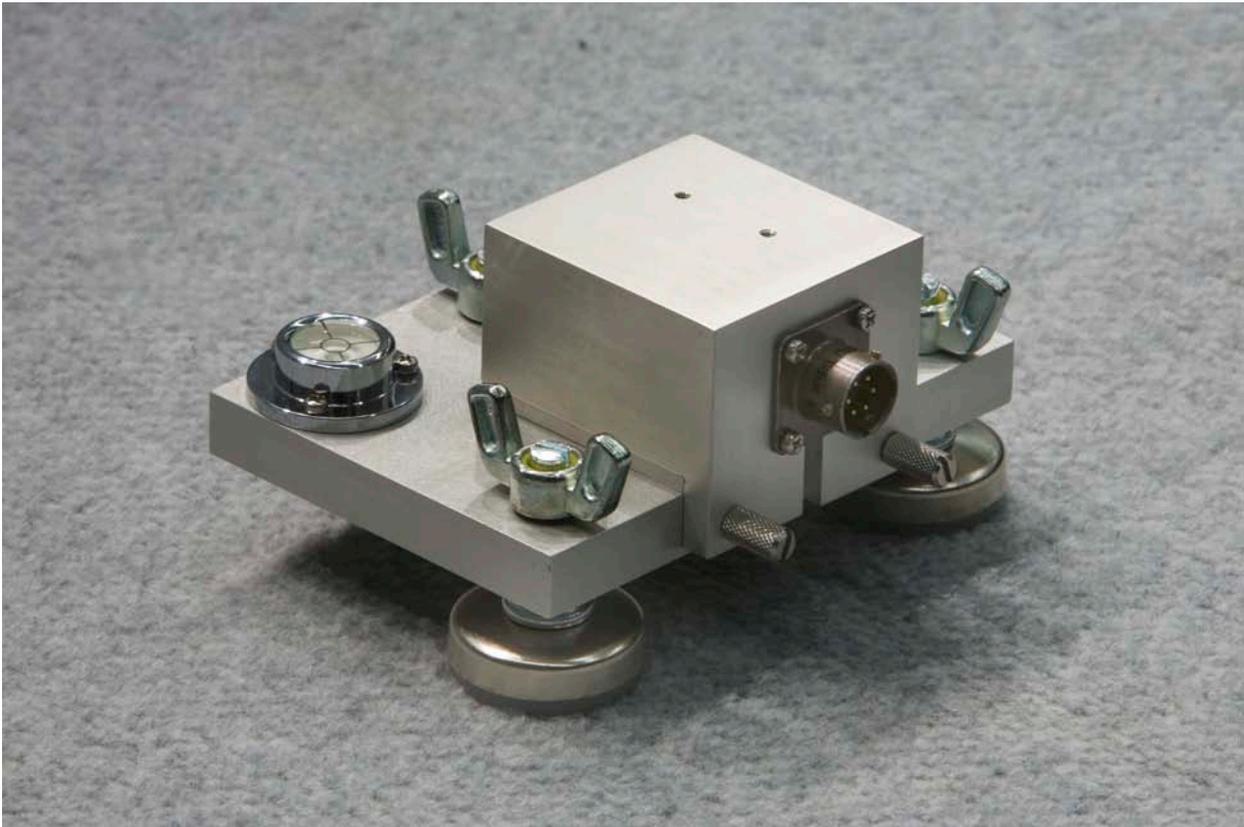
Figure 47. Photo. Accelerometer box.

Table 15. Fabricated parts required for BM-AB accelerometer box assembly.

Drawing Number	Description	Quantity
CLRP-AB02	Accelerometer box bottom	1
CLRP-AB03	Accelerometer box top	1
CLRP-AB04	Calibration platter	1
CLRP-AB05	Accelerometer wiring	1

Table 16. Hardware items required for BM-AB accelerometer box assembly.

Vendor Part Number	Item	Vendor	Quantity
96877A209	Flat head Phillips machine screw, 18-8 SS, 4-40 thread, $^3/_8$-inch length, Mil Spec 51959-15	McMaster-Carr®	4
91400A110	Pan head Phillips machine screw, 18-8 SS, 4-40 thread, $^1/_2$-inch length, Mil Spec 51957-17	McMaster-Carr®	2
91737A072	Fillister head Phillips machine screw, 18-8 SS, 4-40 thread, $^1/_4$-inch length	McMaster-Carr®	7
91746A876	Knurled head thumb screw, slotted, 18-8 SS, 10-24 thread, $^1/_2$-inch length, $^1/_4$-inch head diameter, $^1/_2$-inch length	McMaster-Carr®	2
91755A205	Retaining washer, Nylon 6/6, #4 screw size, $^7/_{64}$-inch inside diameter, $^{17}/_{64}$-inch outside diameter, 0.027–0.037-inch thickness	McMaster-Carr®	2
2198A85	Bull's-eye level, glass, surface mount, center circle and cross lines, $1^1/_4$-inch base diameter, $^7/_{16}$-inch height	McMaster-Carr®	1
23015T64	Leveling mount, polyethylene base, $^3/_8$-inch 16 thread, 50 lbf maximum load, 1-inch length	McMaster-Carr®	3
98520A145	Locking wing nut, zinc alloy, nylon insert, $^3/_8$-inch 16 screw size, $1^1/_2$-inch wing spread	McMaster-Carr®	3
2220-005	Accelerometer, ± 5 *g* with calibration certificate	Silicon Designs	1
654-PT02A106P	Amphenol receptacle, PT02A-10-6P	Mouser Electronics	1

1 inch = 25.4 mm
1 lbf = 4.45 N

Table 17. Vendor contact information for BM-AB accelerometer box assembly.

Vendor	Web site	Notes
McMaster-Carr®	www.mcmaster.com	See Web site for specific contact information located in the "About Us" section.
Silicon Designs	www.silicondesigns.com	1445 NW Mall St, Issaquah, WA 98027, 425-391-8329
Mouser Electronics	www.mouser.com	See Web site for specific contact information located in the "Contact Us" section.
Incodema	www.incodema.com	Incodema Inc. 407 Cliff Street, Ithaca, NY 14850 607-277-7070

Table 18. Hardware costs for BM-AB accelerometer box.

Part	Quantity	Supplier	Cost[1]
Materials and machining	1	Incodema	$912.00
Accelerometer (± 5 g)	1	Silicon Designs	$580.00
Miscellaneous hardware	1		$38.00

[1]Indicates the cost in February 2009.
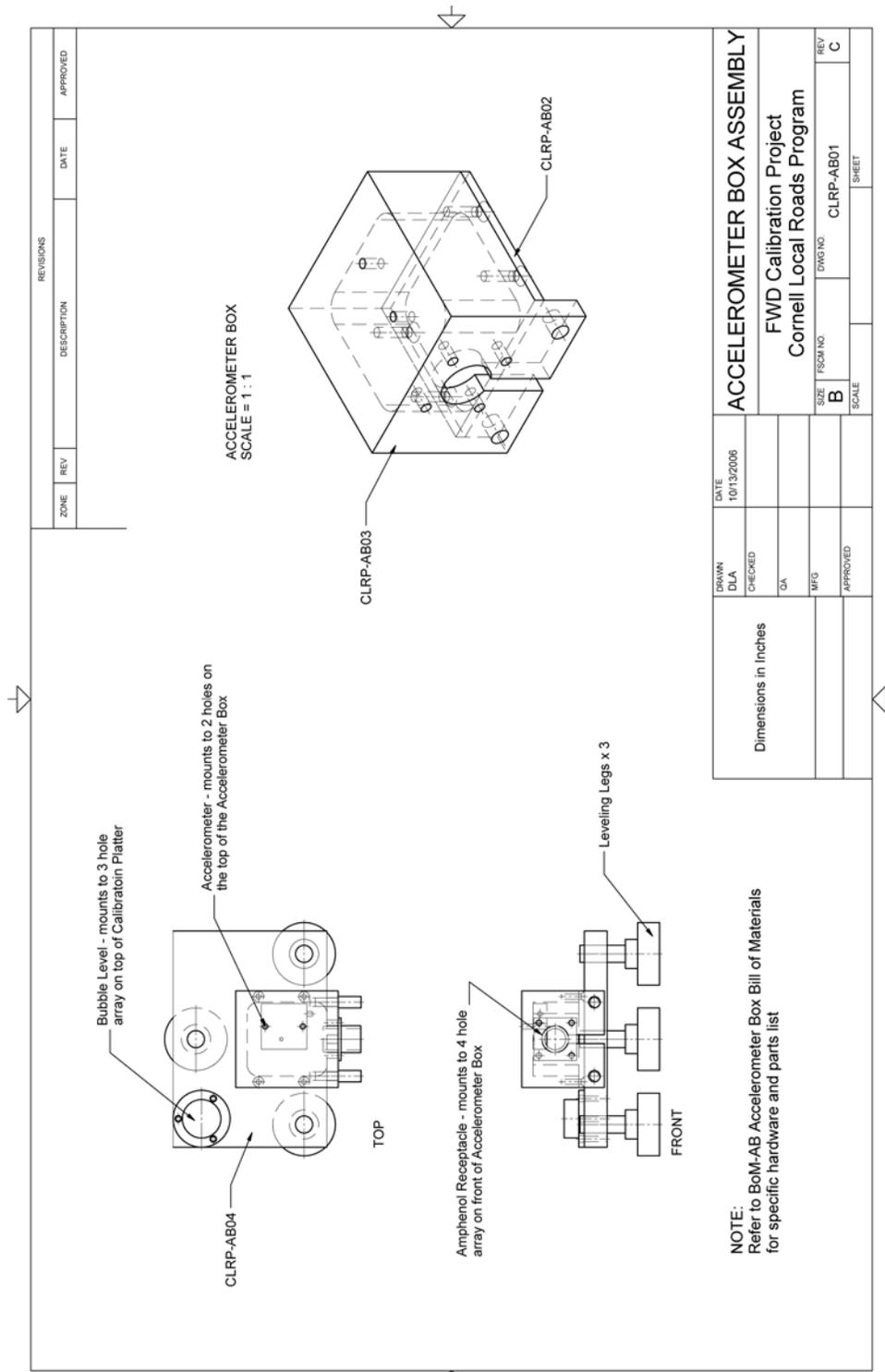
Figure 48. Illustration. CLRP-AB01 accelerometer box assembly.
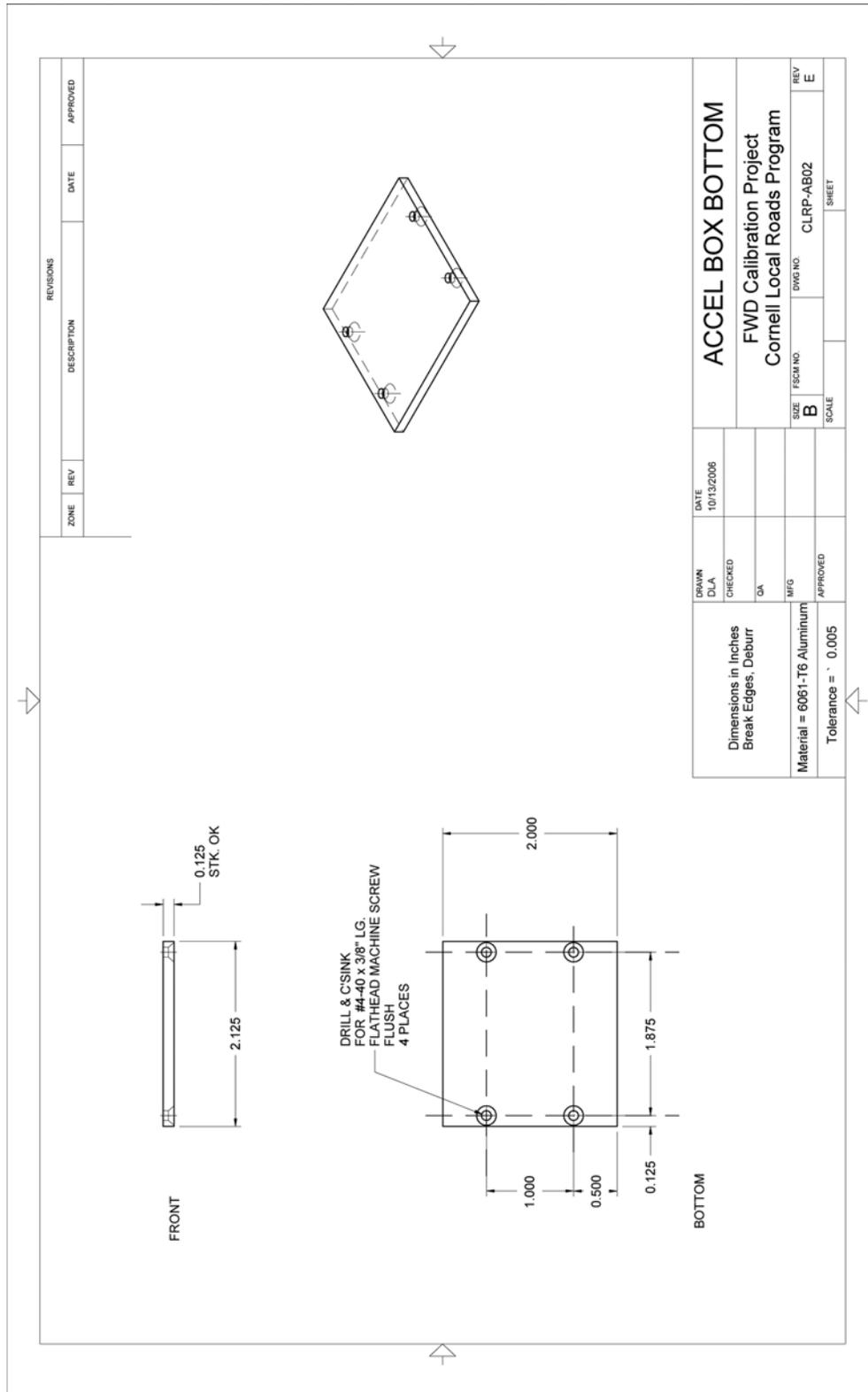
Figure 49. Illustration. CLRP-AB02 accelerometer box bottom.
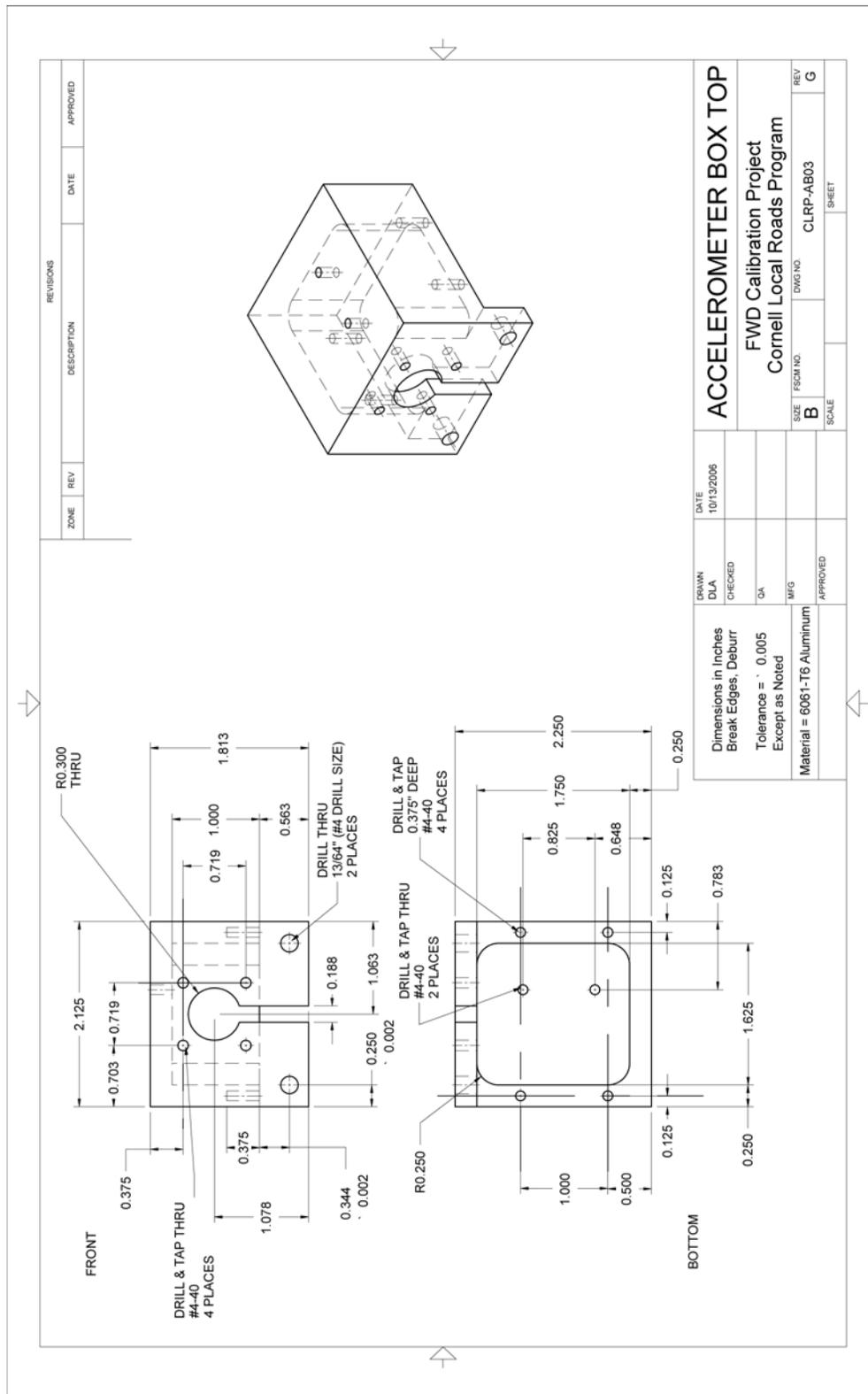
Figure 50. Illustration. CLRP-AB03 accelerometer box top.
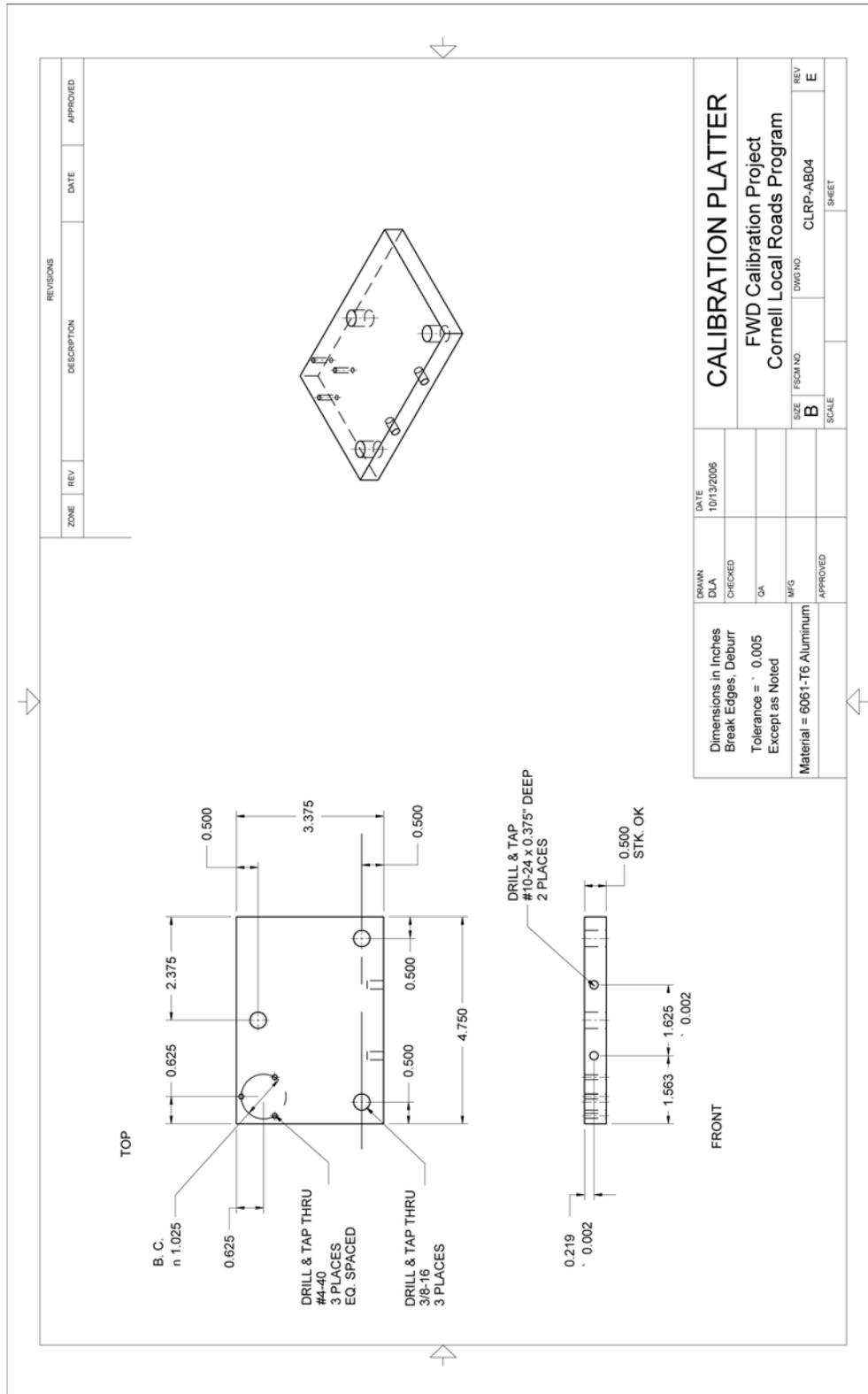
Figure 51. Illustration. CLRP-AB04 calibration platter.

Figure 52. Illustration. CLRP-AB05 accelerometer wiring.
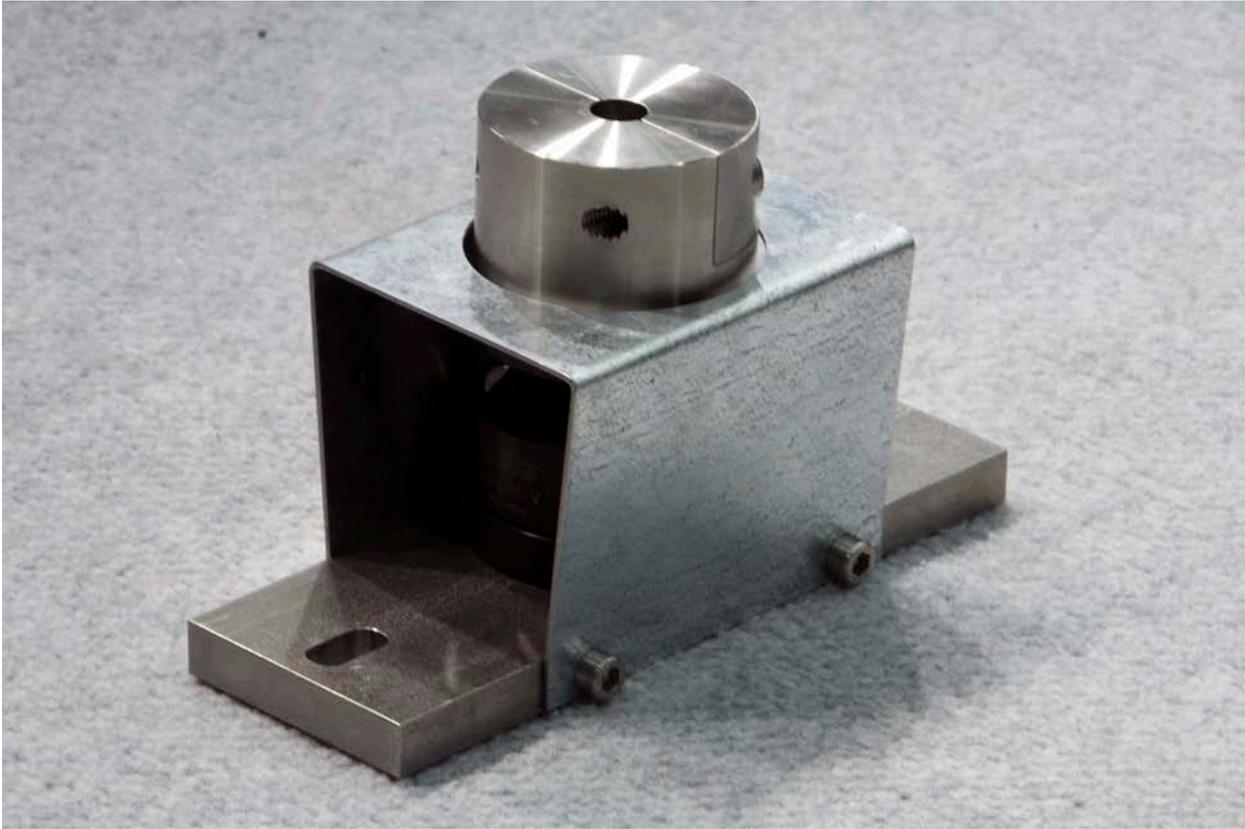
BALL-JOINT ANCHOR

Figure 53. Photo. Ball-joint anchor.

Table 19. Fabricated parts required for the BM-BJ ball-joint anchor assembly.

Drawing Number	Description	Quantity
CLRP-BJ02	Clamp	1
CLRP-BJ03	Clamp base	1
CLRP-BJ04	Base bar	1
CLRP-BJ05	Rest stop	1

Table 20. Hardware items required for the BM-BJ ball-joint anchor assembly.

Vendor Part Number	Item	Vendor	Quantity
KG-60	Ball-joint	Techno/Sommer	1
91292A145	Socket head cap screw, 18-8 stainless steel, M8 thread, 16-mm length, $1\frac{1}{4}$-mm pitch	McMaster-Carr®	6
91292A148	Socket head cap screw, 18-8 stainless, M8 thread, 25-mm length, $1\frac{1}{4}$-mm pitch	McMaster-Carr®	2
91292A135	Socket head cap screw, 18-8 stainless steel, M6 thread, 16-mm length, 1-mm pitch	McMaster-Carr®	4

1 inch = 25.4 mm

Table 21. Vendor contact information.

Vendor	Web site	Notes
Techno/Sommer	www.techno-sommer.com	See Web site for specific contact information located in the "Sales Representatives" section.
McMaster-Carr®	www.mcmaster.com	See Web site for specific contact information located in the "About Us" section.
Incodema	www.incodema.com	Incodema Inc. 407 Cliff Street, Ithaca, NY 14850 607-277-7070

Table 22. Hardware costs for BM-BJ ball-joint anchor.

Part	Quantity	Supplier	Cost[1]
Materials and machining	1	Incodema	$919.00
Techno/Sommer KG60 Ball-joint	1	Techno/Sommer	$143.00
Miscellaneous hardware	1		$31.00

[1]Indicates the cost in February 2009.
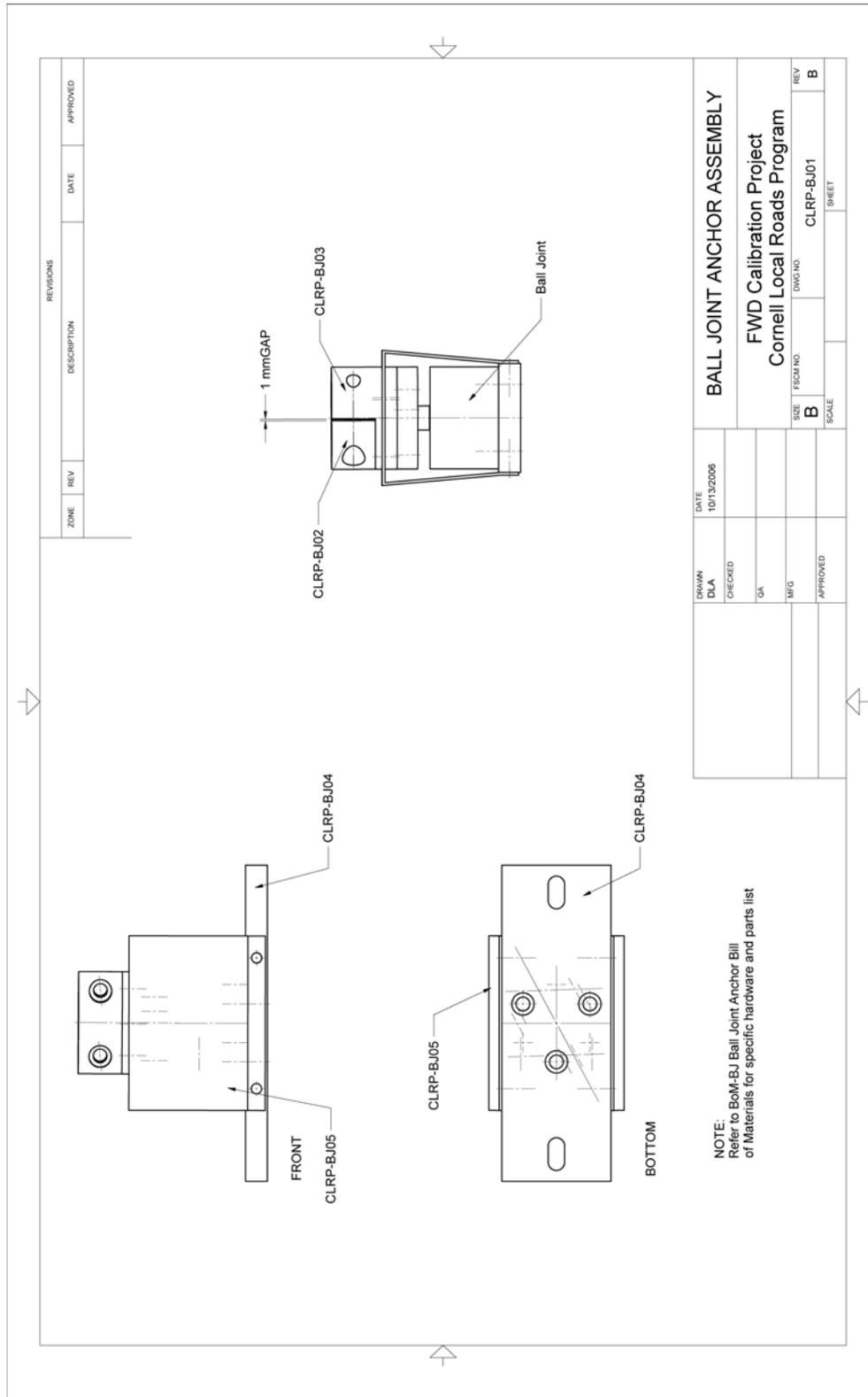
Figure 54. Illustration. CLRP-BJ01 ball-joint anchor assembly.
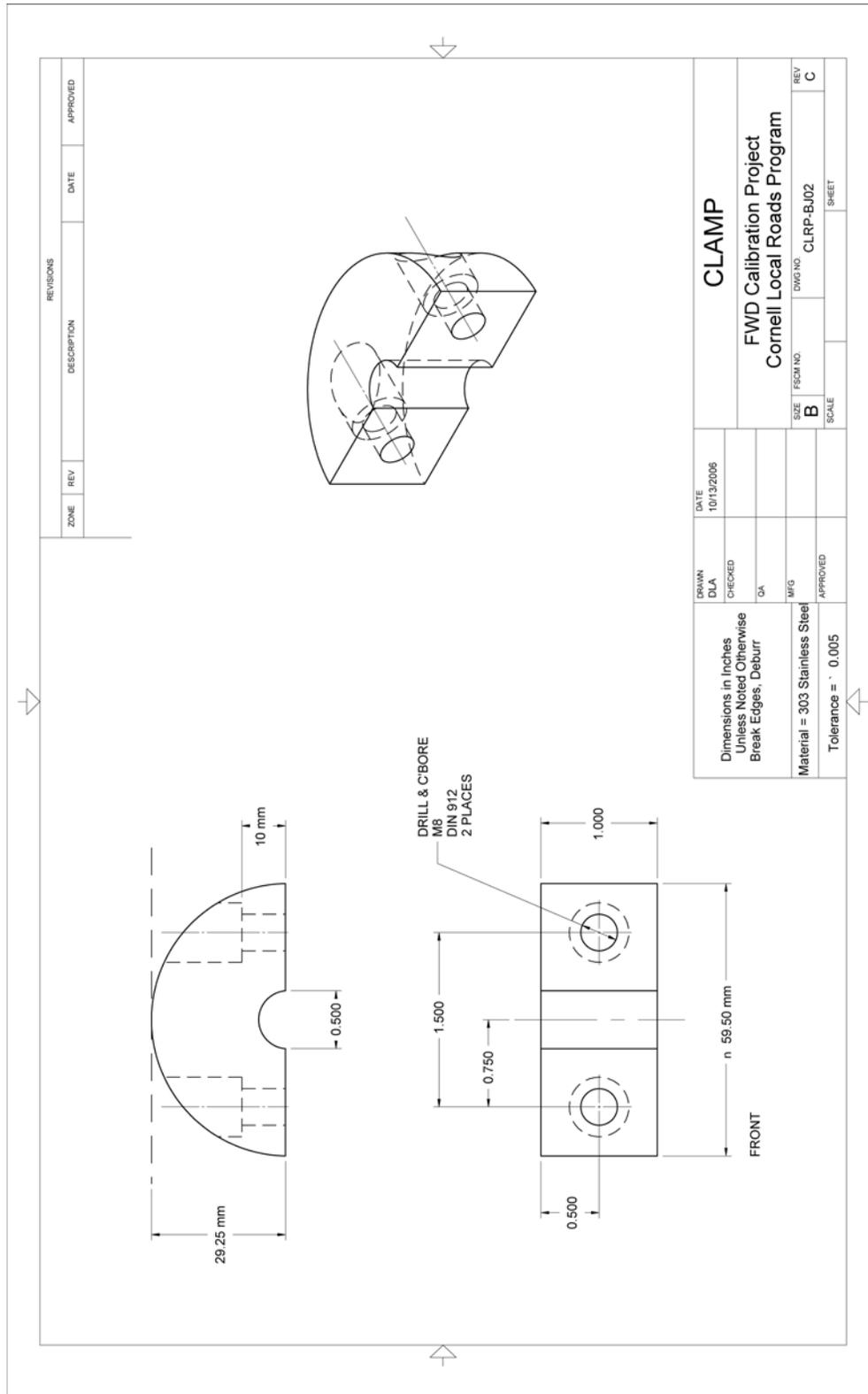
Figure 55. Illustration. CLRP-BJ02 clamp.
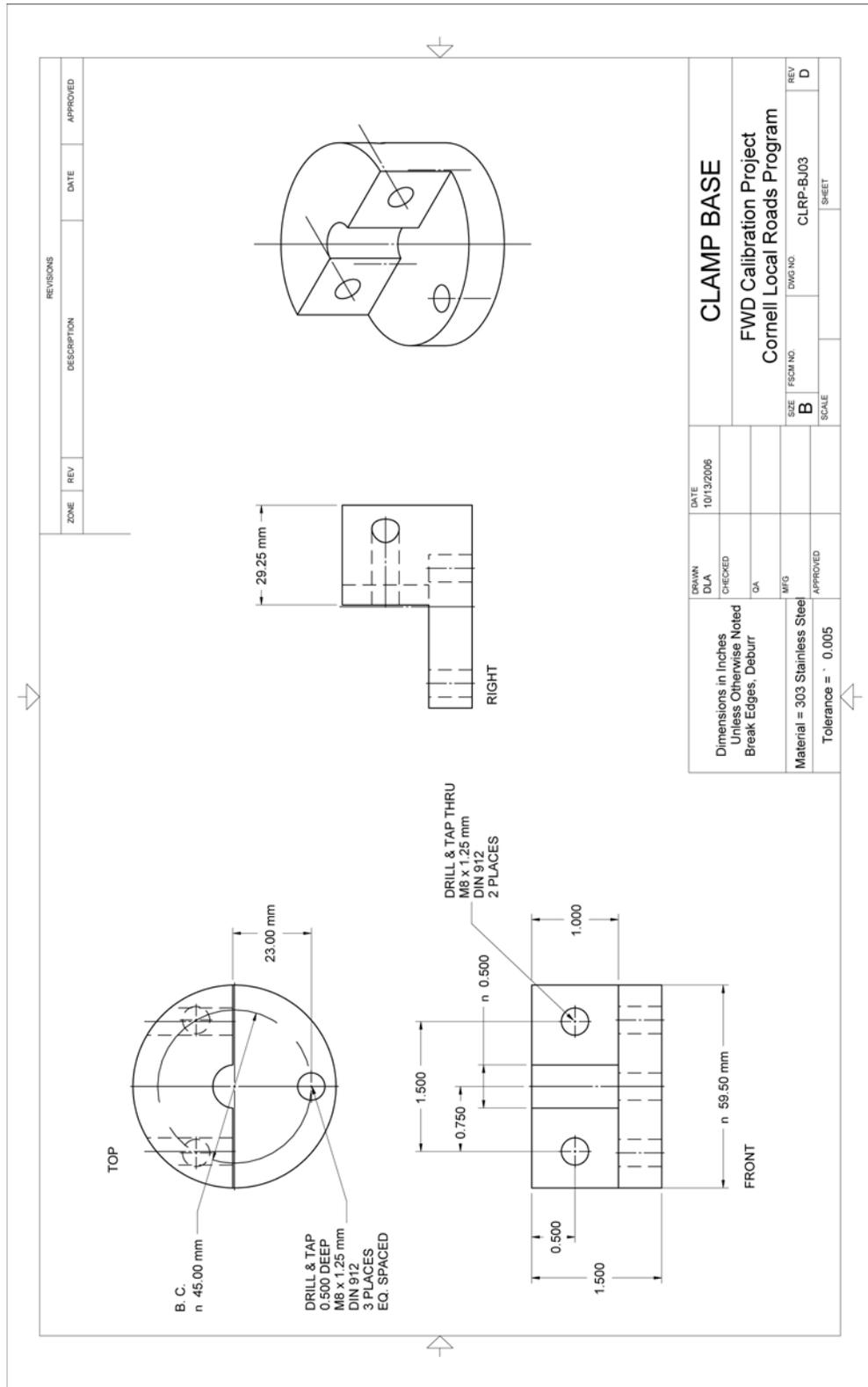
Figure 56. Illustration. CLRP-BJ03 clamp base.
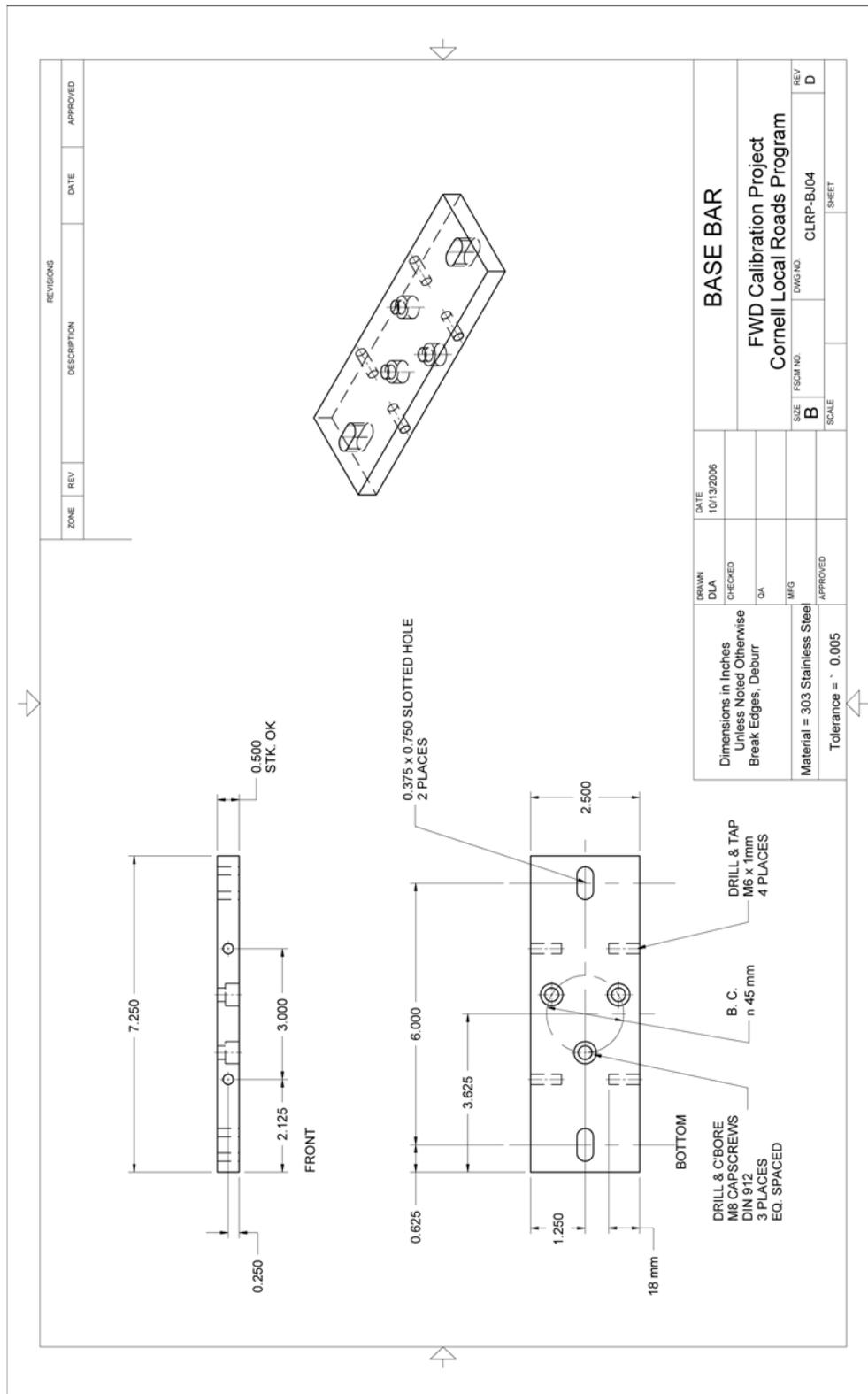
Figure 57. Illustration. CLRP-BJ04 base bar.
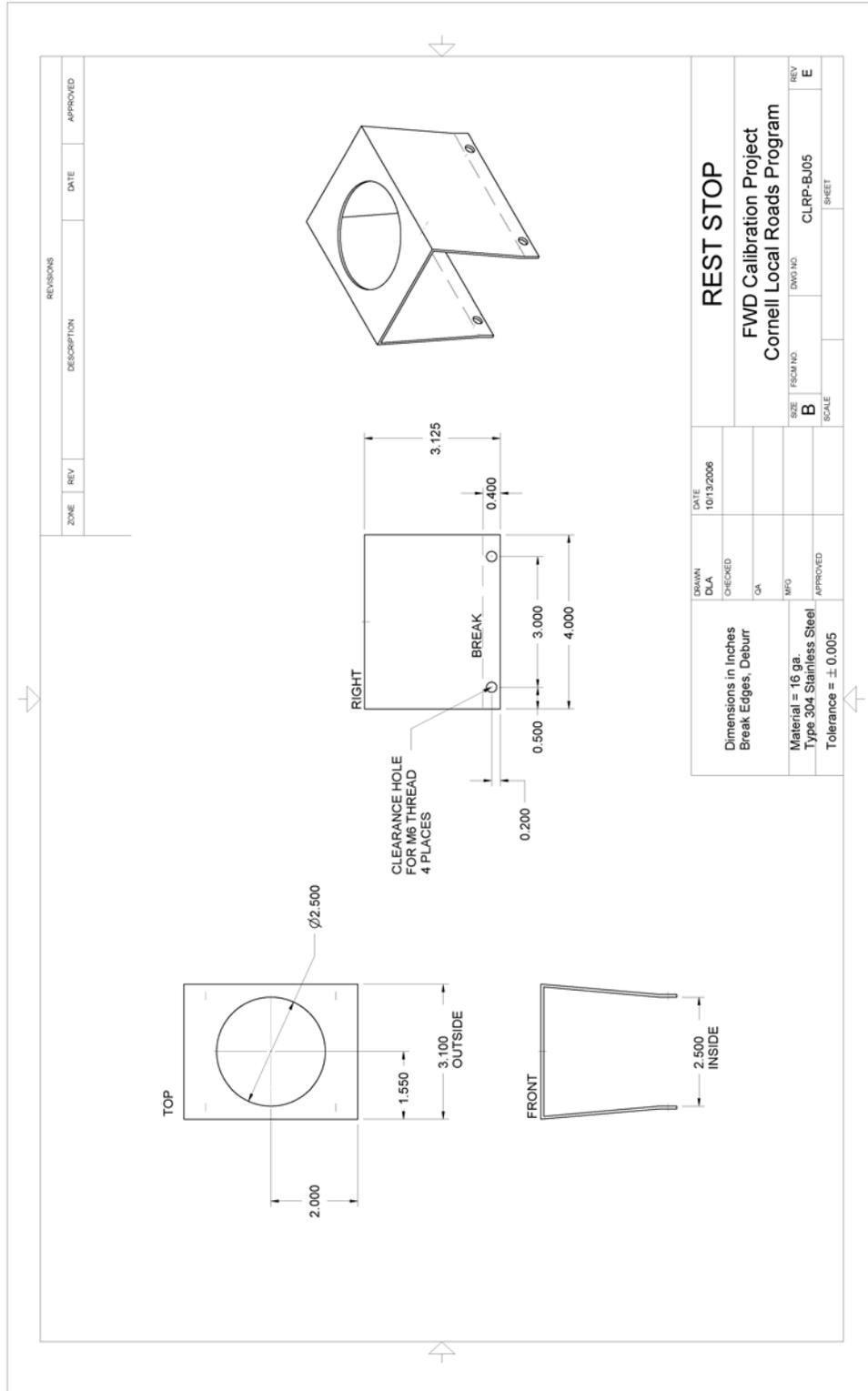
Figure 58. Illustration. CLRP-BJ05 rest stop.

GEOPHONE CALIBRATION STAND
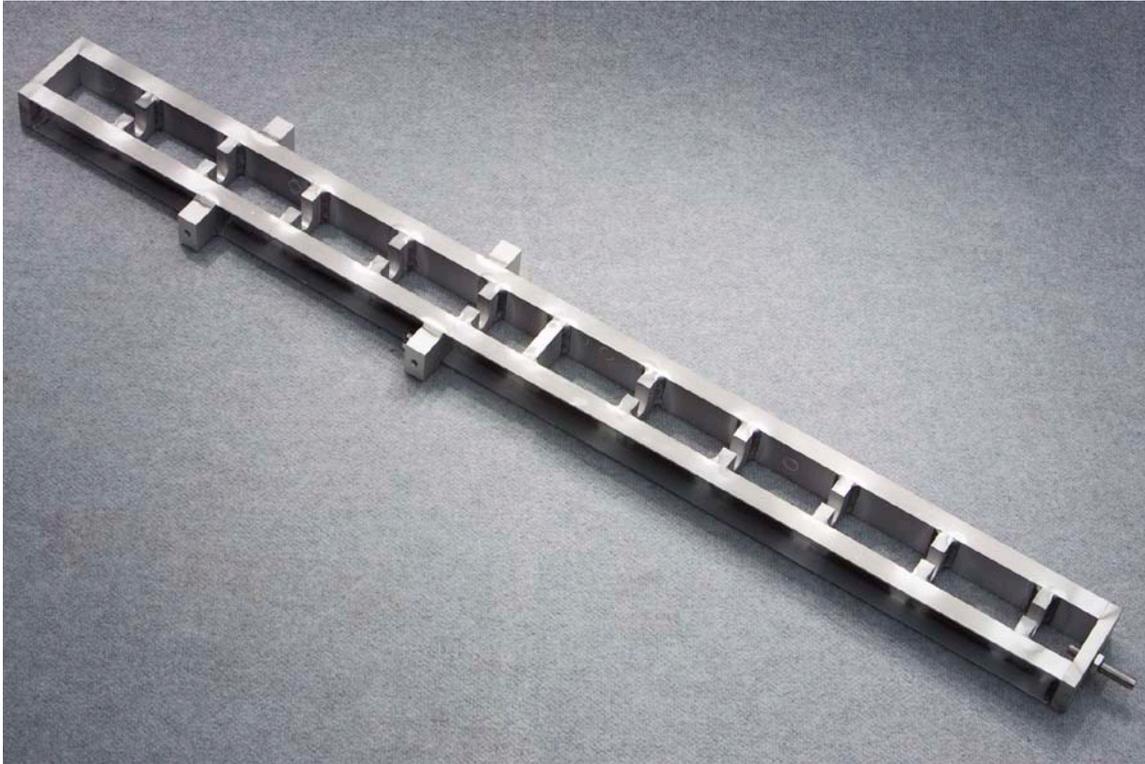
Figure 59. Photo. Geophone calibration stand.

Table 23. Fabricated parts required for BM-GCS geophone calibration stand assembly.

Drawing Number	Item	Quantity
CLRP-GCS02	Geophone stand side rail	2
CLRP-GCS03	Geophone stand top shelf	1
CLRP-GCS04	Geophone stand bottom shelf	1
CLRP-GCS05	Geophone stand sensor shelf	10
CLRP-GCS06	Geophone stand accelerometer shelf	1
CLRP-GCS07	Geophone stand handle holder[1]	4
CLRP-GCS08	Geophone stand connector pin[2]	1

[1]Identical to CLRP-SCS07.
[2]Identical to CLRP-SCS08.

Table 24. Hardware items required for BM-GCS geophone calibration stand assembly.

Vendor Part Number	Item	Vendor	Quantity
62385K65	Tapered handle, Smooth phenolic, $^3/_8$-inch, 16 x $^1/_2$-inch threaded stud, 1-inch diameter	McMaster-Carr®	2
2198A85	Glass surface-mount bull's-eye level center circle and cross lines, $1^1/_4$-inch base diameter, $^7/_{16}$-inch height	McMaster-Carr®	1
91737A072	18-8 stainless steel fillister head Phillips machine screw 4-40 thread, $^1/_4$-inch length	McMaster-Carr®	3

1 inch = 25.4 mm

Table 25. Vendor contact information for BM-GCS geophone calibration stand.

Vendor	Web site	Notes
McMaster-Carr®	www.mcmaster.com	See Web site for specific contact information in the "About Us" section.
Incodema	www.incodema.com	Incodema Inc. 407 Cliff Street, Ithaca, NY 14850 607-277-7070

Table 26. Hardware costs for BM-GCS geophone calibration stand.

Part	Quantity	Supplier	Cost[1]
Materials and machining	1	Incodema	$1407.00
Miscellaneous hardware	1		$30.00

[1]Indicates the cost in February 2009.
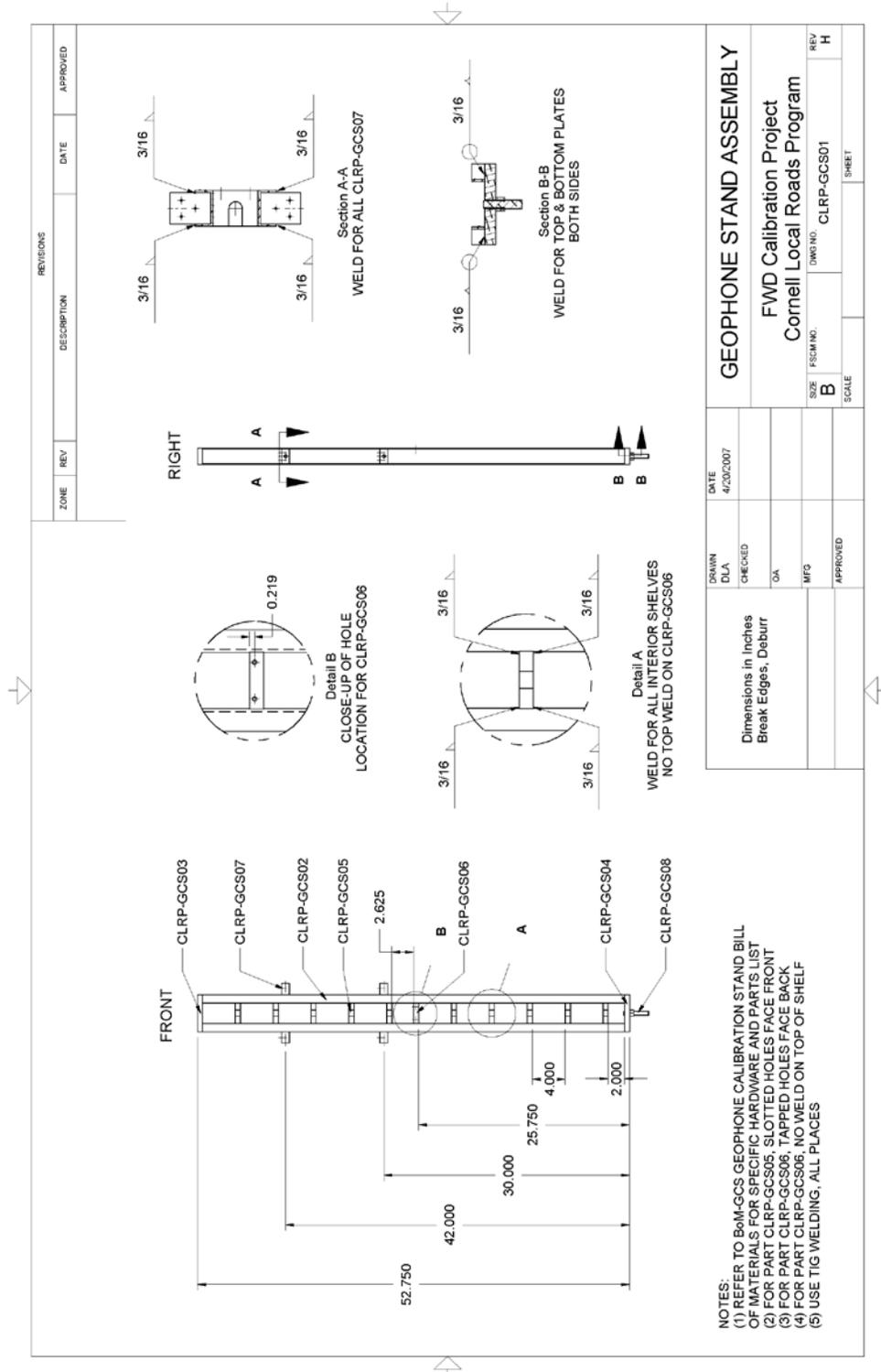
Figure 60. Illustration. CLRP-GCS01 geophone stand assembly.
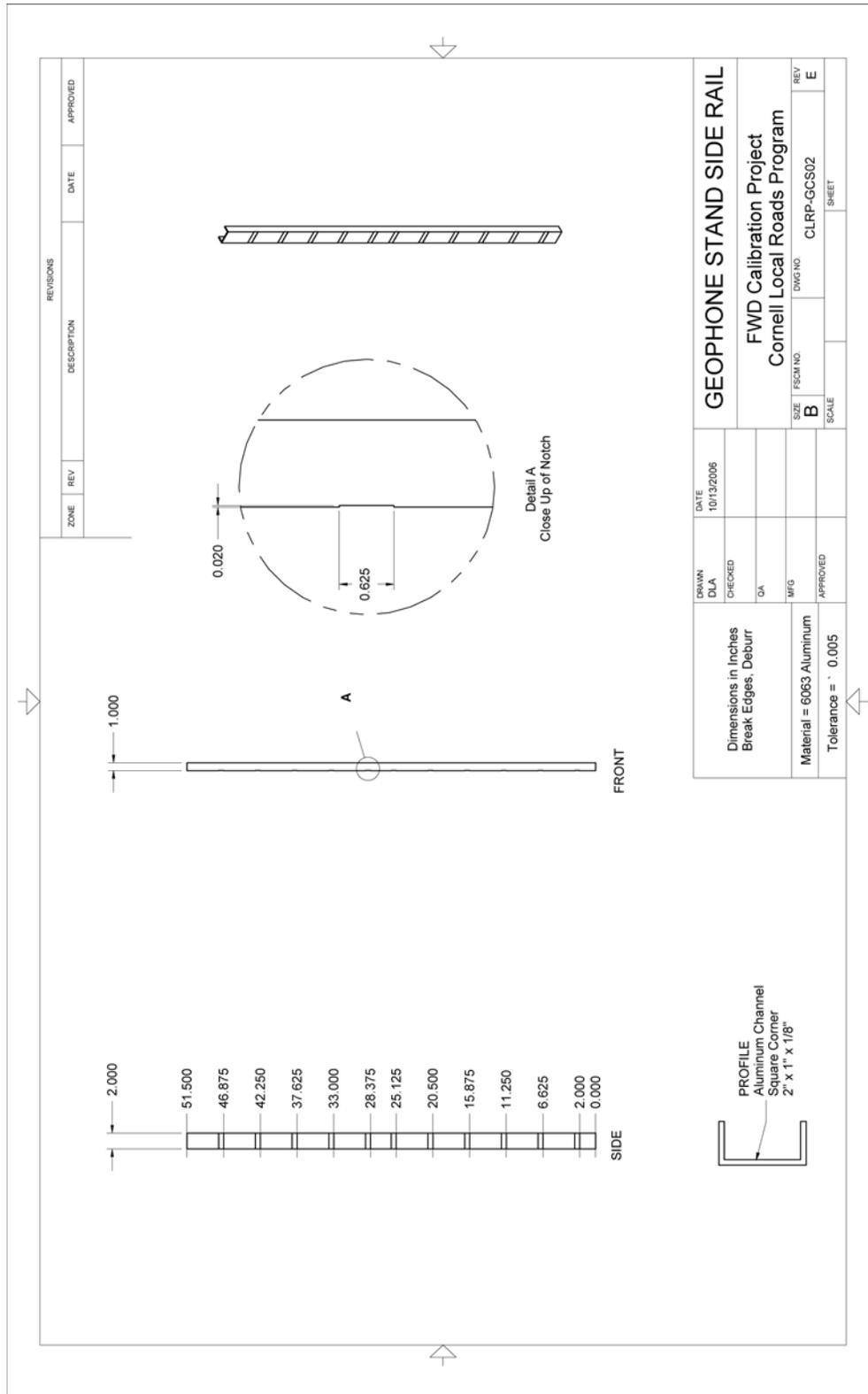
Figure 61. Illustration. CLRP-GCS02 geophone stand side rail.
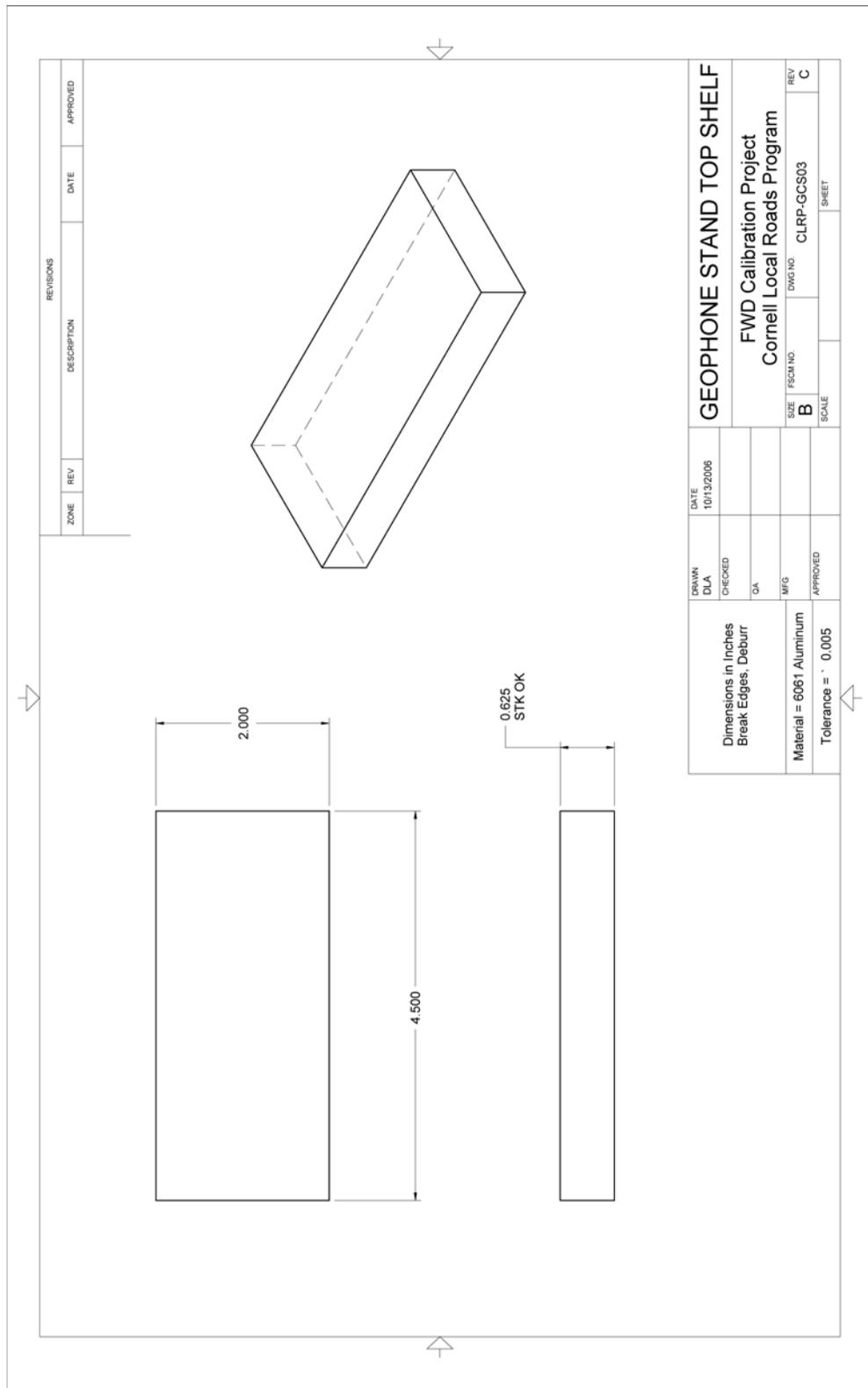
Figure 62. Illustration. CLRP-GCS03 geophone top shelf.
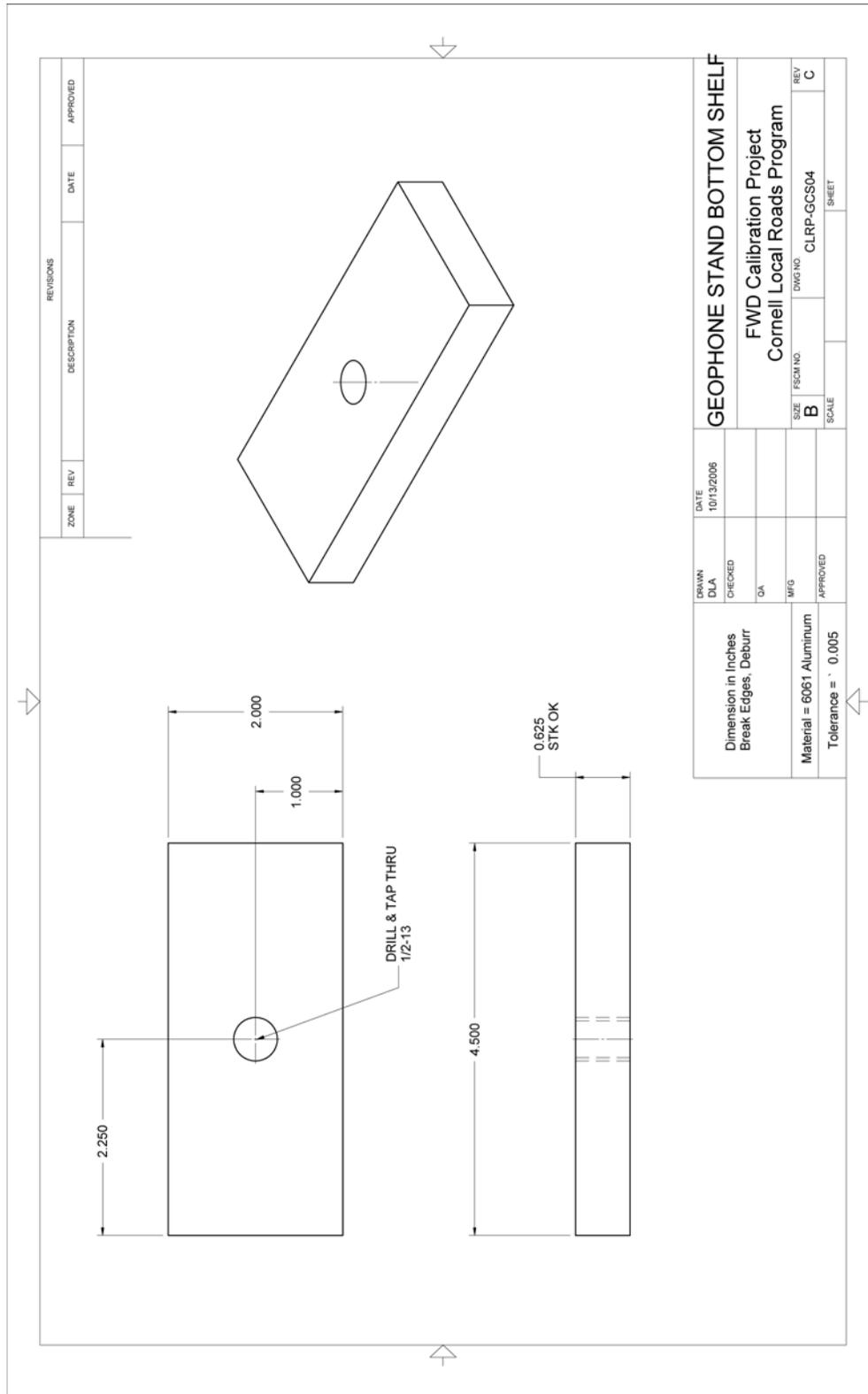
Figure 63. Illustration. CLRP-GCS04 geophone stand bottom shelf.
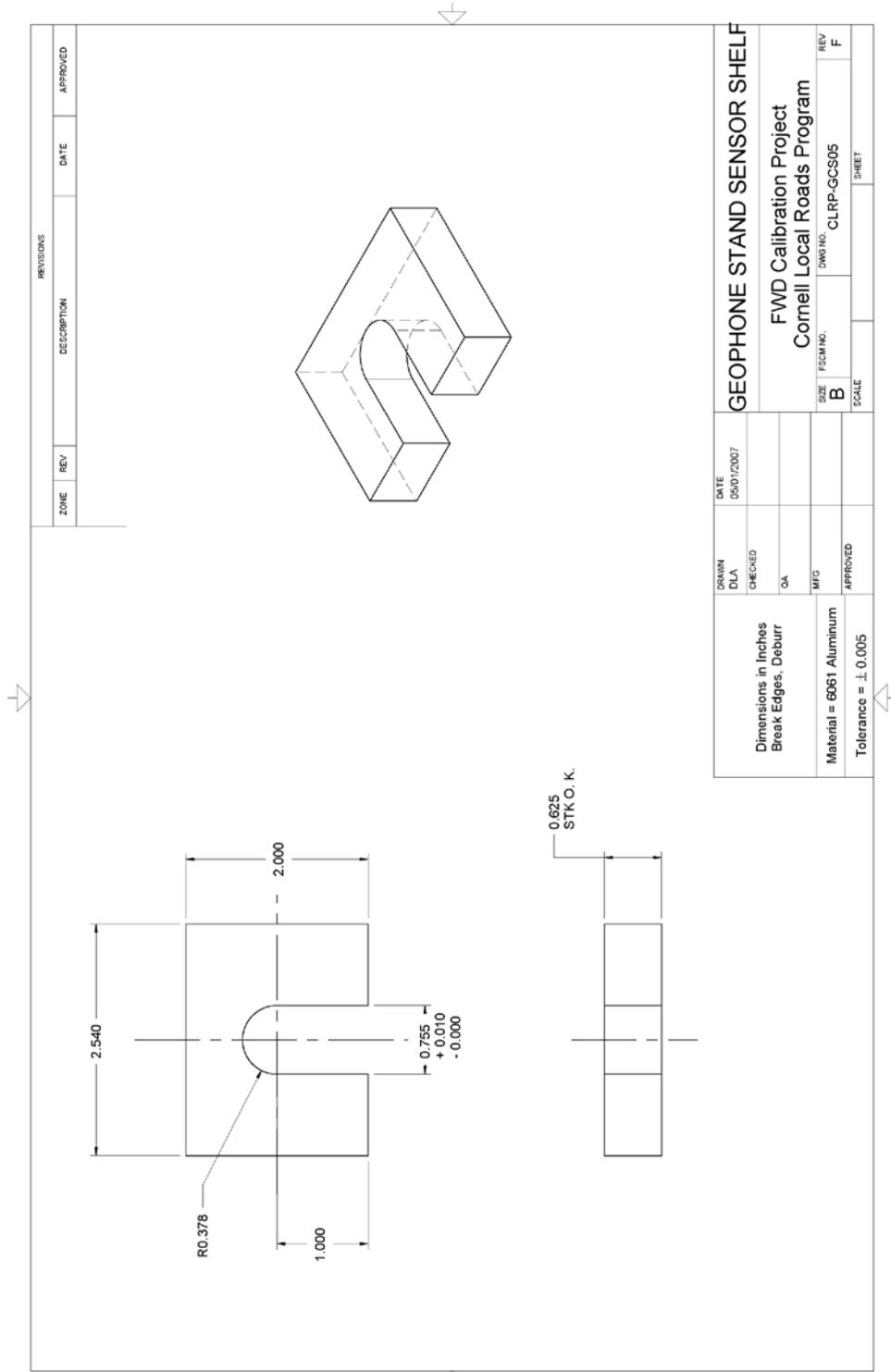
Figure 64. Illustration. CLRP-GCS05 geophone stand sensor shelf.
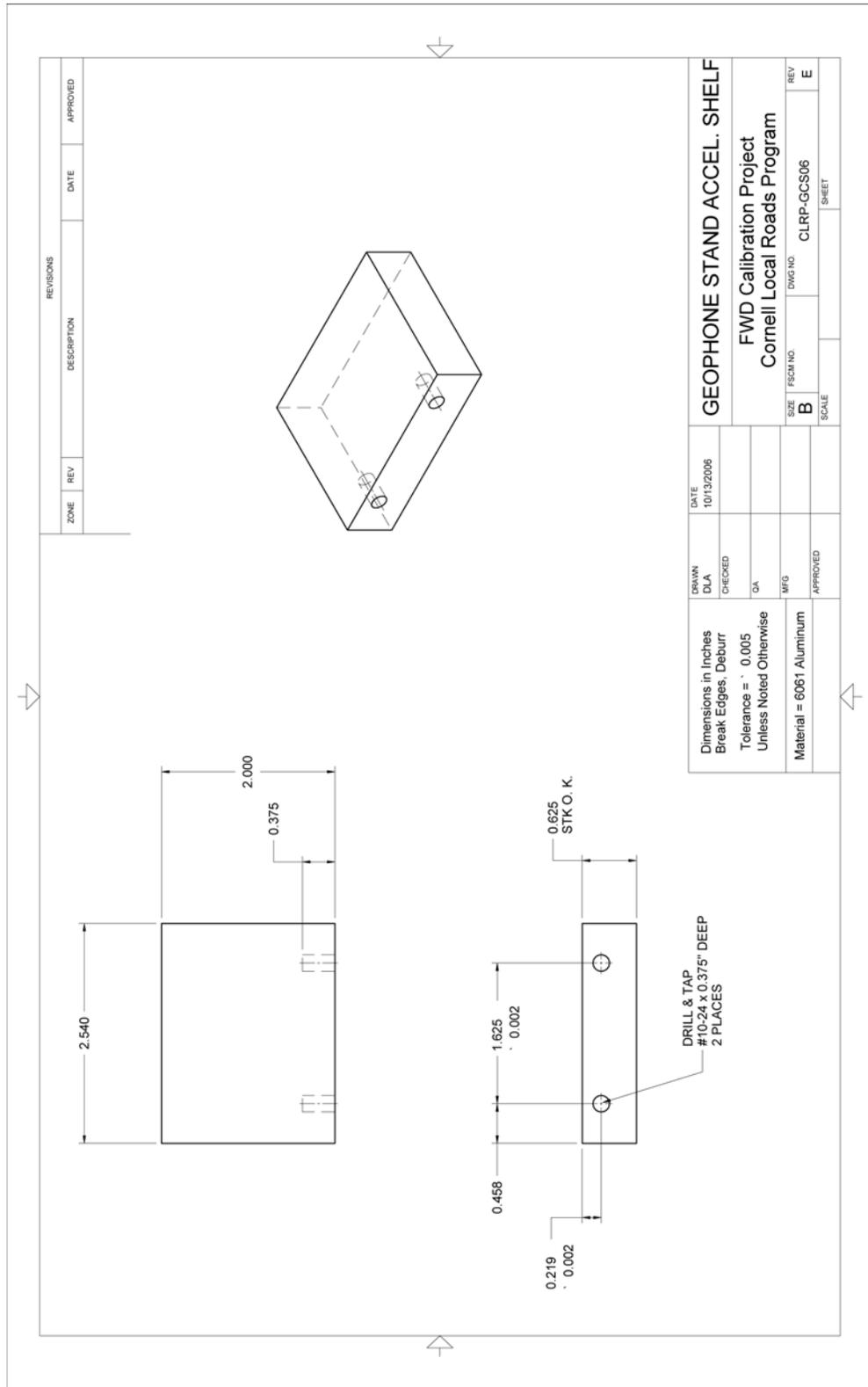
Figure 65. Illustration. CLRP-GCS06 geophone stand accelerometer shelf.
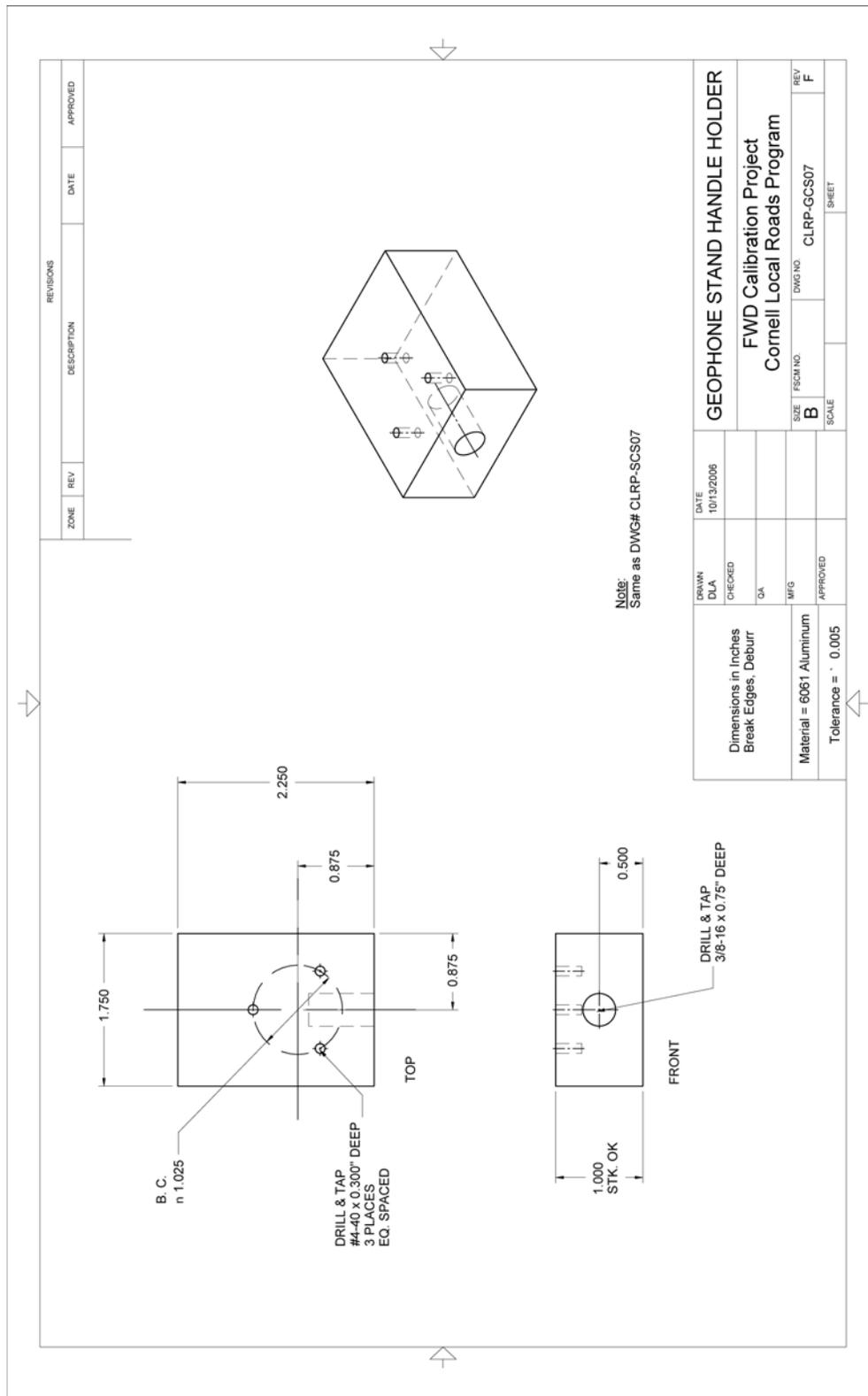
Figure 66. Illustration. CLRP-GCS07 geophone stand handle holder.
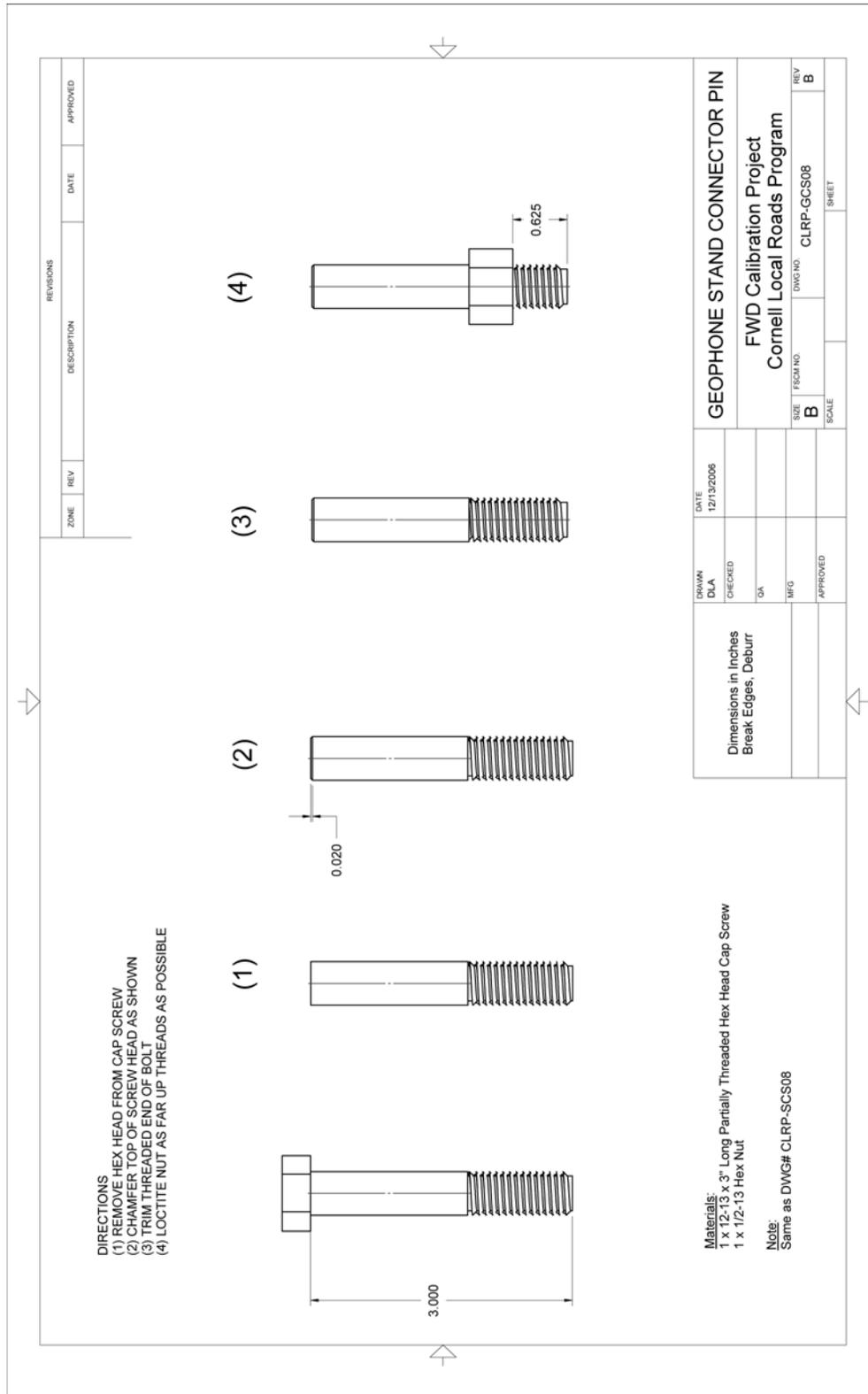
Figure 67. Illustration. CLRP-GCS08 geophone stand connector pin.

SEISMOMETER CALIBRATION STAND
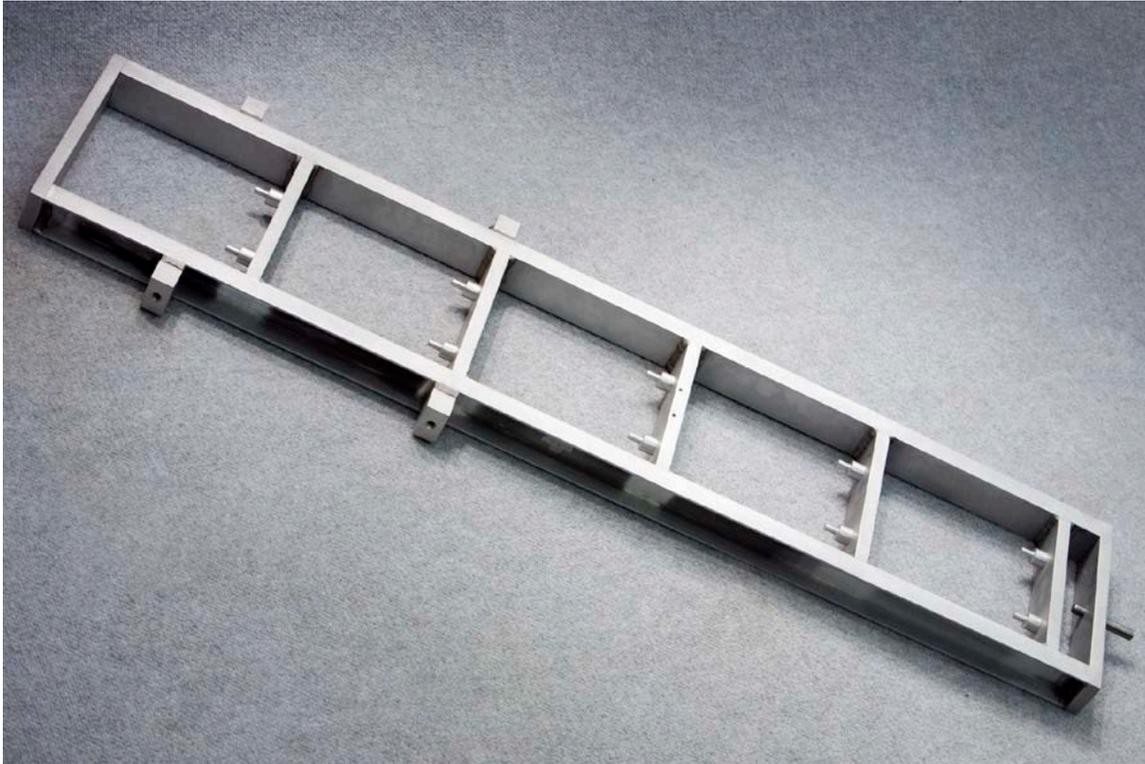
Figure 68. Photo. KUAB seismometer calibration stand.

Table 27. Fabricated parts required for BM-SCS seismometer calibration stand assembly.

Drawing Number	Description	Quantity
CLRP-SCS02	Seismometer stand side rail	2
CLRP-SCS03	Seismometer stand top shelf	1
CLRP-SCS04	Seismometer stand sensor shelf	4
CLRP-SCS05	Seismometer stand standoff	10
CLRP-SCS06	Seismometer stand bottom shelf	1
CLRP-SCS07	Seismometer stand handle holder[1]	4
CLRP-SCS08	Seismometer stand connector pin[2]	1
CLRP-SCS09	Seismometer stand shelf subassembly	4
CLRP-SCS10	Seismometer stand accelerometer shelf	1
CLRP-SCS11	Seismometer stand accelerometer shelf subassembly	1

[1]Identical to CLRP-SCS07.
[2]Identical to CLRP-SCS08.

Table 28. Hardware items required for BM-SCS seismometer calibration stand assembly.

Vendor Part Number	Item	Vendor	Quantity
62385K65	Tapered handle, smooth phenolic, $^3/_8$-inch, 16 x $^1/_2$-inch threaded stud, 1-inch diameter	McMaster-Carr®	2
2198A85	Glass surface-mount bull's-eye level center circle and cross lines, $1^1/_4$-inch base diameter, $^7/_{16}$-inch height	McMaster-Carr®	1
91737A072	18-8 stainless steel fillister head Phillips machine screw 4-40 thread, $^1/_4$-inch length	McMaster-Carr®	3

1 inch = 25.4 mm

Table 29. Vendor contact information for BM-SCS seismometer calibration stand assembly.

Vendor	Web site	Notes
McMaster-Carr®	www.mcmaster.com	See Web site for specific contact information in the "About Us" section.
Incodema	www.incodema.com	Incodema Inc. 407 Cliff Street, Ithaca, NY 14850 607-277-7070

Table 30. Hardware costs for BM-SCS seismometer calibration stand assembly.

Part	Quantity	Supplier	Cost[1]
Materials and machining	1	Incodema	$1425.00
Miscellaneous hardware	1		$30.00

[1]Indicates the cost in February 2009.
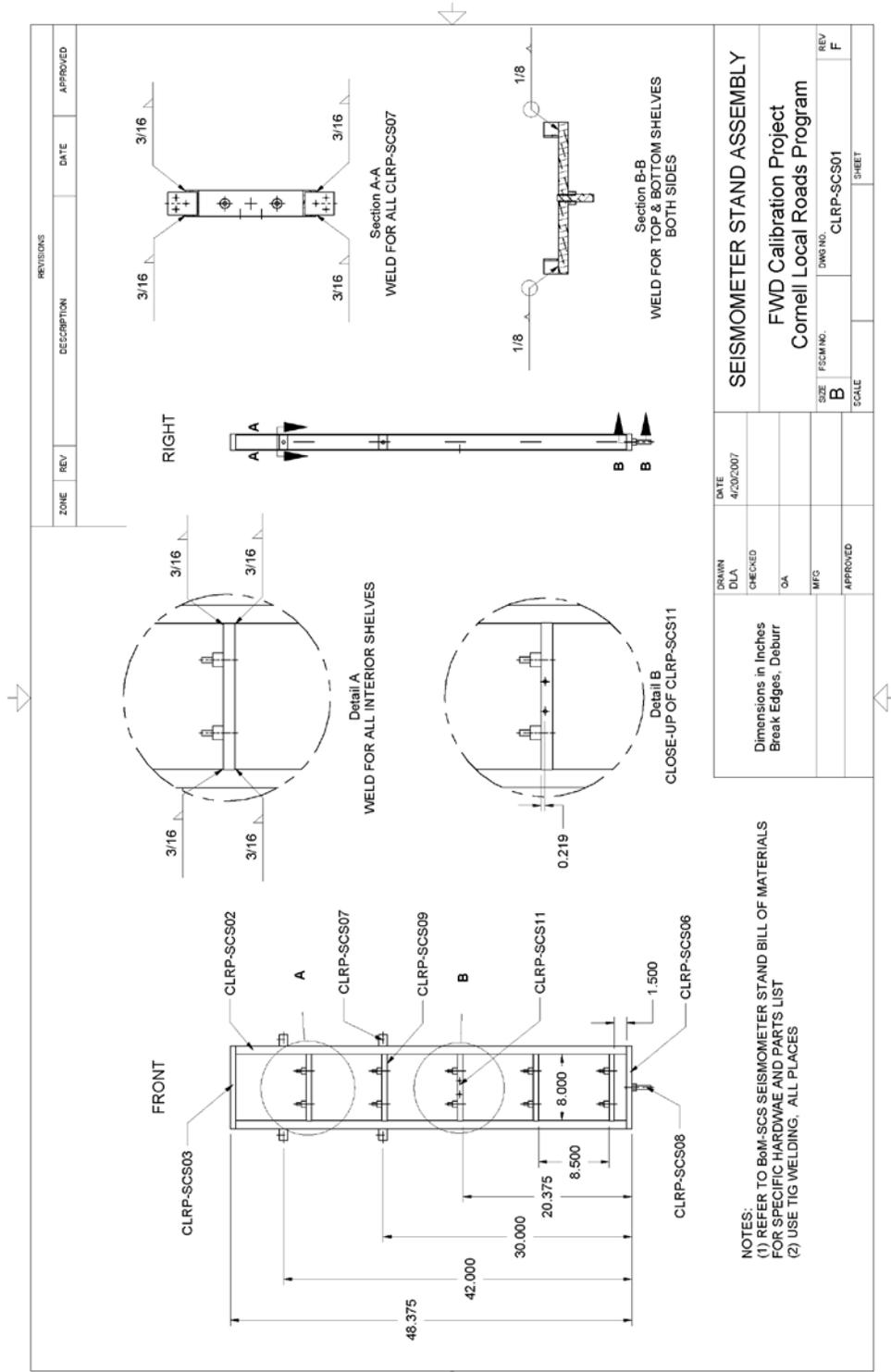
Figure 69. Illustration. CLRP-SCS01 seismometer stand assembly.
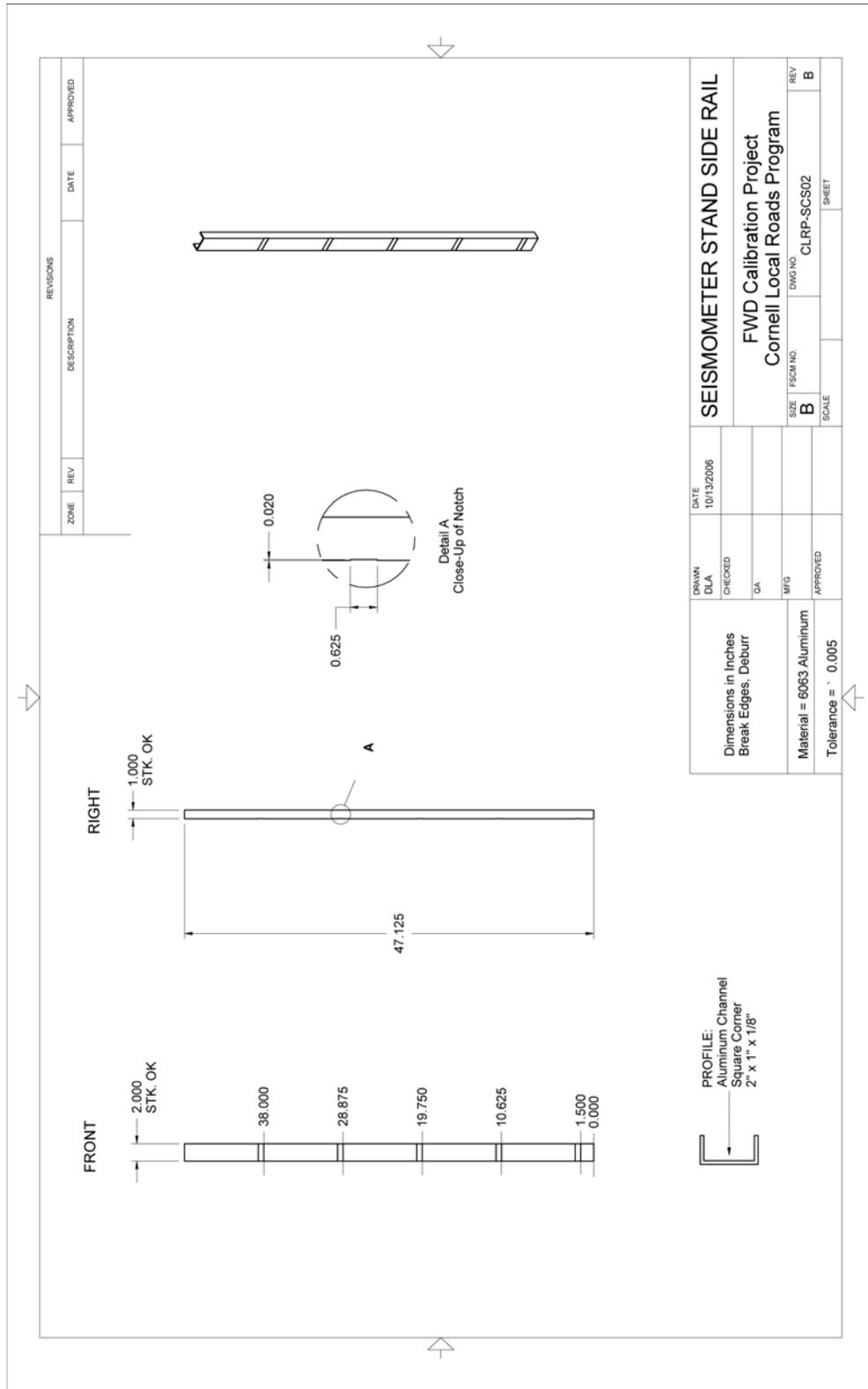
Figure 70. Illustration. CLRP-SCS02 seismometer stand side rail.
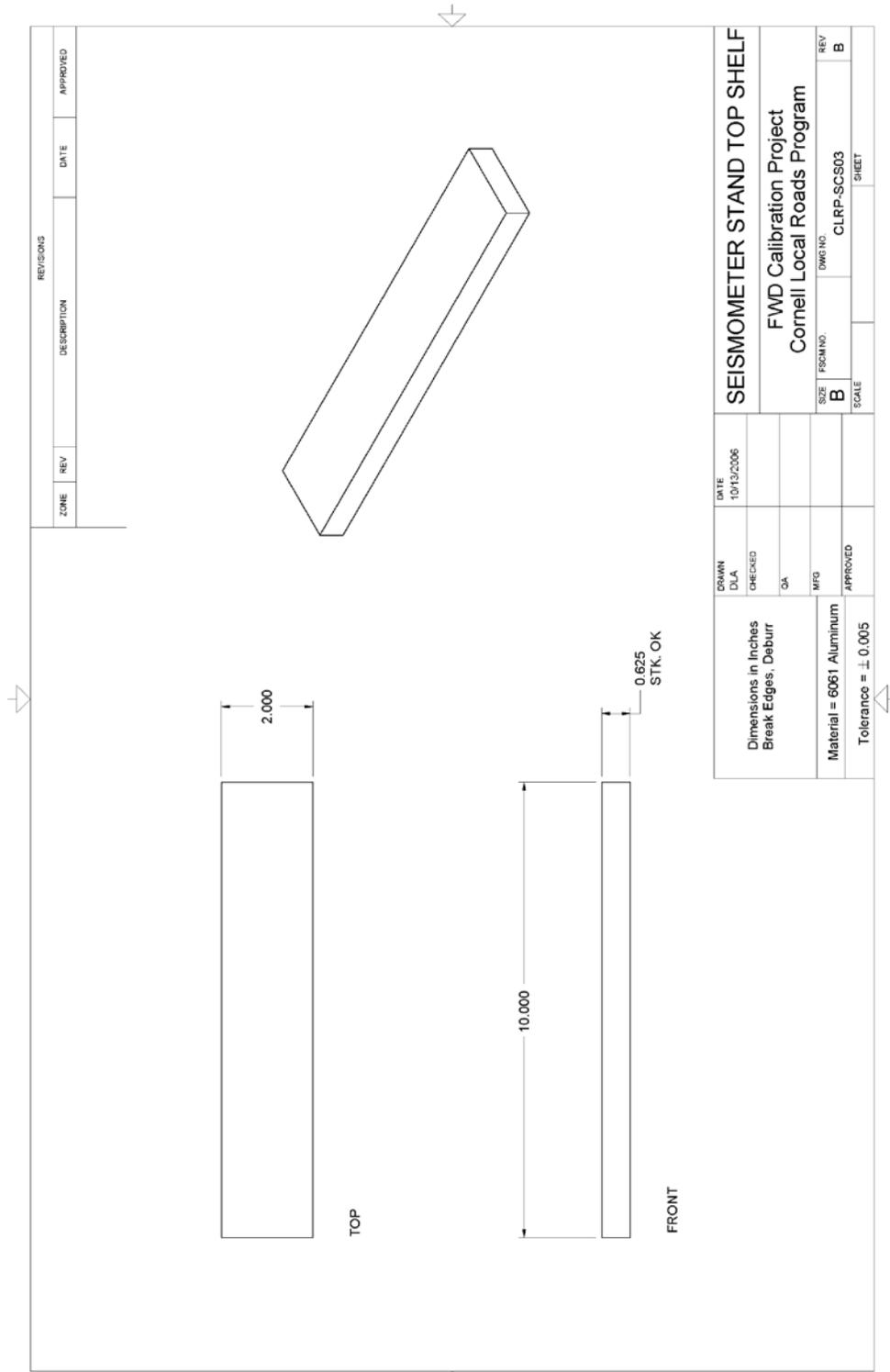
Figure 71. Illustration. CLRP-SCS03 seismometer stand top shelf.
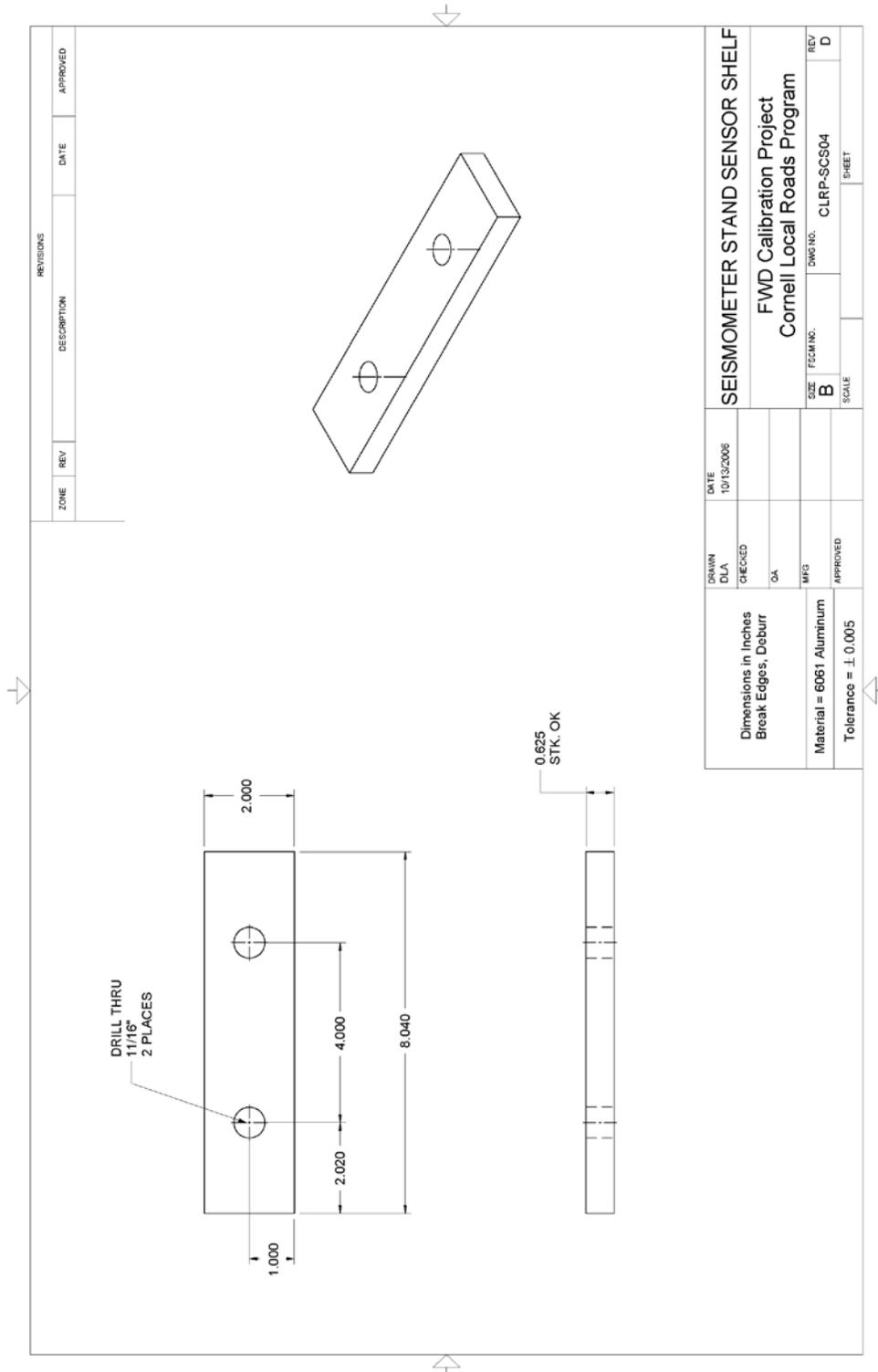
Figure 72. Illustration. CLRP-SCS04 seismometer stand sensor shelf.
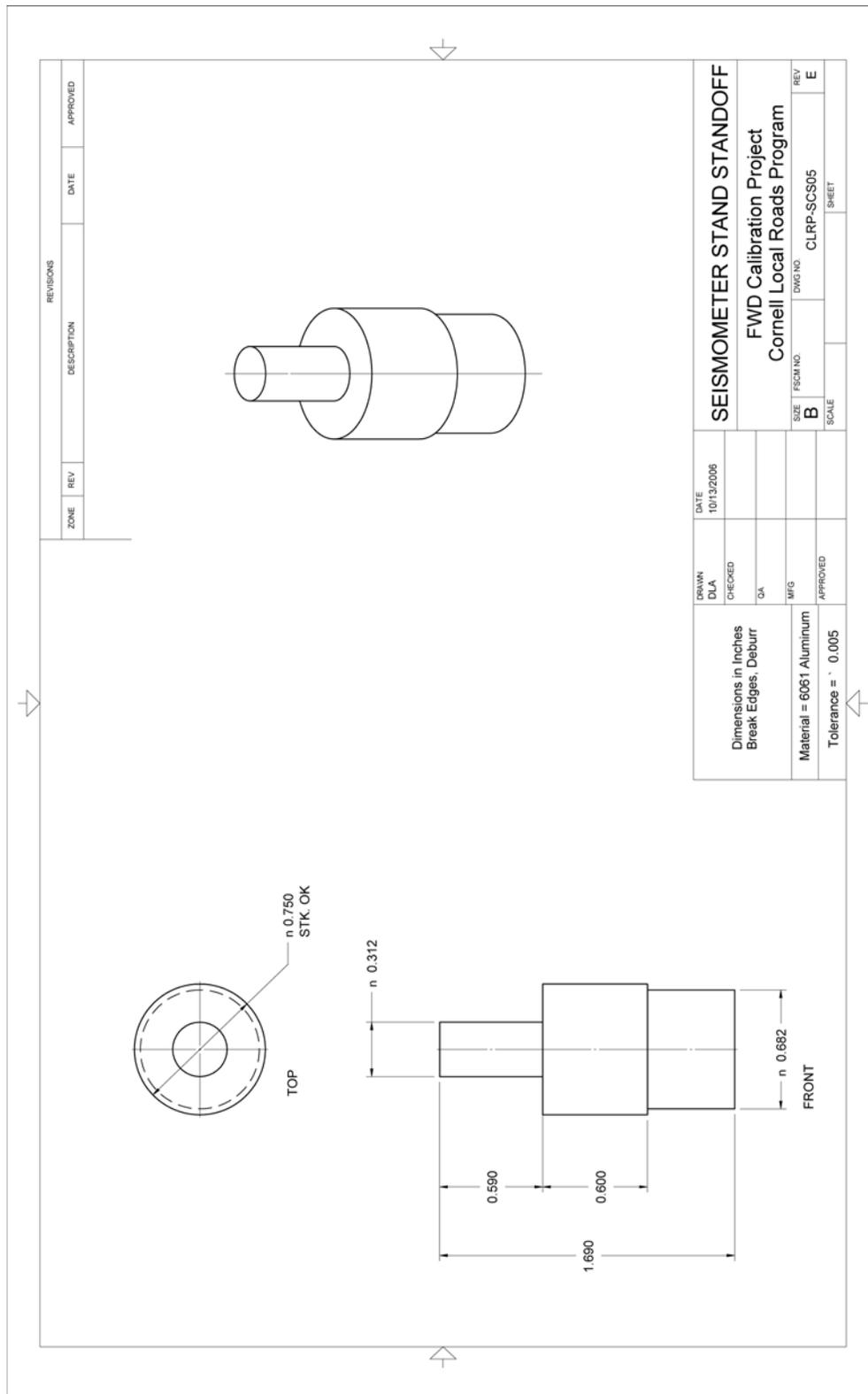
Figure 73. Illustration. CLRP-SCS05 seismometer stand standoff.

Figure 74. Illustration. CLRP-SCS06 seismometer stand bottom shelf.
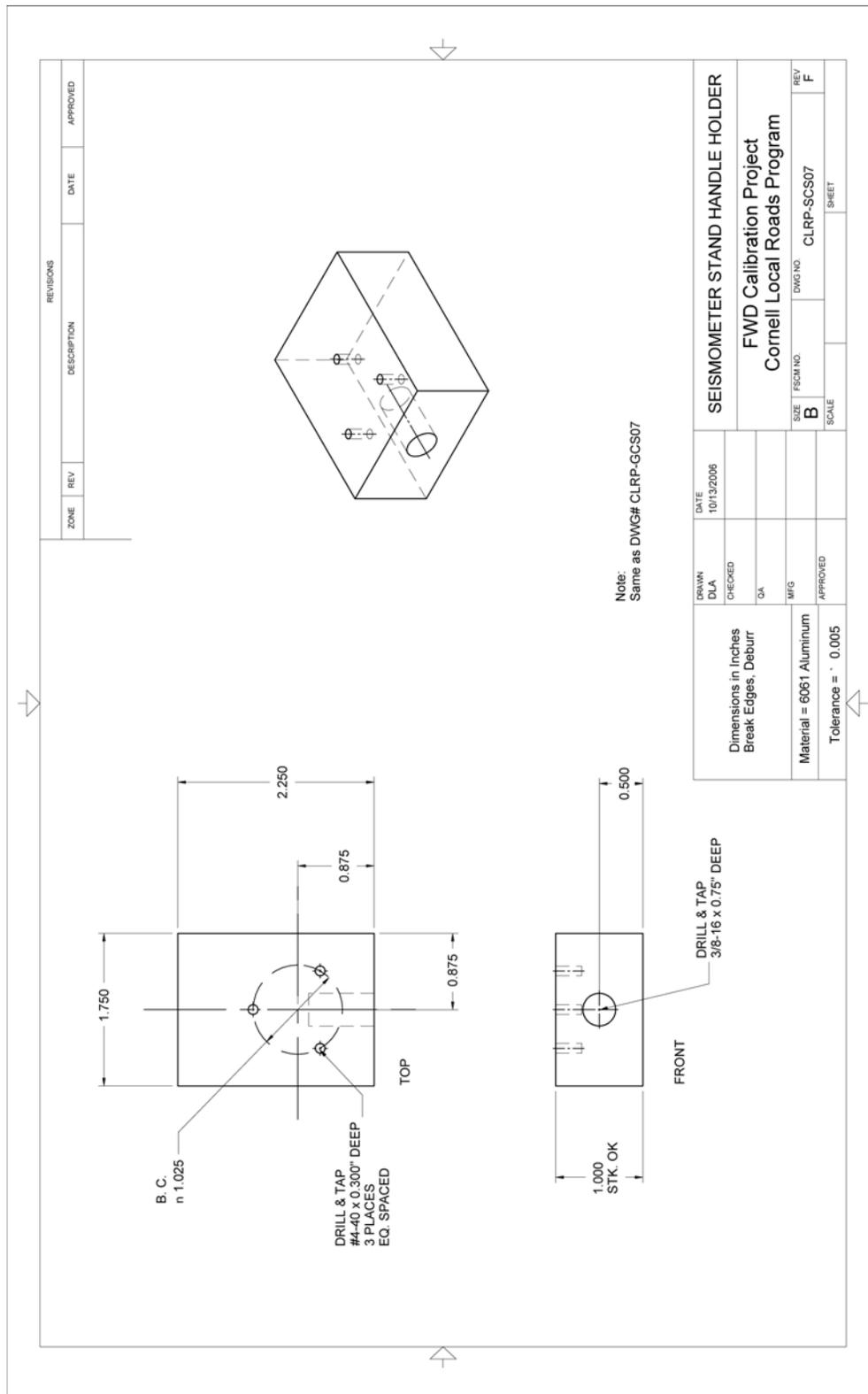
Figure 75. Illustration. CLRP-SCS07 seismometer stand handle holder.
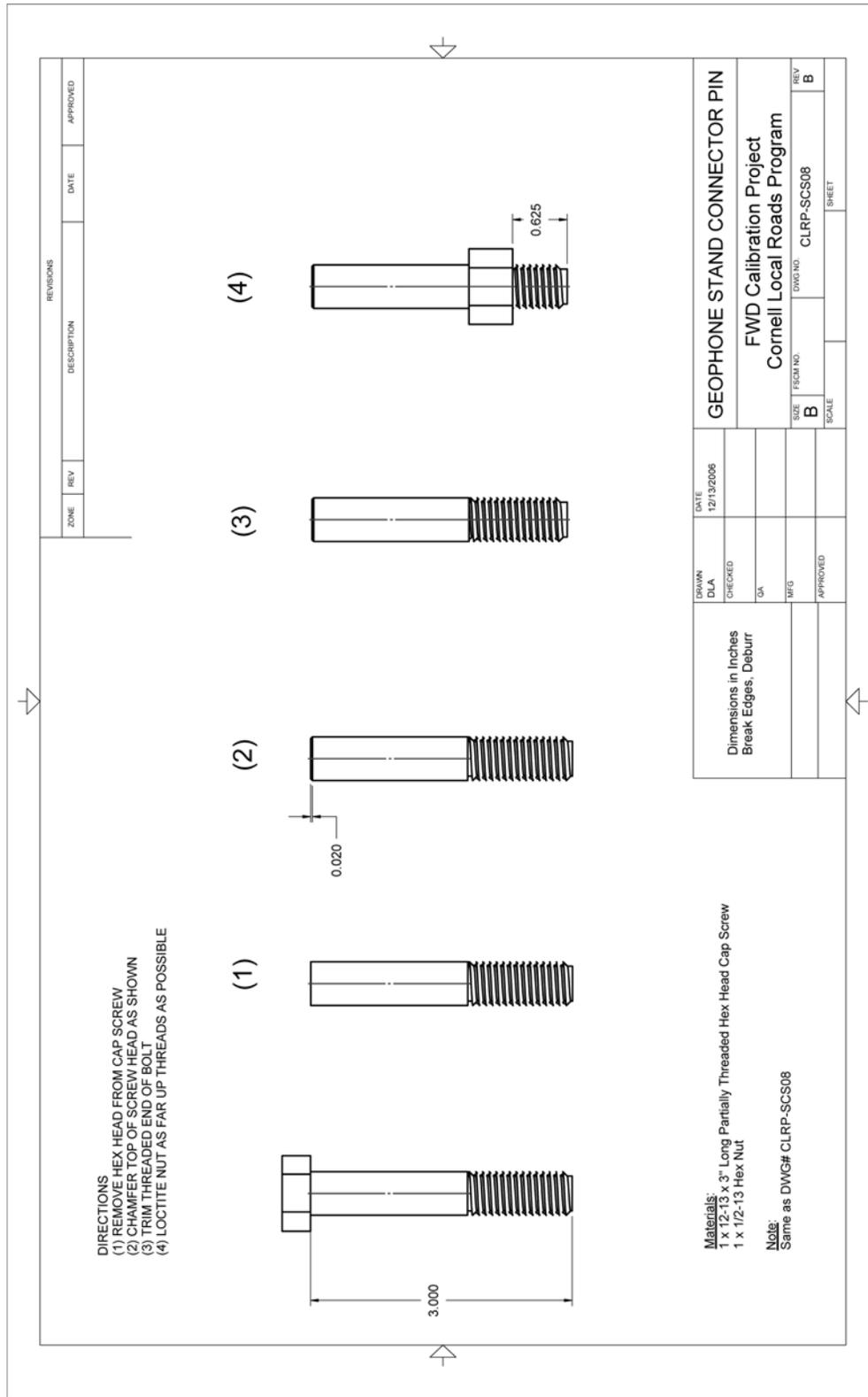
Figure 76. Illustration. CLRP-SCS08 seismometer stand connector pin.
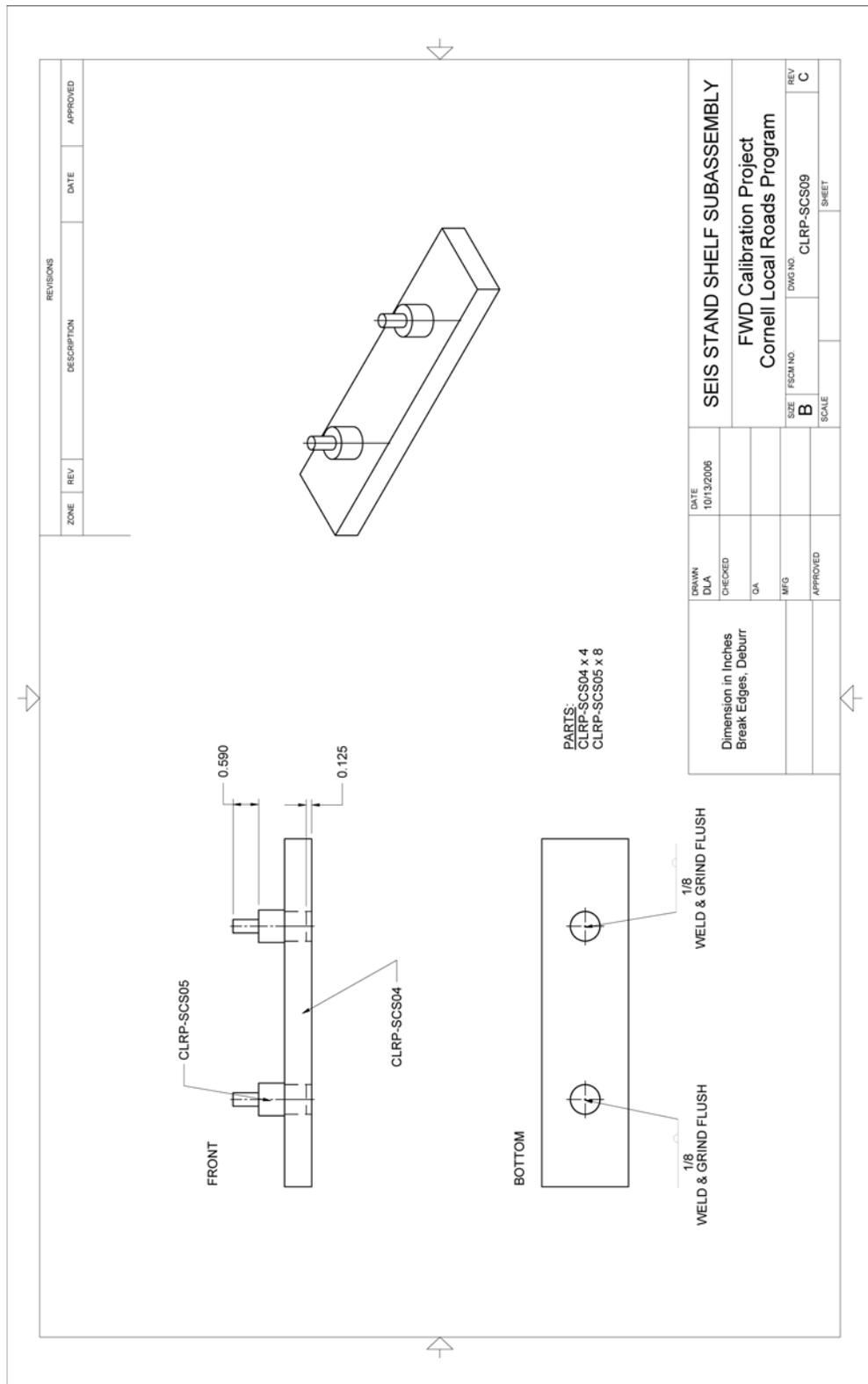
Figure 77. Illustration. CLRP-SCS09 seismometer stand shelf subassembly.
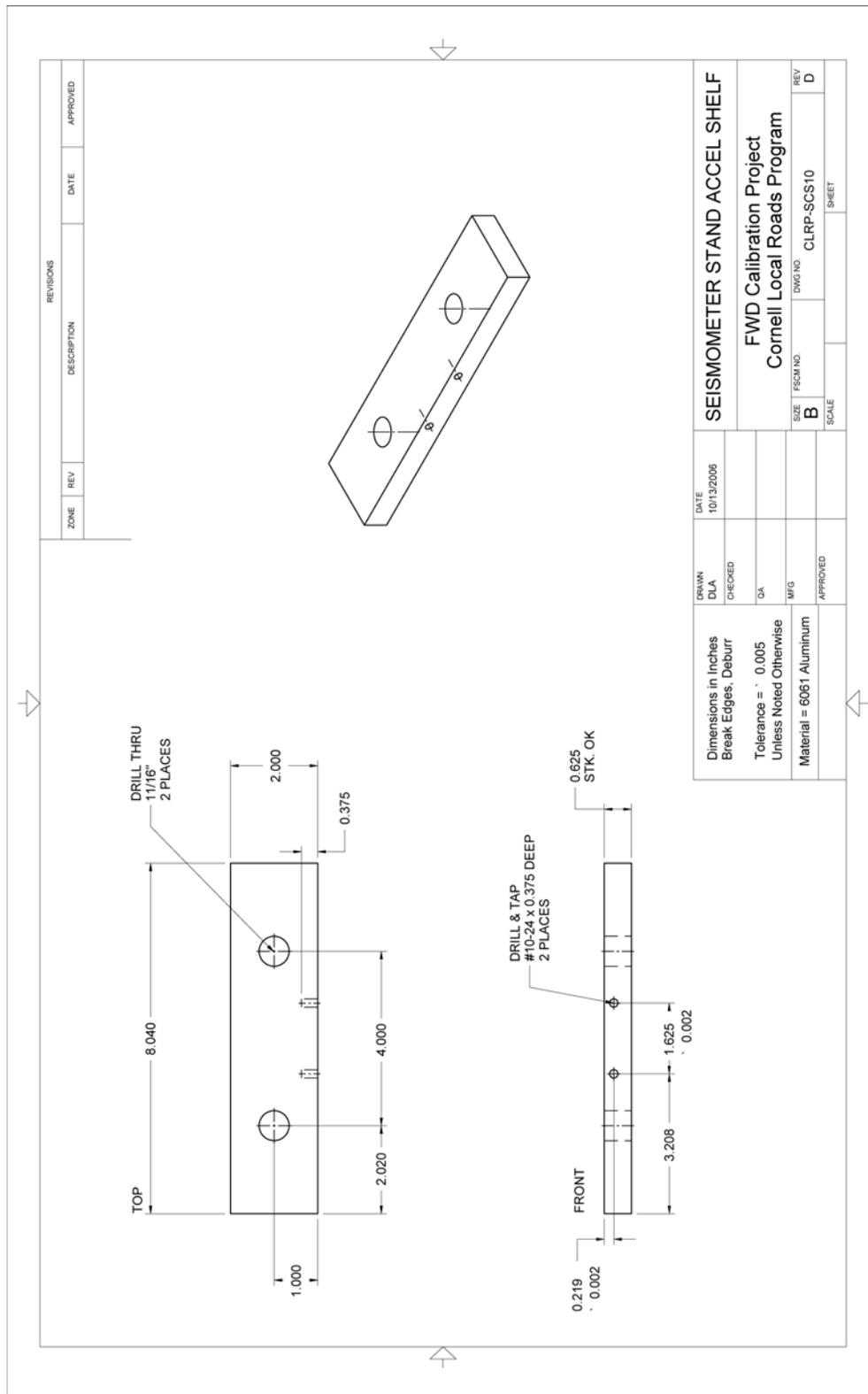
Figure 78. Illustration. CLRP-SCS10 seismometer stand accelerometer shelf.
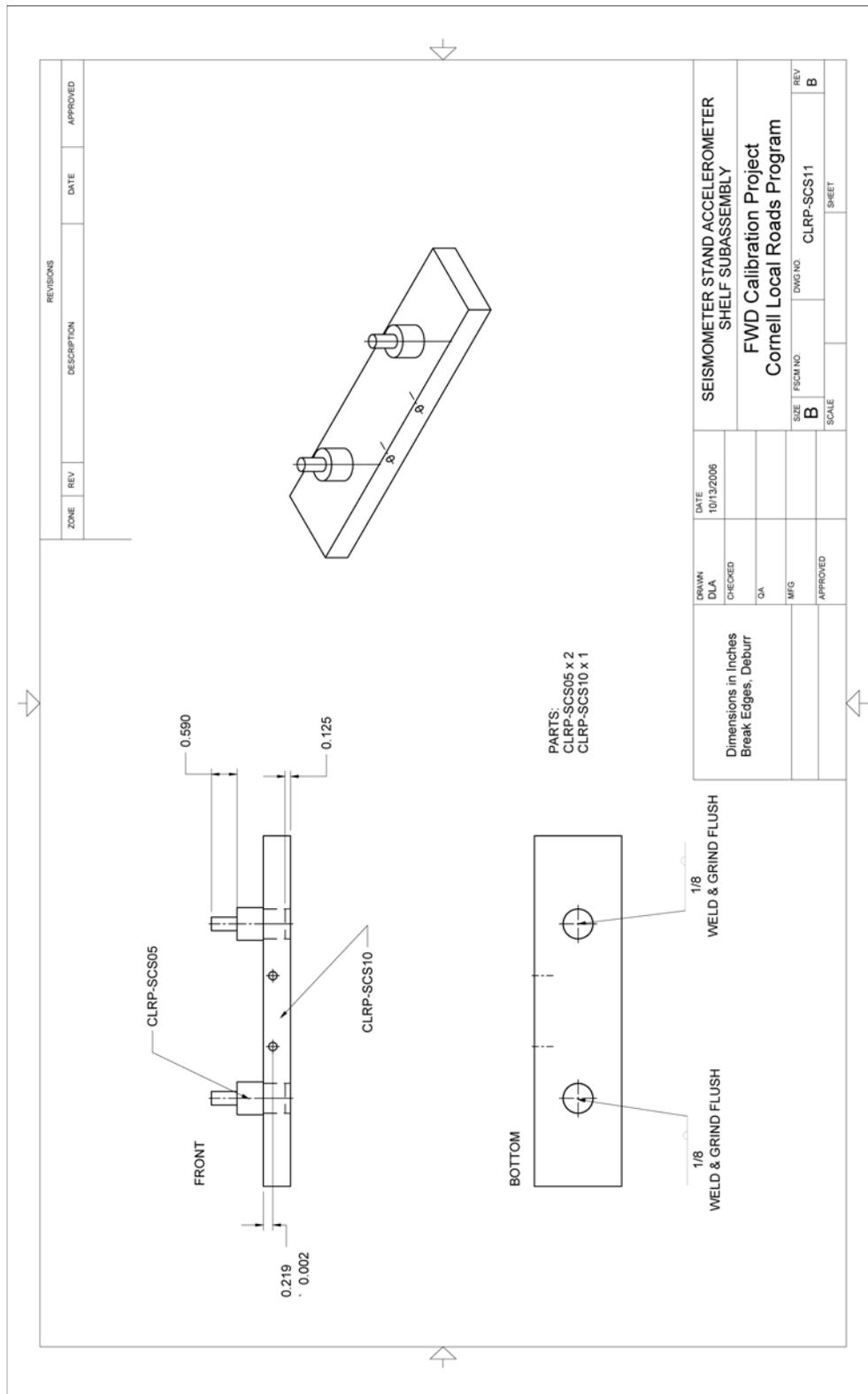
Figure 79. Illustration. CLRP-SCS11 seismometer stand accelerometer shelf subassembly.

GEOPHONE ADAPTERS

Table 31. Fabricated parts for use as BM-GA geophone adapters.

Drawing Number	Description	Quantity
CLRP-GA02	Carl Bro adapter	10
CLRP-GA03	JILS adapter	10
CLRP-GA04	KUAB adapter	10

Table 32. Hardware items required for use of BM-GA geophone adapters.

Vendor Part Number	Item	Vendor	Quantity
90126A036	Society of Automotive Engineers flat washer, zinc-plated steel, $^3/_4$-inch size, $^{13}/_{16}$-inch inside diameter, $1^1/_2$-inch outside diameter, 0.108-inch minimum thickness	McMaster-Carr®	10
94744A273	Flat washer, zinc-plated steel, $^3/_8$-inch screw size, 0.406-inch inside diameter, $1^1/_4$-inch outside diameter, 0.090–0.112 inches thick	McMaster-Carr®	10
92865A212	Hex head cap screw, grade 5 zinc-plated steel, $^3/_8$-inch 24 Thread, $^5/_8$ inches long, fully threaded	McMaster-Carr®	10
KK-GA02	Knurled knob, steel with black oxide finish, M8 x 1 mm threaded through hole	Morton Machine Works	10
KK-GA03	Knurled knob, steel with black oxide finish, $^3/_8$-24 threaded through hole	Morton Machine Works	10
6063K19	Metric steel two-piece clamp on shaft collar 20-mm bore, 40-mm outside diameter, 15-mm width	McMaster-Carr®	10
5685K26	Encased ceramic round magnet W/hole $1^{13}/_{32}$-inch diameter, $^9/_{32}$-inch thick, 20 pull lb	McMaster-Carr®	10
6121K93	Steel round knurled-rim knob solid hub, 1.5-inch diameter	McMaster-Carr®	10
92949A246	18-8 SS button head socket cap screw 10-24 thread, $^7/_8$-inch length	McMaster-Carr®	10
90730A011	18-8 SS undersized machine screw hex nut 10-24 screw size, $^5/_{16}$-inch width, $^7/_{64}$-inch height	McMaster-Carr®	10

1 inch = 25.4 mm

Table 33. Vendor contadct information for BM-GA geophone adapters.

Vendor	Web site	Notes
McMaster-Carr®	http://www.mcmaster.com	See Web site for area specific contact information located in the "About Us" section.
Morton Machine Works	http://www.mortonmachine.com	125 Gearhart St, PO Box 97 Millersburg, PA 17061 800-441-2751

Table 34. Hardware costs for BM-GA geophone adapters.

Part	Quantity	Cost[1]	Notes
Dynatest®/JILS adapter	10	$50.00	Price for all 10 adapters including bolts and washers.
Carl Bro adapter	10	$50.00	Price for all 10 adapters.
KUAB Geophone adapter	10	$150.00	Price for all 10 adapters including collars, magnets, knobs, washers, bolts, and nuts.

[1]Indicates the cost in February 2009.
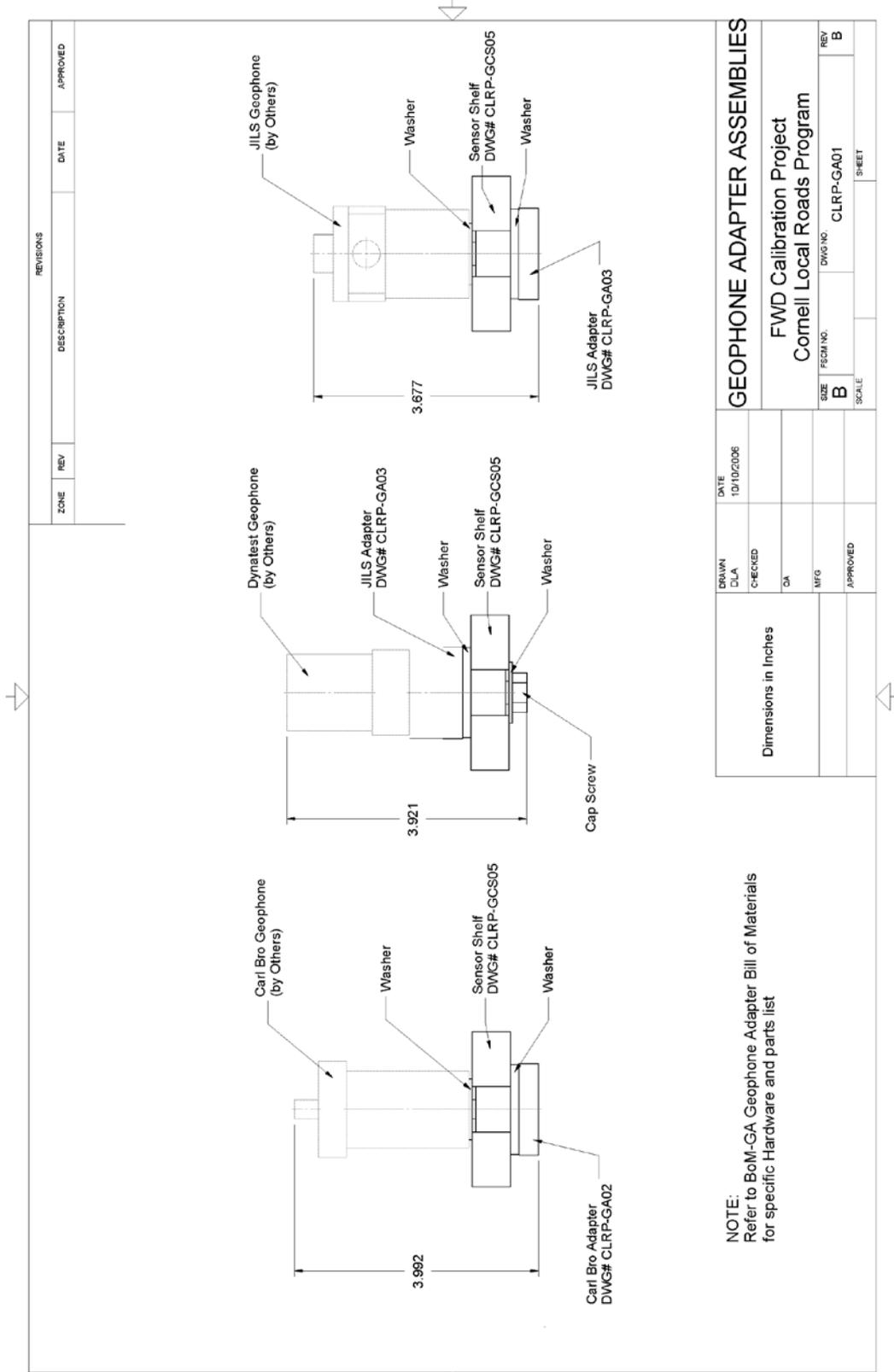
Figure 80. Illustration. CLRP-GA01 geophone adapter assemblies.
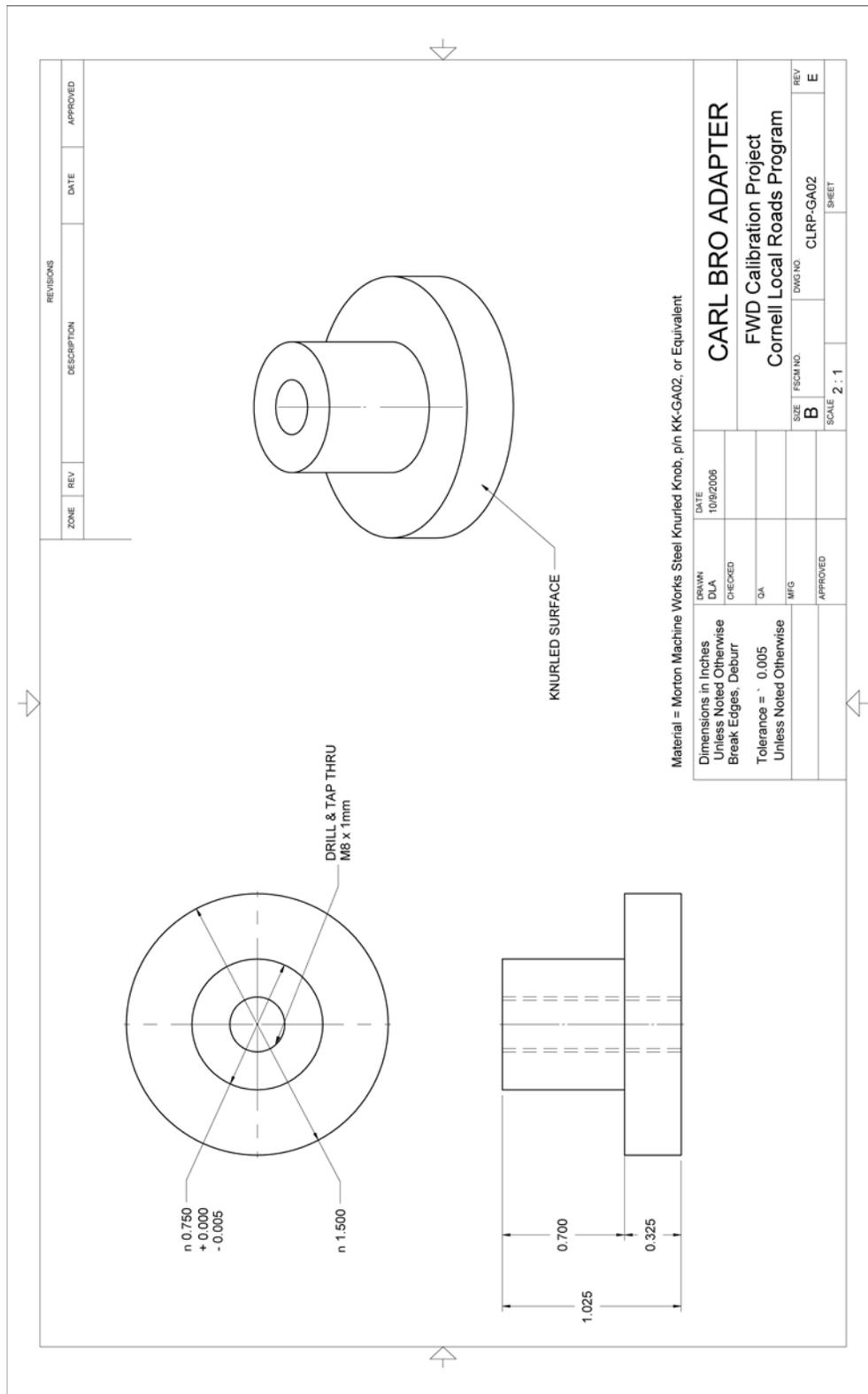
Figure 81. Illustration. CLRP-GA02 Carl Bro adapter.
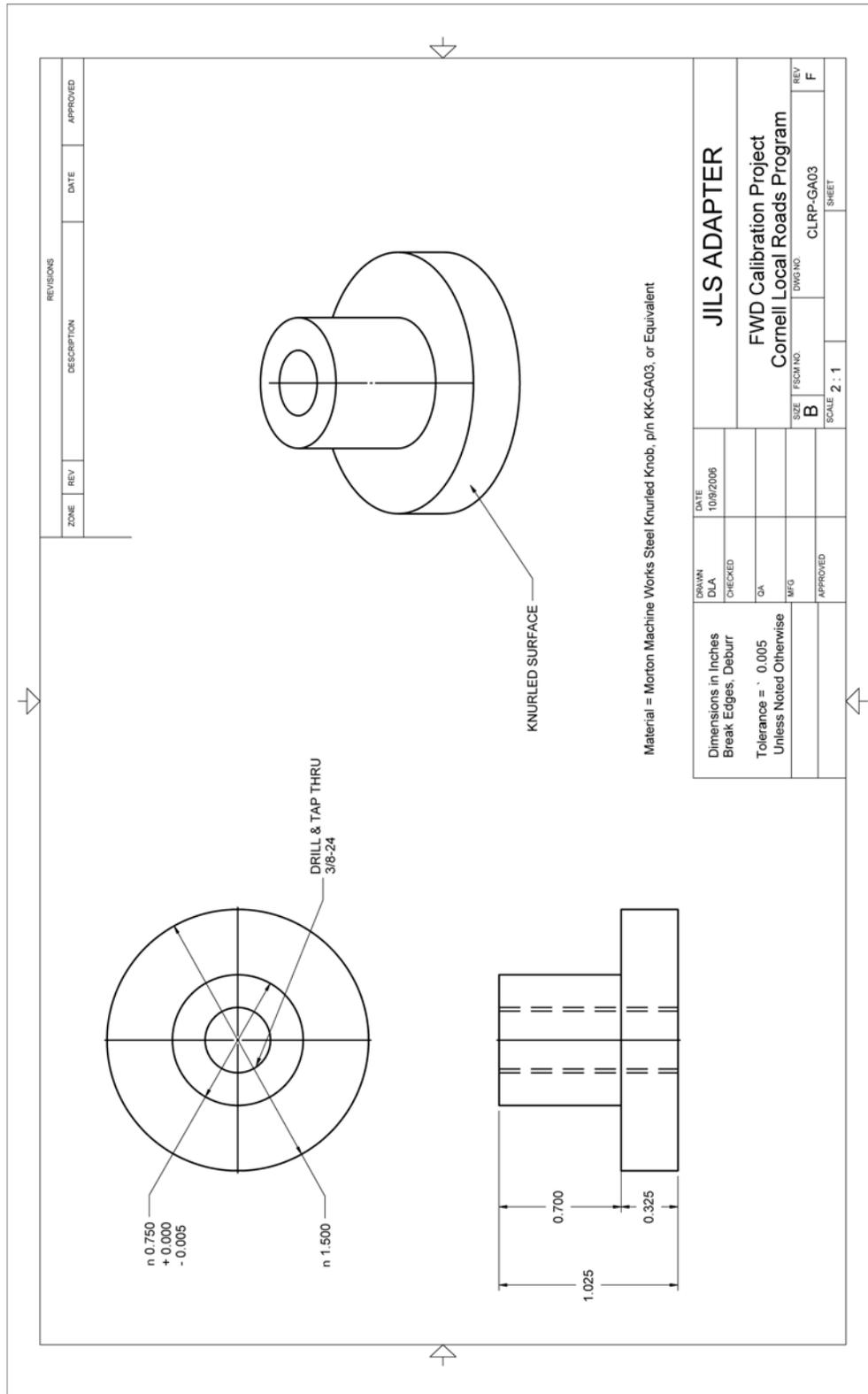
Figure 82. Illustration. CLRP-GA03 JILS adapter.
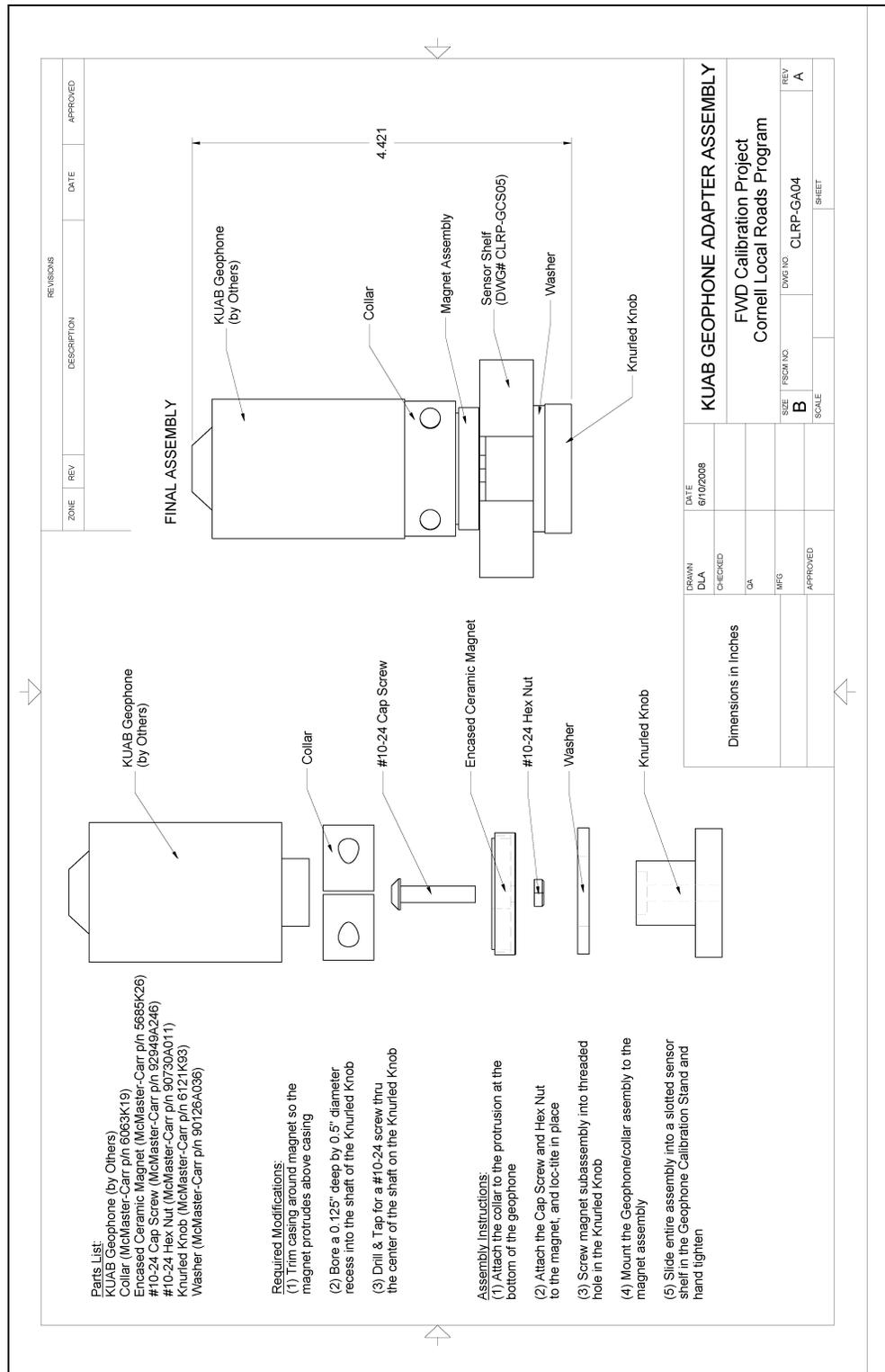
Figure 83. Illustration. CLRP-GA04 KUAB adapter.

REFERENCE LOAD CELL

For a photo of the reference load cell, see figure 104.

Table 35. Fabricated parts for the BM-LC reference load cell.

Drawing Number	Description	Quantity
CLRP-LC02	Reference load cell body	1
CLRP-LC03	Base plate	1
CLRP-LC04	Measuring link	3
CLRP-LC05	Cover plate	1
CLRP-LC06	Foot	3
CLRP-LC07	Guide finger	3
CLRP-LC08	Interior connector wiring	1
CLRP-LC09	Strain gauge layout	3
CLRP-LC10	Bridge wiring detail	1

Table 36. Equipment and hardware items required for the BM-LC reference load cell.

Vendor Part Number	Item	Vendor	Quantity
92196A327	Socket head cap screw, 18-8 SS, $\frac{1}{4}$-inch 28 thread, $1\frac{1}{4}$-inch length	McMaster-Carr®	6
92196A323	Socket head cap screw, 18-8 SS, $\frac{1}{4}$-inch 28 thread, $\frac{7}{8}$-inch length	McMaster-Carr®	6
92210A337	Flat head socket cap screw, 18-8 SS, $\frac{1}{4}$-inch 28 thread, $1\frac{1}{4}$-inch length	McMaster-Carr®	6
91737A072	Fillister head Phillips machine screw, 18-8 SS, #4-40 thread, $\frac{1}{4}$-inch length	McMaster-Carr®	4
654-MS3102A14S-5P	Amphenol box mount receptacle, MS3102A-14S-5P	Mouser Electronics	1
N2A-13-S054Y-350	Transducer-class strain gauges, general purpose 90-degree rosette, $\frac{1}{8}$-inch gauge length, 350 Ω resistance	Vishay Micro-Measurements	12

1 inch = 25.4 mm

Table 37. Vendor contact information for the BM-LC reference load cell.

Vendor	Web site	Notes
McMaster-Carr®	http://www.mcmaster.com	See Web site for specific contact information located in the "About Us" section.
Mouser Electronics	http://www.mouser.com	See Web site for specific contact information located in the "Contact Us" section.
Vishay Micro-Measurements	http://www.vishay.com	See Web site for specific contact information located in the "Sales Representatives" section.

Note: A complete reference load cell assembly, cable, and case can be purchased from Half-Space Engineering, 6055 Quaking Aspen Road, Reno NV, 89510 (pete@half-space.com). Cost depends on what additional hardware is needed (signal conditioner, data acquisition board, etc.).
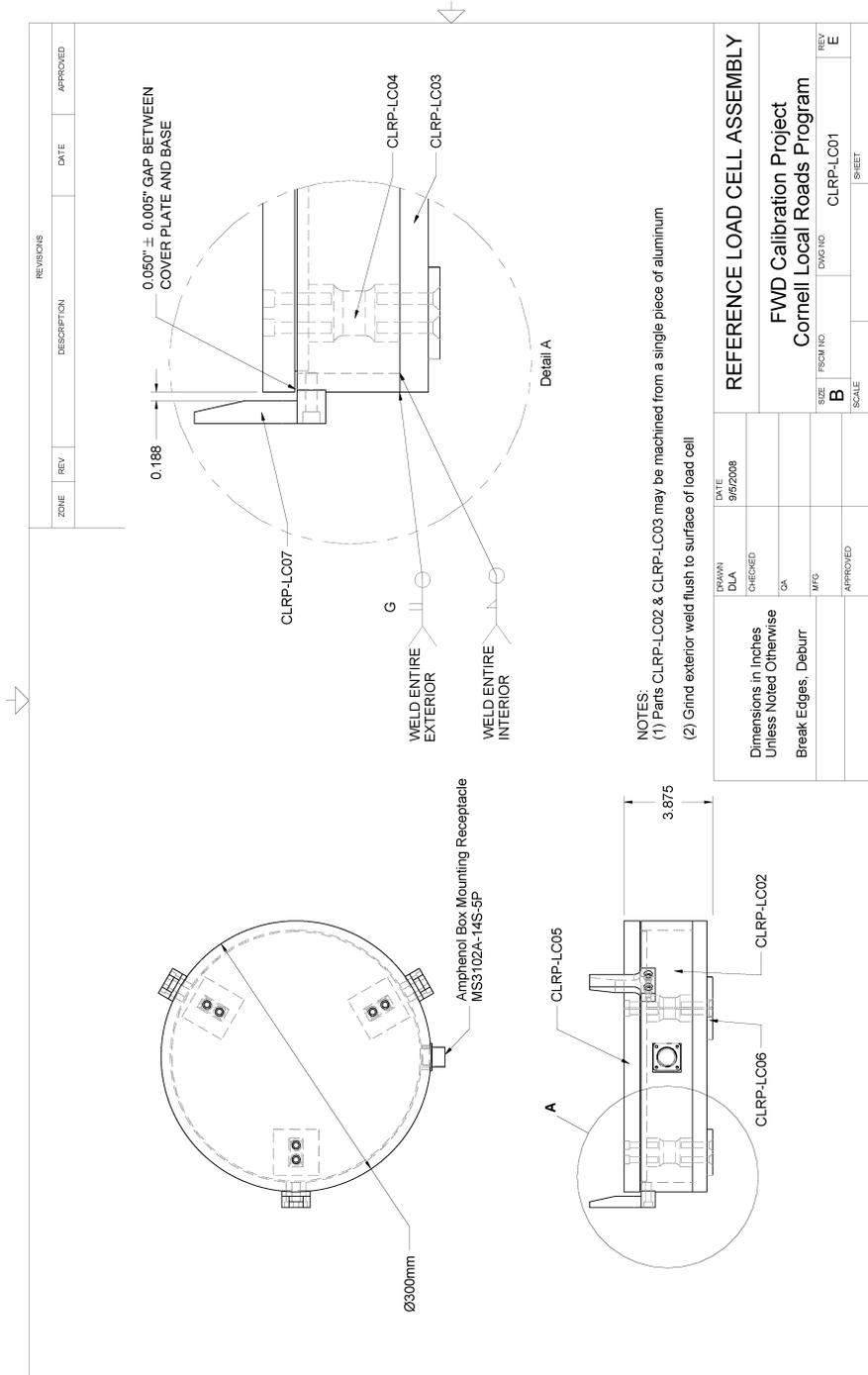
Figure 84. Illustration. CLRP-LC01 load cell assembly.
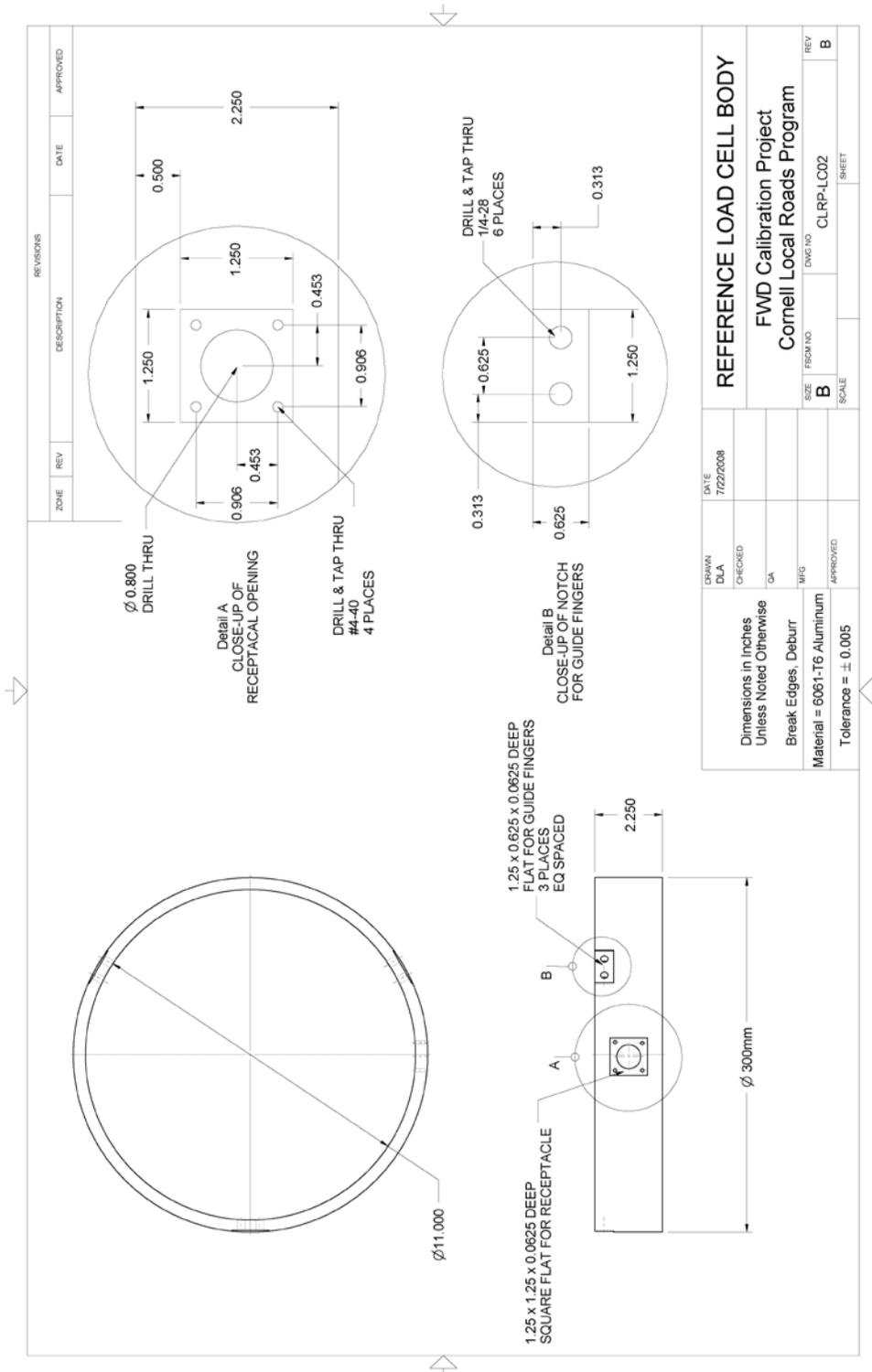
Figure 85. Illustration. CLRP-LC02 load cell body.
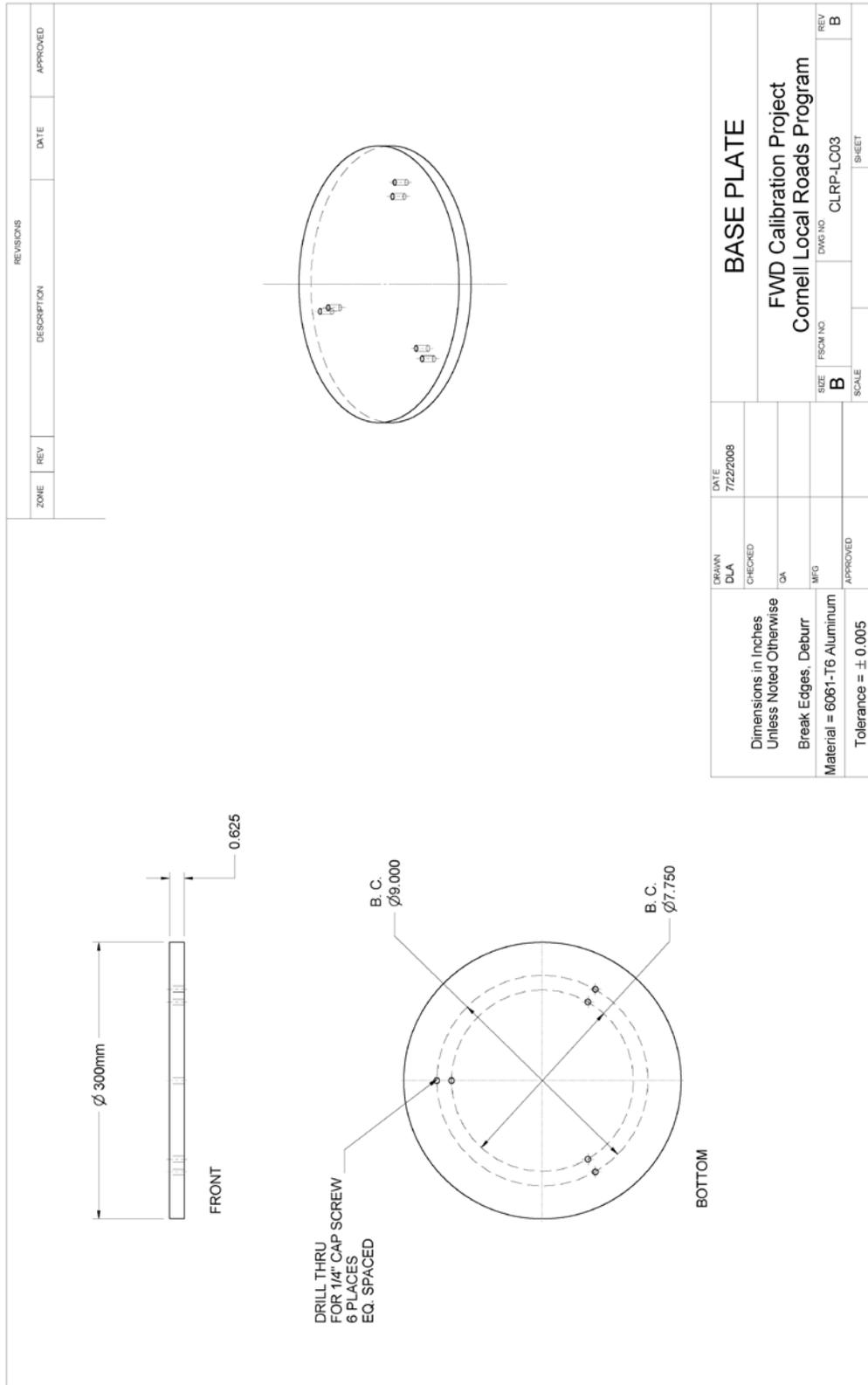
Figure 86. Illustration. CLRP-LC03 base plate.
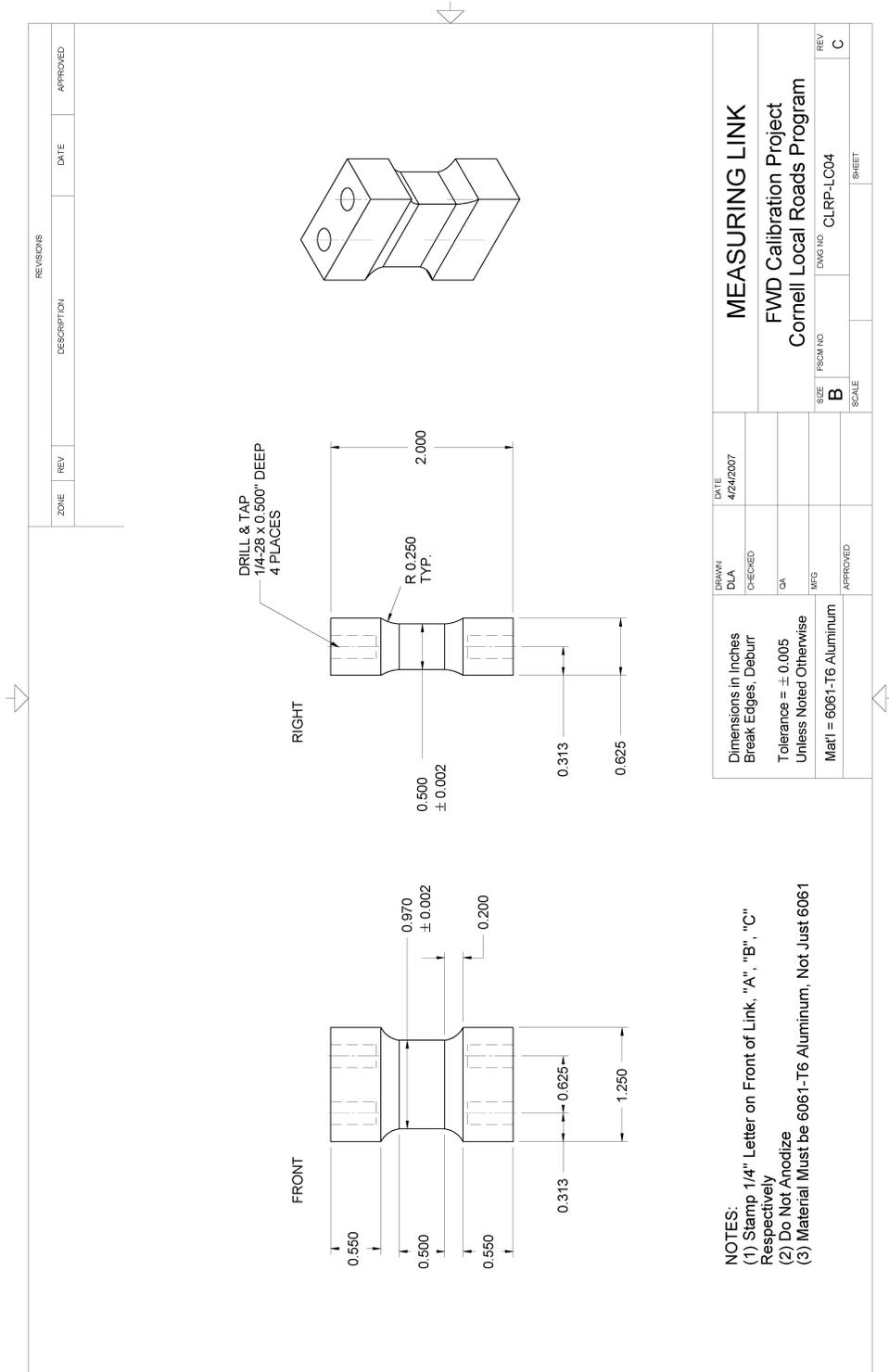
Figure 87. Illustration. CLRP-LC04 measuring link.
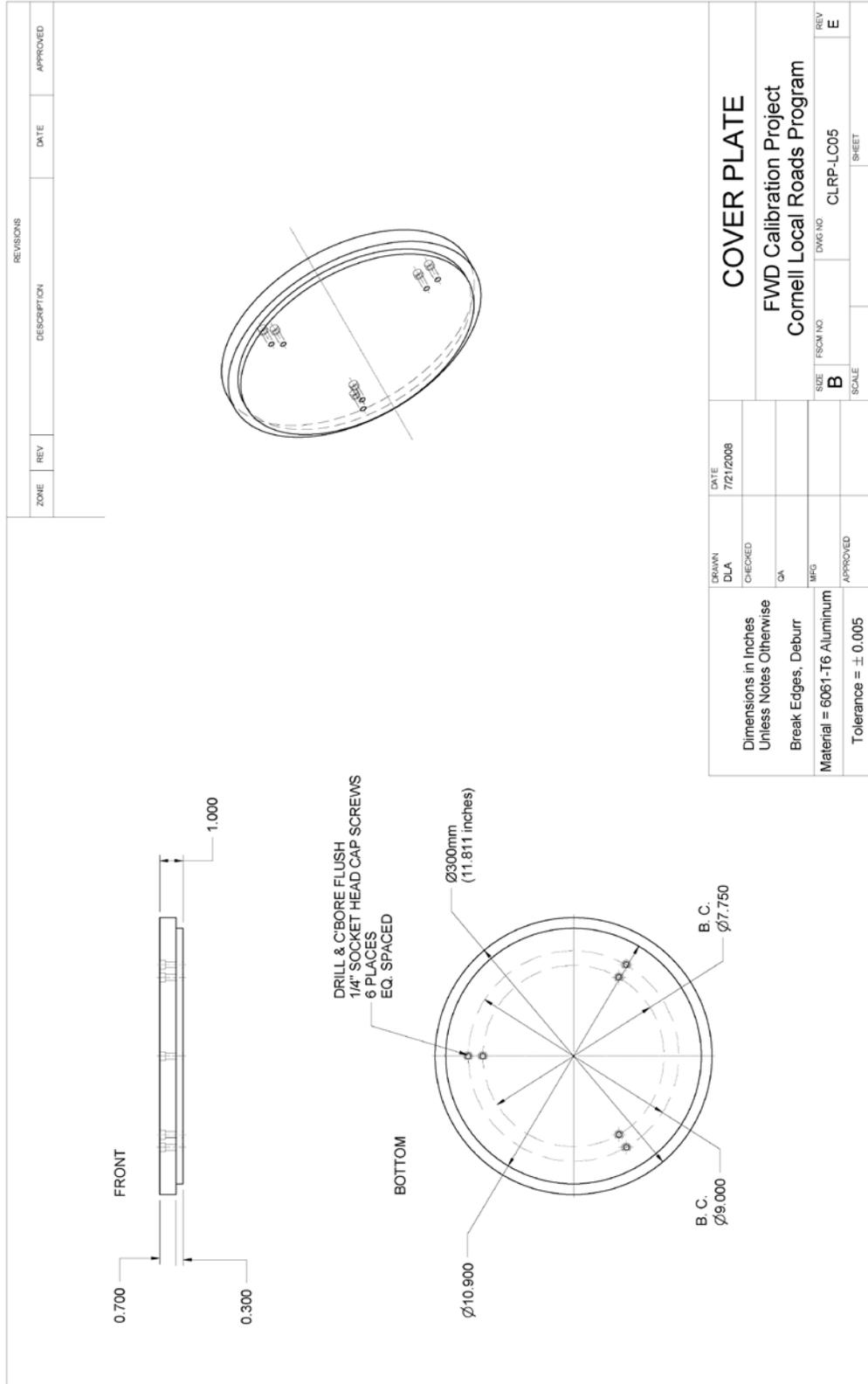
Figure 88. Illustration. CLRP-LC05 cover plate.

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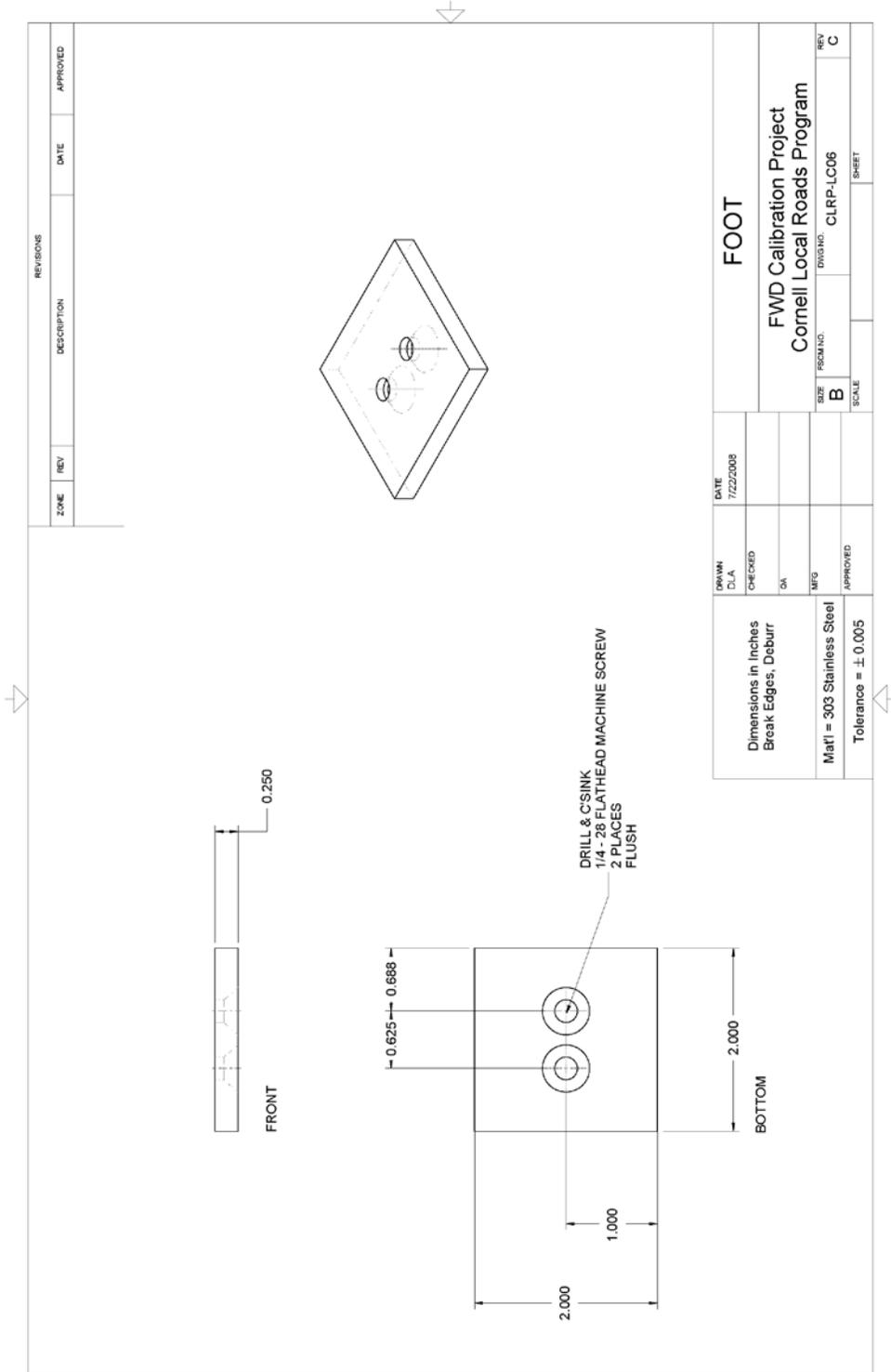
Figure 89. Illustration. CLRP-LC06 foot.
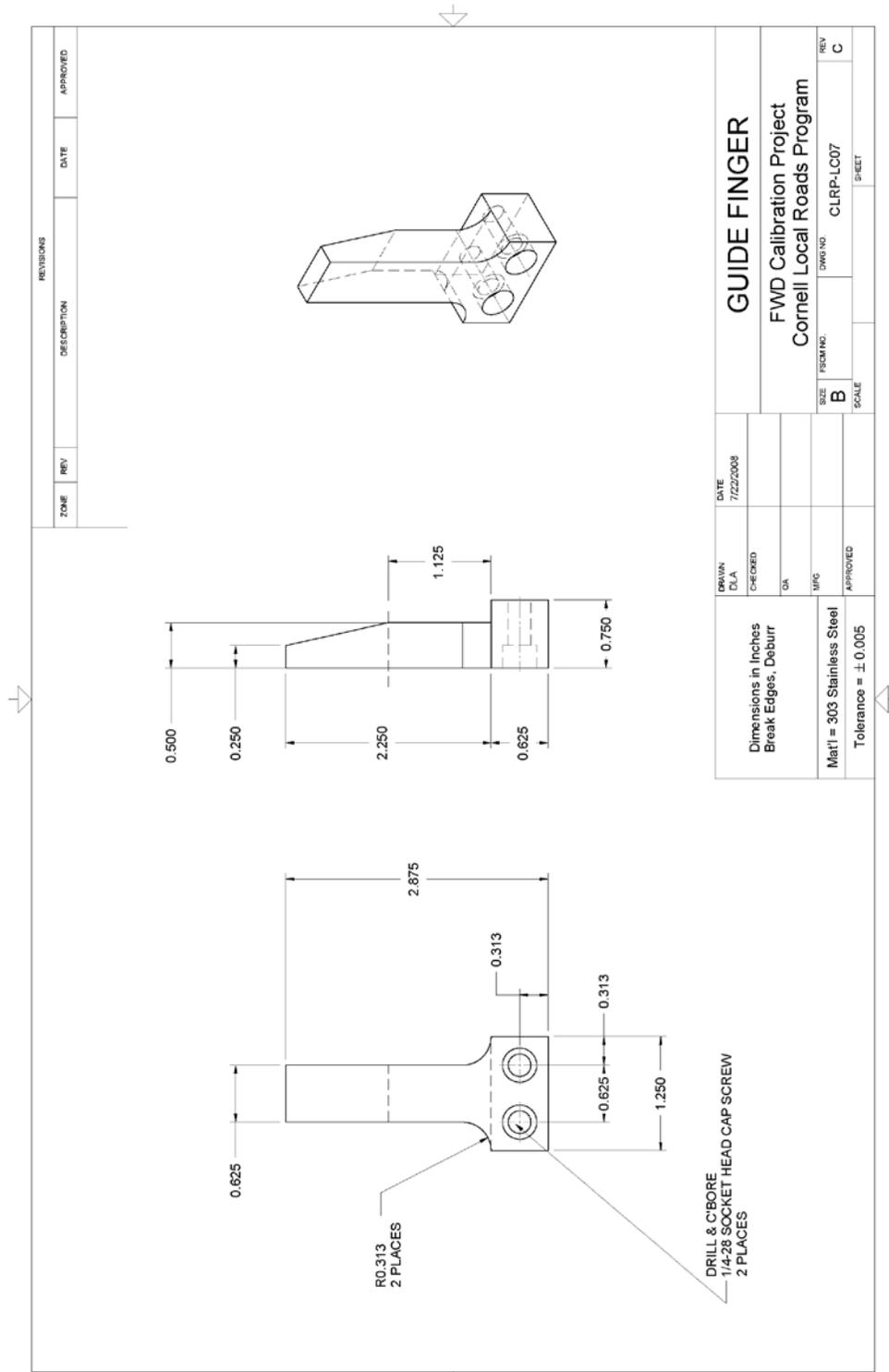
Figure 90. Illustration. CLRP-LC07 guide fingers.
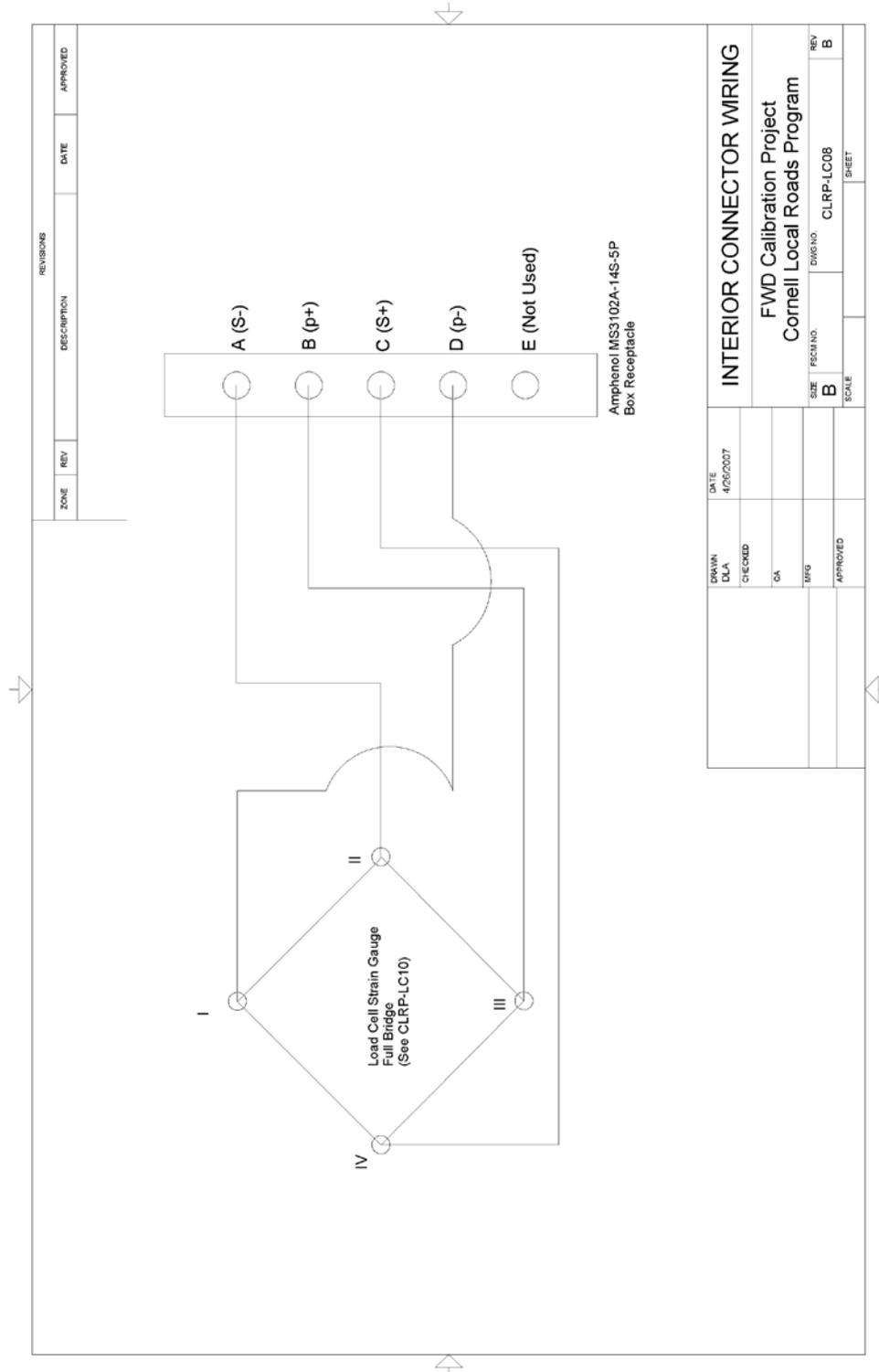
Figure 91. Illustration. CLRP-LC08 interior connector wiring.
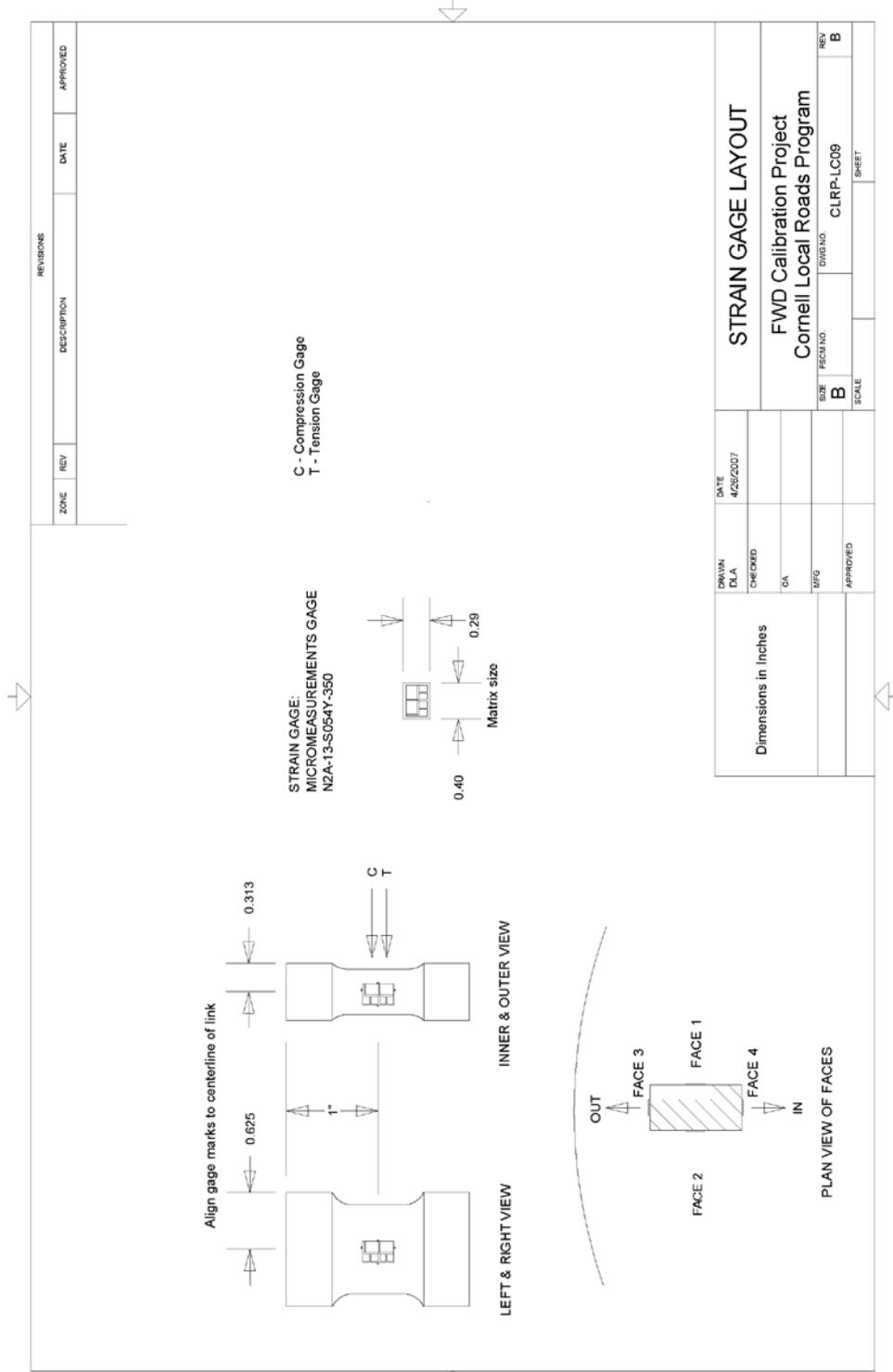
Figure 92. Illustration. CLRP-LC09 strain gauge layout.
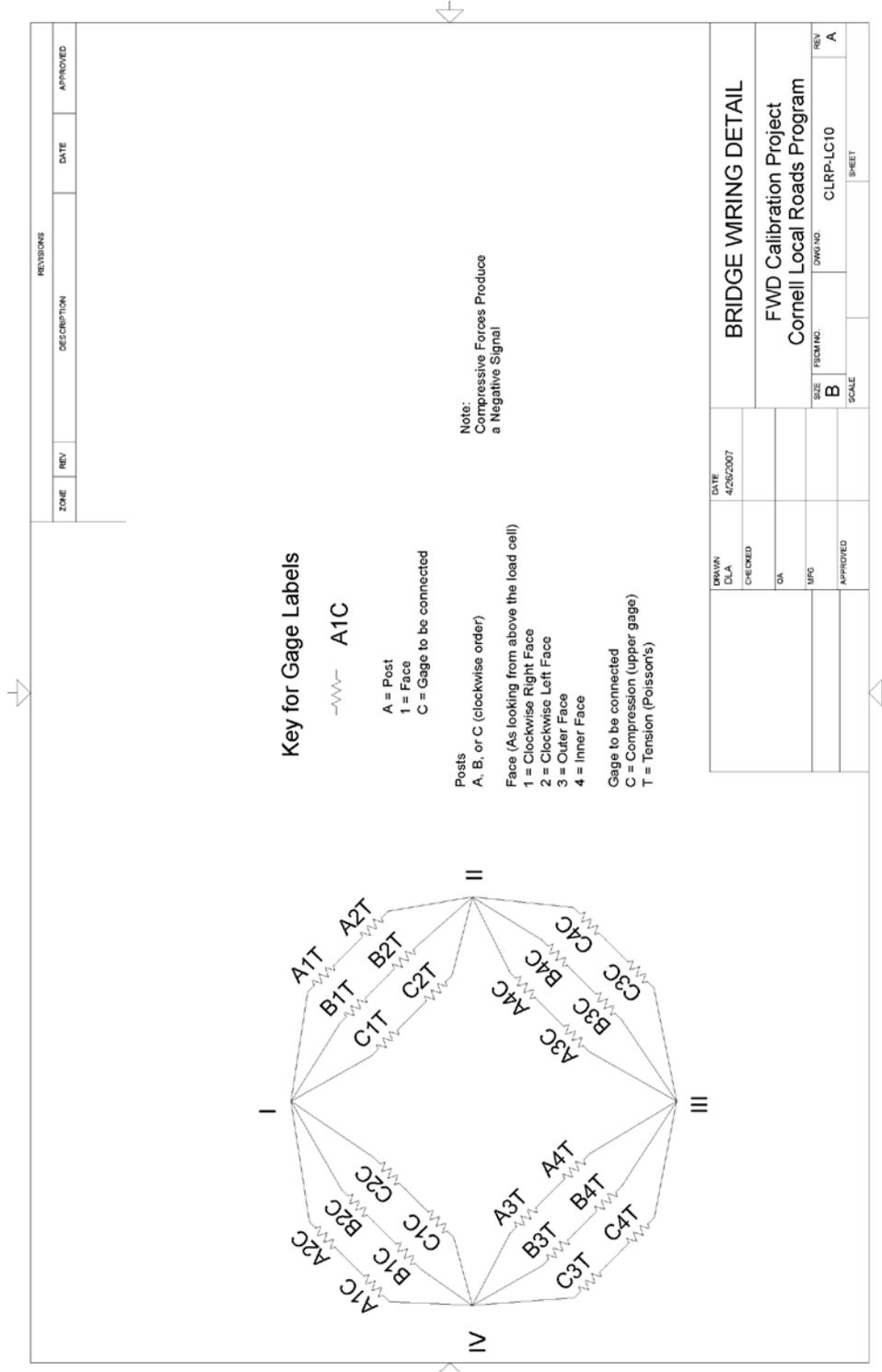
Figure 93. Illustration. CLRP-LC10 bridge wiring.

DATA ACQUISITION SYSTEM

Table 38. Cable diagrams required for BM-DAQ.

Drawing Number	Description	Quantity
CLRP-DAQ01	Vishay to KUSB DAQ cable	1
CLRP-DAQ01A	Vishay 2310B BNC to DAQ cable	1
CLRP-DAQ01B	Vishay 2310B BNC to DAQ cable (stock parts)	1
CLRP-DAQ02	Vishay to load cell cable	1
CLRP-DAQ03	Accelerometer signal cable	1
CLRP-DAQ04	Pushbutton to KUSB DAQ cable	1

Table 39. Equipment and hardware items required for BM-DAQ.

Vendor Part Number	Item	Vendor	Quantity
Model 2310B	Vishay 2310 signal conditioner	Vishay Micro-Measurements	1
2310-A20 Kit	Vishay stabilizer bar and line cord accessory package	Vishay Micro-Measurements	1
KUSB-3108	Keithley 16-bit USB DAQ	Keithley	1
571-5-1634504-1	BNC panel mount radio frequency (RF) connector	Mouser Electronics	1
566-8723	Belden 8732, two-pair shielded cable, 25-ft sections	Mouser Electronics	4
654-PT06A-14-15P-SR	Amphenol PT06A-14-15P <SR> straight plug	Mouser Electronics	2
654-PT06A-10-6S-SR	Amphenol PT06A-10-6S <SR> straight plug	Mouser Electronics	1
654-MS3106F-14S-5S	Amphenol MS3106A 14S-5S straight plug	Mouser Electronics	1
2062325	Resistors, 2.2 kΩ, $^1/_4$ Watt, 5 percent carbon film	Radio Shack®	2
2103233	Terminal strip, 5 position	Radio Shack®	1
2062543	Pushbutton, momentary, 1.5 A	Radio Shack®	1
278-0232	Enclosure, black plastic	Allied Electronics	1
91772A123	Pan head Philips machine screw, 18-8 stainless steel, #5-40 x $^5/_{16}$-inch length	McMaster-Carr®	1
91841A006	Nut, 18-8 stainless steel, #5-40 thread, $^7/_{64}$-inch height	McMaster-Carr®	1
510-0194	BNC to BNC cable, 10-ft length	Allied Electronics	1
523-T3324-501	Amphenol circular DIN connector	Mouser Electronics	1
546-1455T2202	Hammond enclosure, aluminum extruded, 8.66 x 6.3 x 2.1 inches	Mouser Electronics	1
523-T3327-100	Amphenol circular DIN connector, panel mount	Mouser Electronics	1
571-5-1634504-1	BNC panel mount RF connector	Mouser Electronics	1
523-T3327-100	Amphenol circular DIN connector, panel mount	Mouser Electronics	1
523-T3324-501	Amphenol circular DIN connector	Mouser Electronics	1
546-1455T2202	Hammond enclosure, aluminum extruded, 8.66 x 6.3 x 2.1 inches	Mouser Electronics	1
	Velcro, hook and loop, adhesive backed, industrial strength	Local hardware store	

1 inch = 25.4 mm
1 ft = 0.305 m

Table 40. Vendor contact information for BM-DAQ.

Vendor	Web site	Notes
McMaster-Carr®	http://www.mcmaster.com	See Web site for specific contact information located in the "About Us" section.
Mouser Electronics	http://www.mouser.com	See Web site for specific contact information located in the "Contact Us" section.
Allied Electronics	http://www.alliedelec.com	See Web site for specific contact information located in the "Customer Service" section.
Radio Shack®	http://www.radioshack.com	See Web site for specific contact information located in the "Contact Us" section.
Keithley Instruments	http://www.keithley.com	See Web site for specific contact information located in the "Contact Us" section.
Vishay Micro-Measurements	http://www.vishay.com	See Web site for specific contact information located in "Sales Representatives" section.
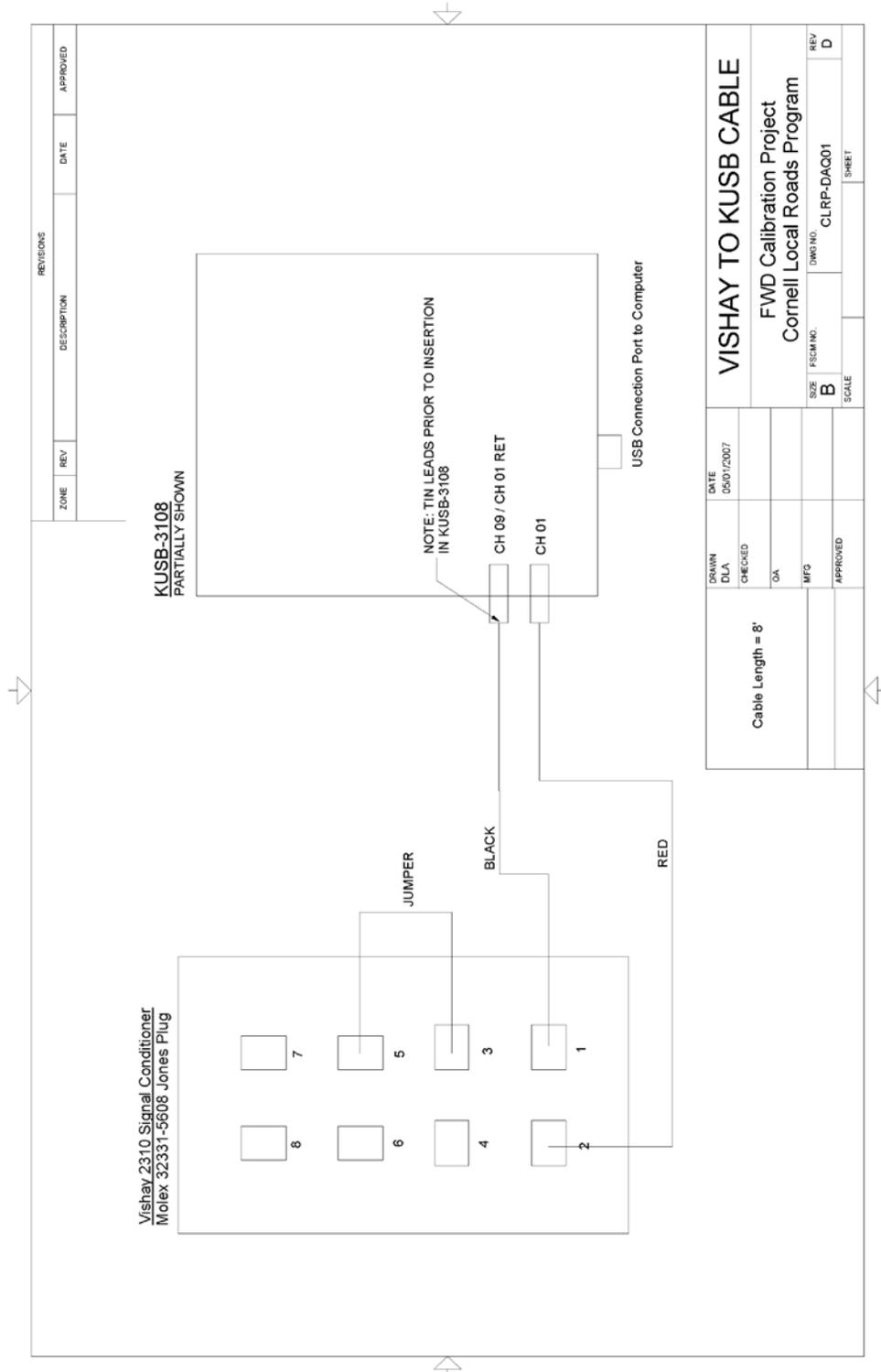
Figure 94. Illustration. CLRP-DAQ01 Vishay 2310 to DAQ cable.
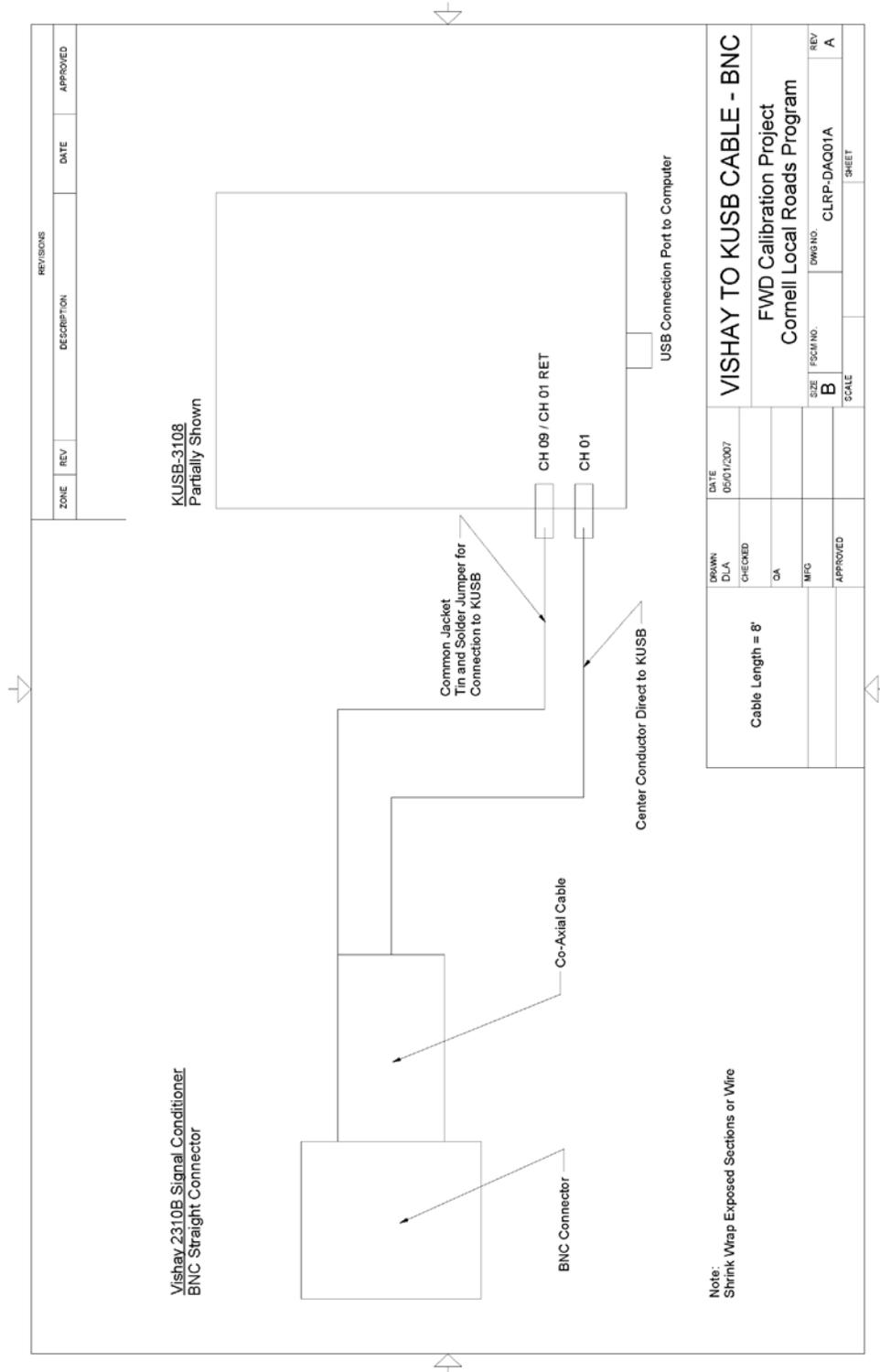
Figure 95. Illustration. CLRP-DAQ01A Vishay 2310B BNC to DAQ cable.
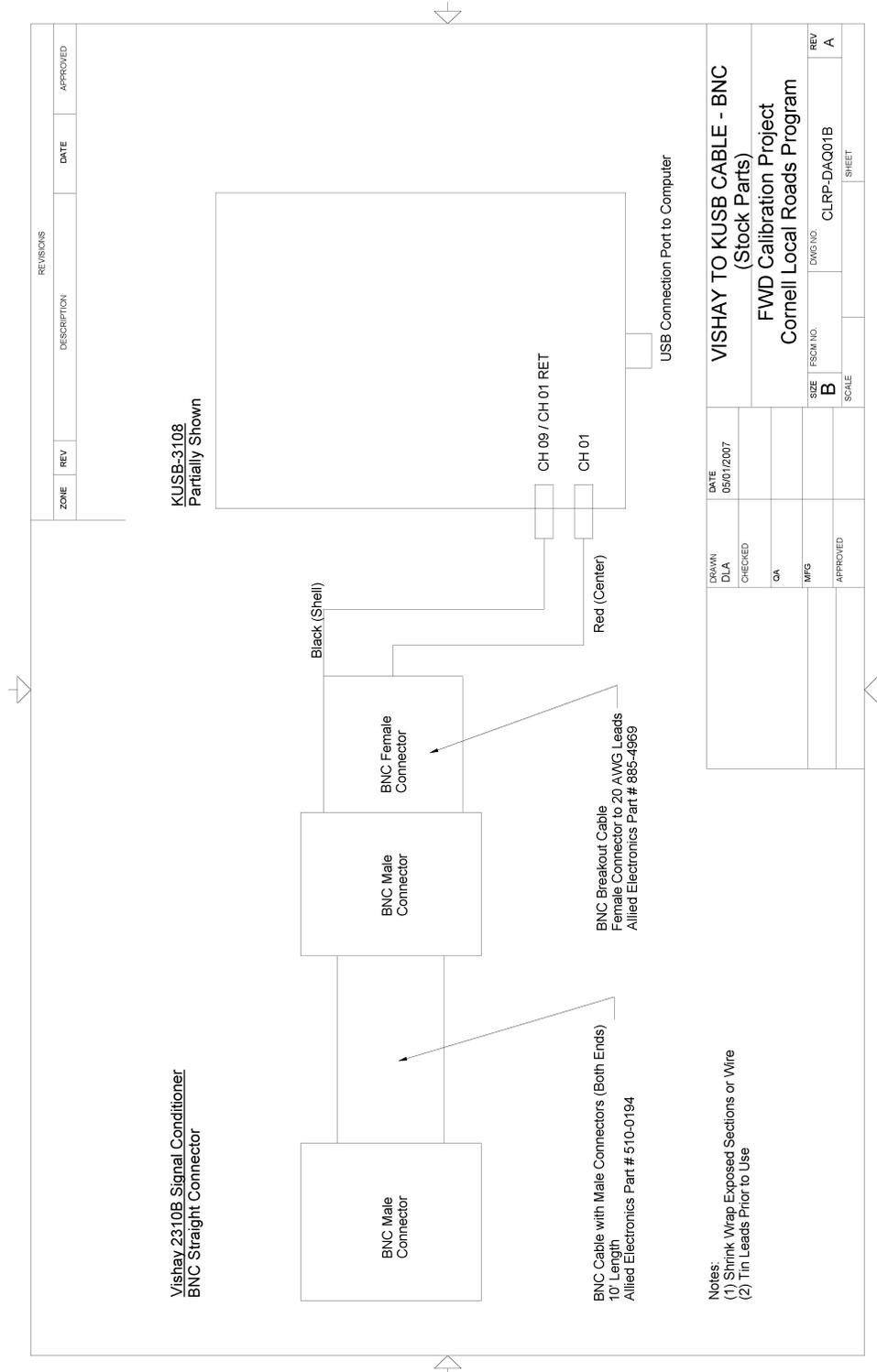
Figure 96. Illustration. CLRP-DAQ01B Vishay 2310B BNC to DAQ cable (stock parts).
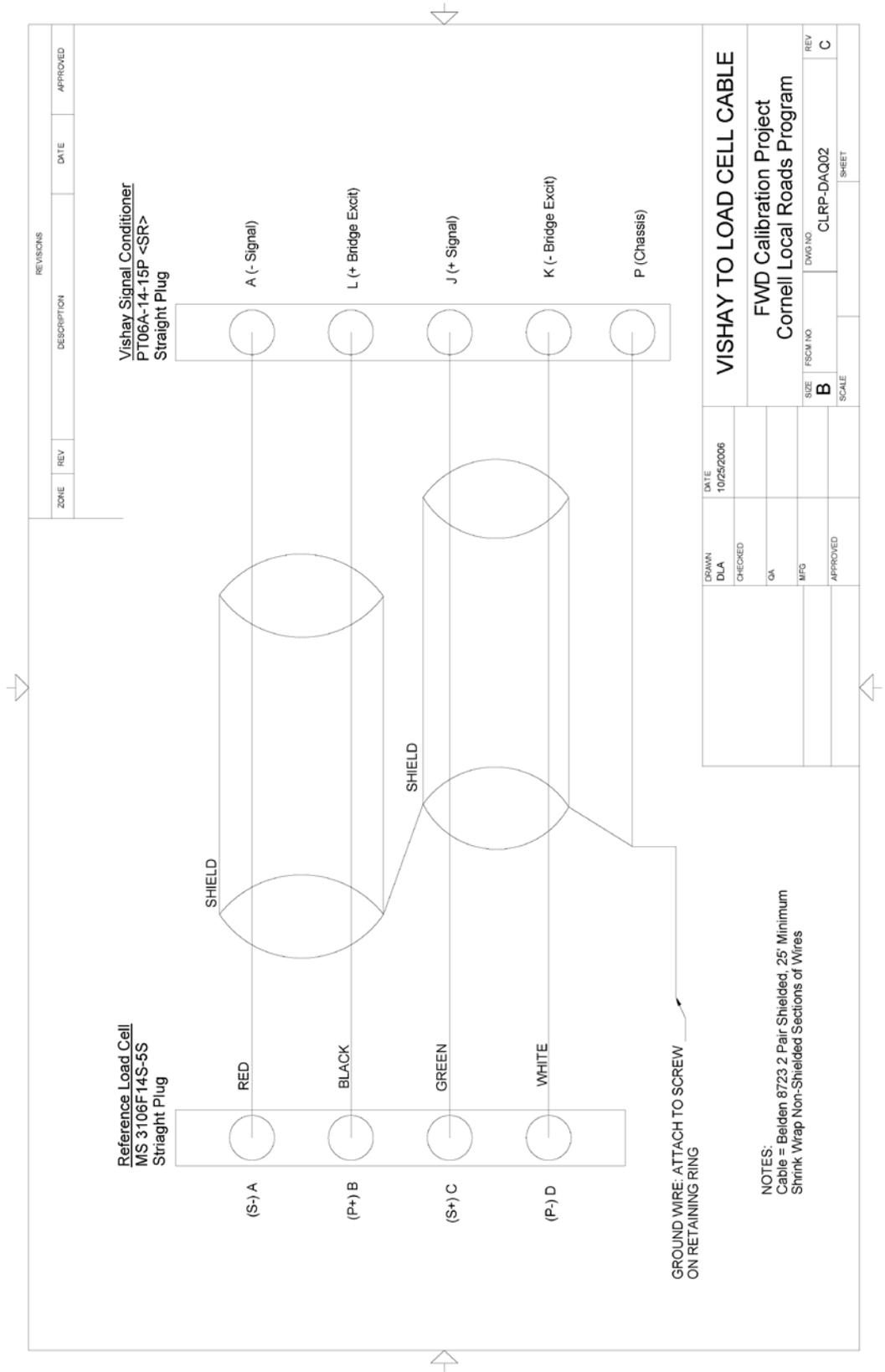
Figure 97. Illustration. CLRP-DAQ02 Vishay to load cell cable.
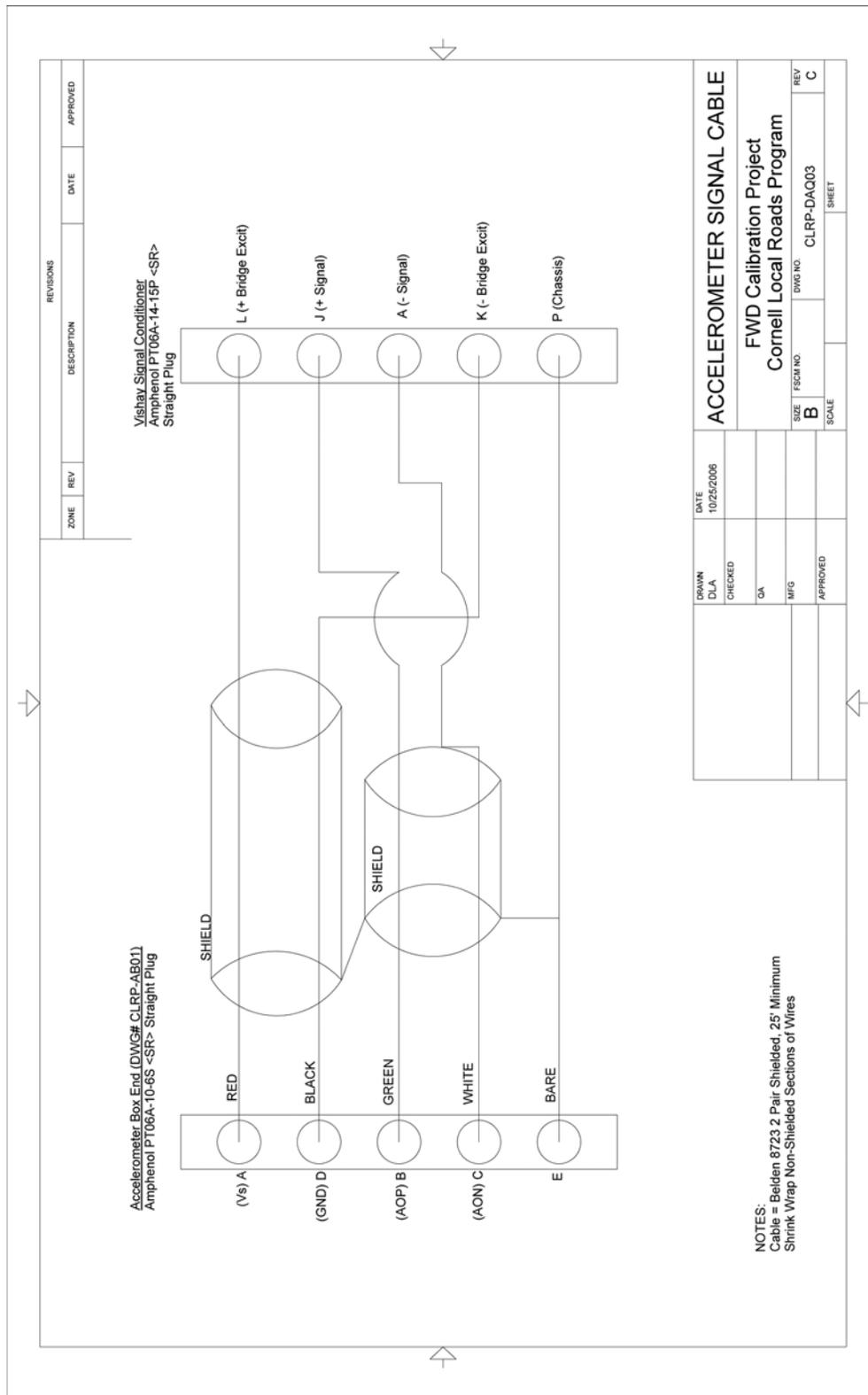
Figure 98. Illustration. CLRP-DAQ03 accelerometer signal cable.
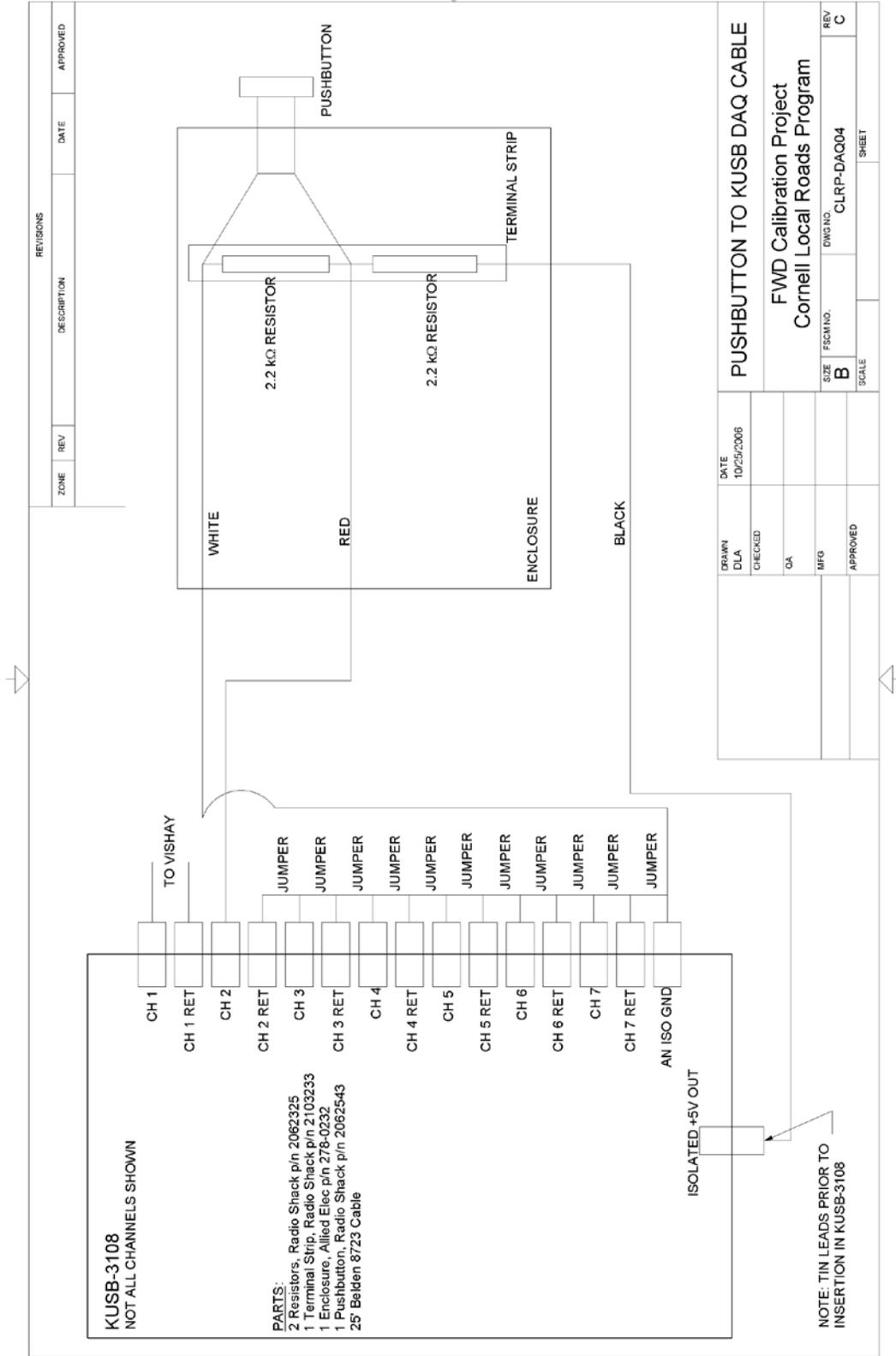
Figure 99. Illustration. CLRP-DAQ04 pushbutton to KUSB DAQ cable and cable wiring.
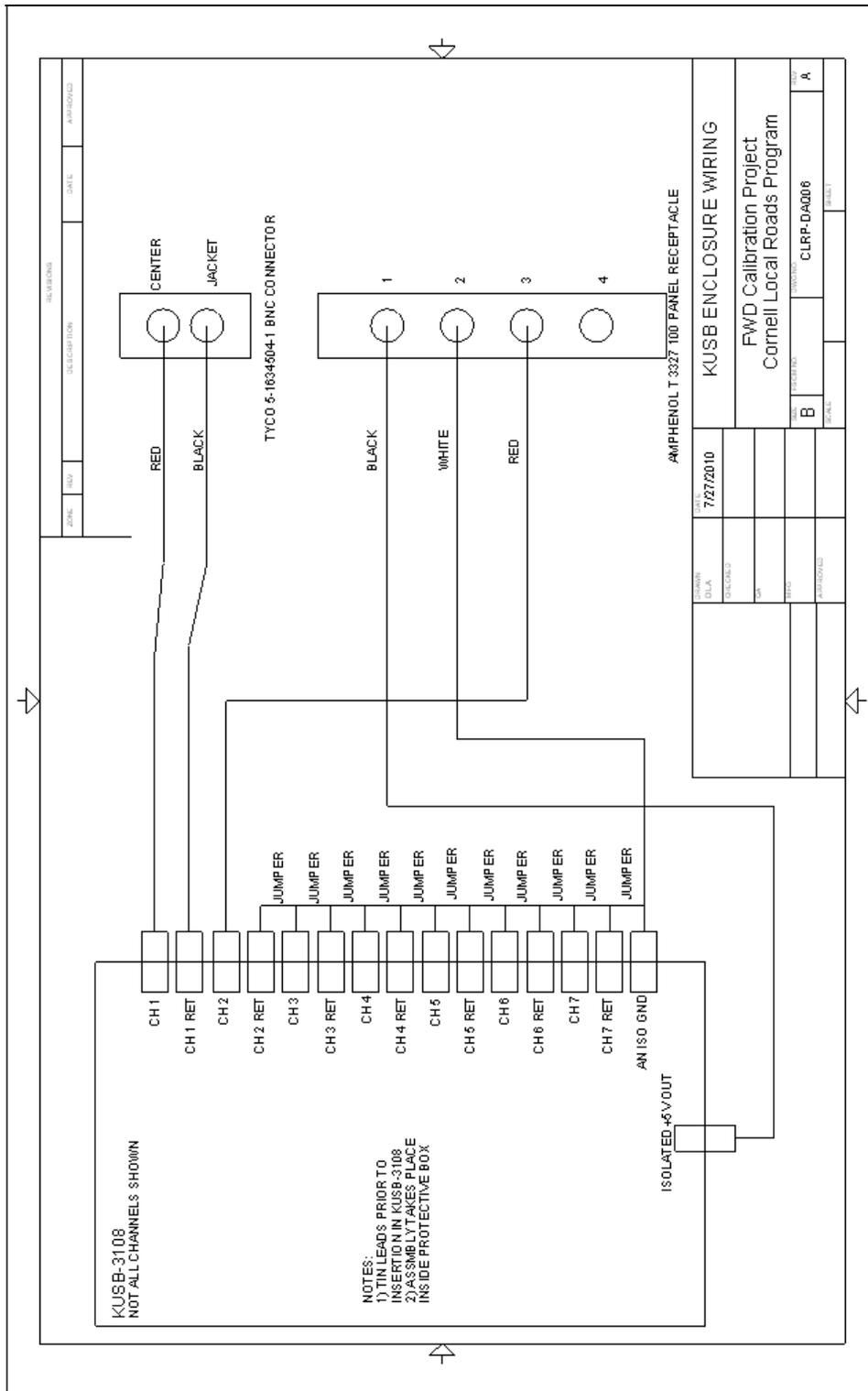
Figure 100. Illustration. CLRP-DAQ06 KUSB protection wiring.

Figure 101. Illustration. CLRP-DAQ07 KUSB enclosure rear panel.
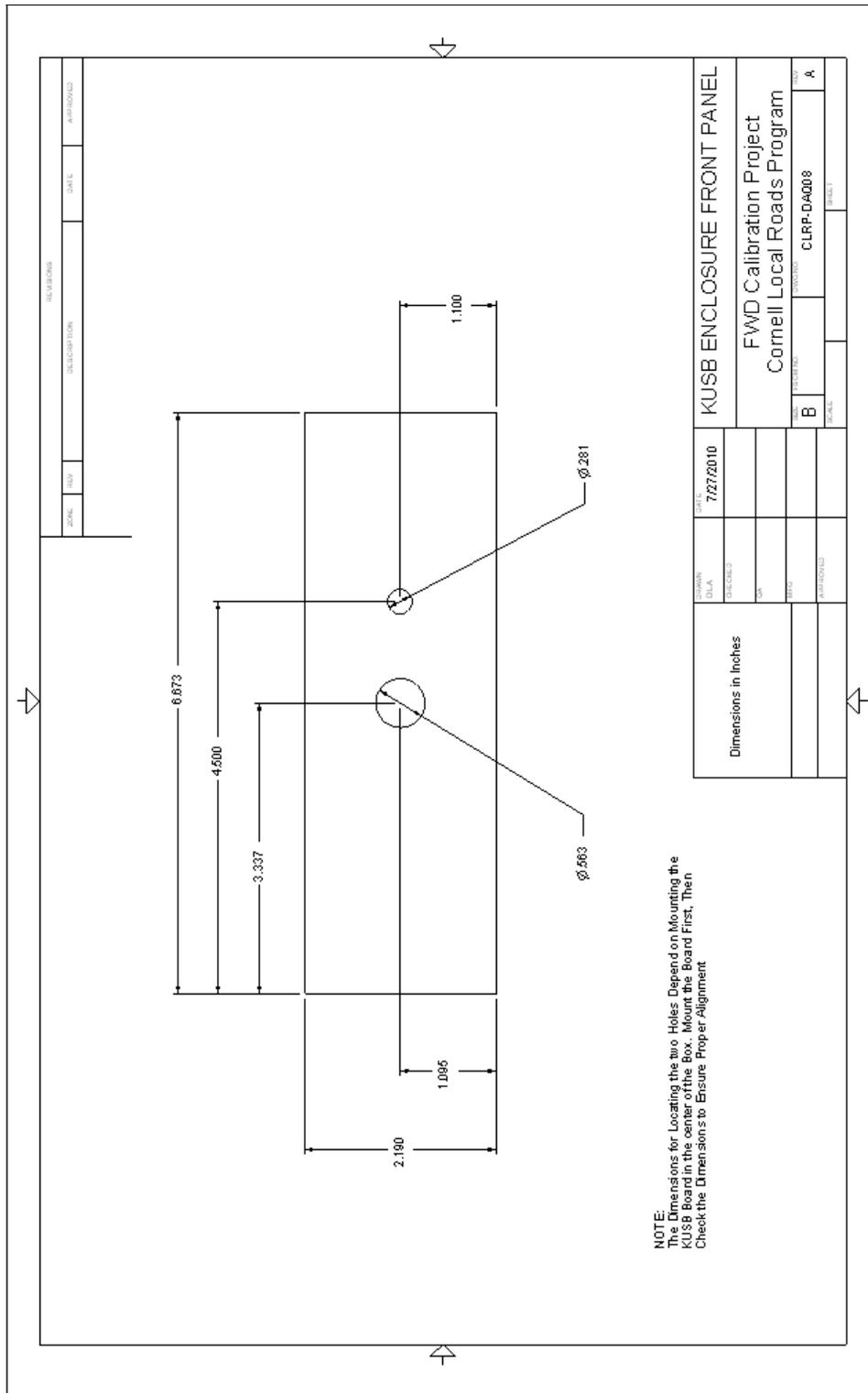
Figure 102. Illustration. CLRP-DAQ08 KUSB enclosure front panel.

APPENDIX F. HARDWARE USE AND INSTALLATION GUIDE

OVERVIEW/SCOPE

The purpose of this guide is to describe the installation and proper use of the following components of the FWD calibration system (see figure 103):

- Calibration facilities.

- Concrete test pad.

- Reference load cell.

- Concrete anchors.

- Ball-joint anchor.

- Accelerometer box.

- Geophone calibration stand.

- Seismometer calibration stand.

- Geophone adapters.

- Data acquisition components (Keithley DAQ and Vishay signal conditioner).

- Portable computer.

The instructions provided here assume the use of the *WinFWDCal* software package.
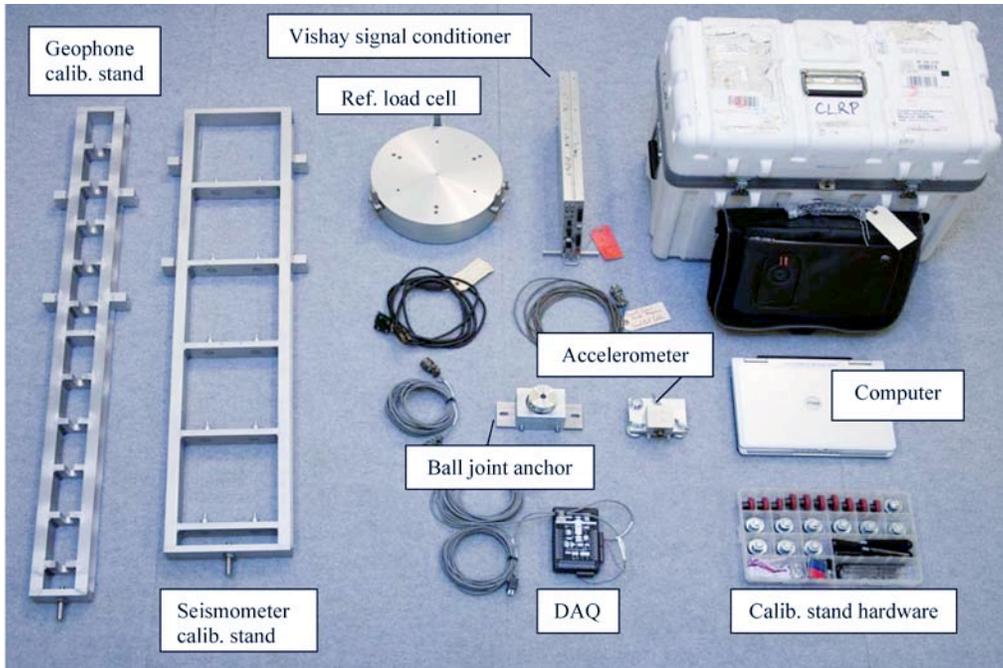
Figure 103. Photo. Calibration system components.

FACILITIES

Calibration center facilities require the following characteristics:

- Easy access for the FWD trailer and the tow vehicle.

- A large level floor that can accommodate both the FWD trailer and the tow vehicle indoors.

- A stable indoor temperature between 50 and 100 °F (10 and 38 °C).

- Good security cabinets for calibration equipment.

TEST PAD

While a specially built test area for FWD calibration is not required by AASHTO R32-09, some agencies either need or prefer to build a concrete test pad.[1] If so, the test pad should have the following specifications:

- A 12- by 15-ft (4- by 4.5-m) height and an 8-ft (2.5-m)-wide (5-ft (1.75-m) minimum allowable) clear zone around the perimeter to allow for maneuvering of FWD and the calibration equipment.

- A level, smooth, crack-free Portland cement concrete surface. A modest amount of hairline cracking is permissible. Should the test pad develop cracks that are visibly open 0.0585 inches (1.5 mm) or more, it should be replaced.

- It should be isolated from the surrounding floor by impregnated felt bond breaker or sawed and caulked joint.

- It should be at a distance of 20 to 24 inches (500 to 600 mm) behind the FWD load plate, the test pad should deflect 20 ±4 mil (500 ±100 μm) at a peak dynamic load of 16,000 lbf (71 kN).

REFERENCE LOAD CELL

Parts and Tools

Table 41. Parts and tools for load cell calibration.

Tool/Equipment	Quantity	Notes
Reference load cell assembly	1	Drawing CLRP-LC01
$^{1}/_{4}$ 28 x 1-inch socket head cap screw	6	McMaster-Carr® part number (p/n) 92196A325
$^{1}/_{4}$ 28 x $^{3}/_{4}$-inch socket head cap screw	6	McMaster-Carr® p/n 92196A321
Vishay signal conditioner	1	
Load cell signal cable	1	Drawing CLRP-DAQ02
$^{3}/_{16}$-inch hex wrench	1	
Torque wrench	1	Capable of 100 inch-lbf

1 inch = 25.4 mm
1 lbf = 4.45 N

Figure 104. Photo. Reference load cell assembly.

Calibration

The reference load cell requires annual calibration to ensure accuracy. To calibrate the reference load cell, a universal testing machine with a load capacity of 120,000 lbf (500 kN) or more is needed. Although the load cell is calibrated to only 24,000 lbf (107 kN), the higher capacity of the testing machine assures that the test frame will be adequately rigid.

The Vishay 2310 signal conditioner, Keithley KUSB-3108 DAQ, the reference load cell, and the load cell signal cable are considered one system and must be calibrated together. Once the calibration is complete, it only applies to the entire system that was used during the calibration. If any component of the system changes, then the load cell needs a new calibration.

The bolts that hold the cover plate and feet onto the load cell (see figure 105) should not be removed under any circumstances. If any of these bolts are removed, the load cell calibration becomes invalid and must be returned to an approved calibration center for recalibration.
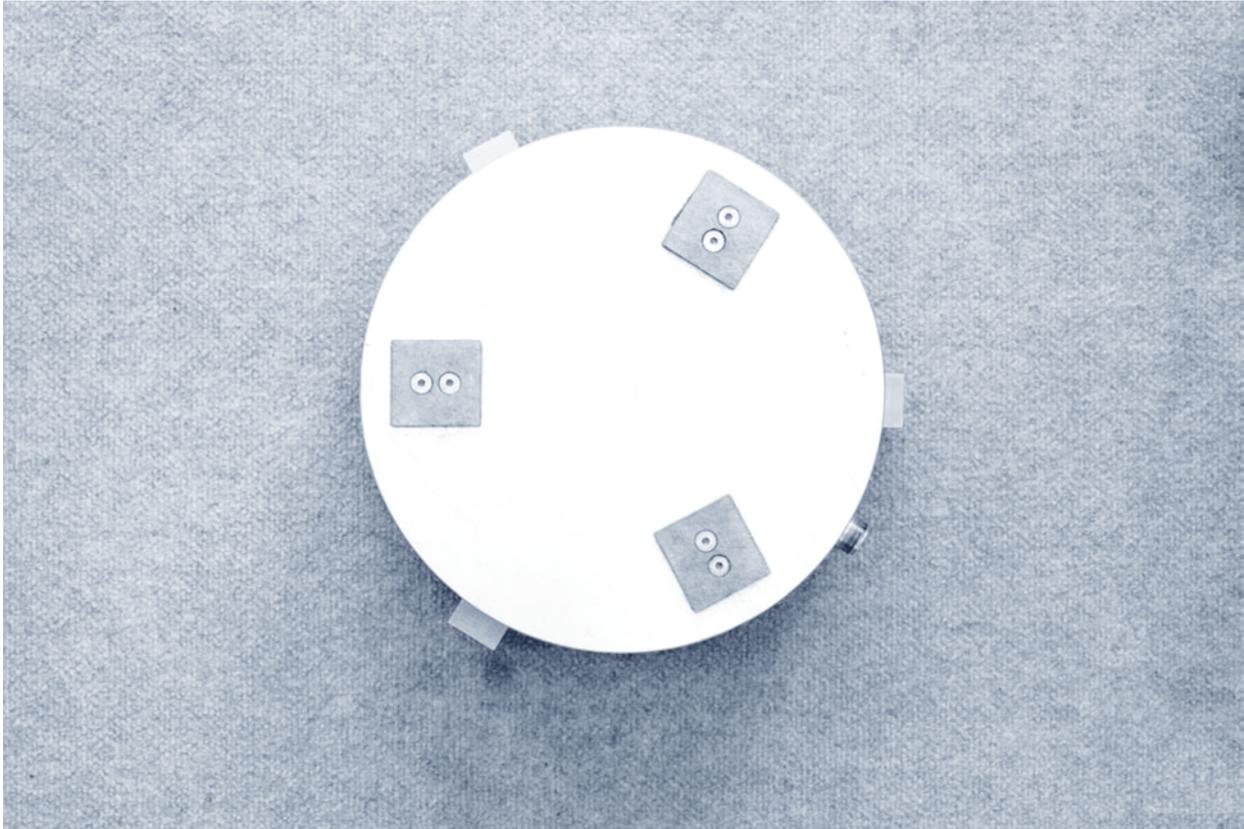
Figure 105. Photo. Bottom view of the reference load cell.

Use

1. Ensure that the guide fingers are tightened to the load cell body during FWD load cell calibration.

2. Attach the signal cable form the load cell to the signal conditioner and allow the electronics to warm up for at least 1 h.

3. Carefully align the reference load cell under the FWD load plate, ensuring that the guide fingers and the load plate do not interact (see figure 106).

4. Follow the on-screen instructions provided by *WinFWDCal* for a complete load cell calibration.

Figure 106. Photo. Reference load cell positioned under the FWD load plate.

CONCRETE ANCHOR INSTALLATION

The concrete anchors suggested for use with the FWD calibration hardware are of the drop-in variety (see figure 107). These instructions are for anchors from McMaster-Carr® p/n 97082A031 only. For any other equivalent anchor, refer to the manufacturer's installation instructions.

Parts and Tools

Table 42. Parts and equipment for concrete anchor install.

Tool/Equipment	Quantity	Notes
Concrete anchors	2	McMaster-Carr®, p/n 97082A031
Anchor setting tool	1	McMaster-Carr® p/n 97077A120
Hammer	1	
Drill	1	Optionally a hammer drill
$^1/_4$-inch masonry drill bit	1	
$^1/_2$-inch masonry drill bit	1	
$^3/_8$-inch inside diameter washers	2	McMaster-Carr® p/n 94744A273

1 inch = 25.4 mm
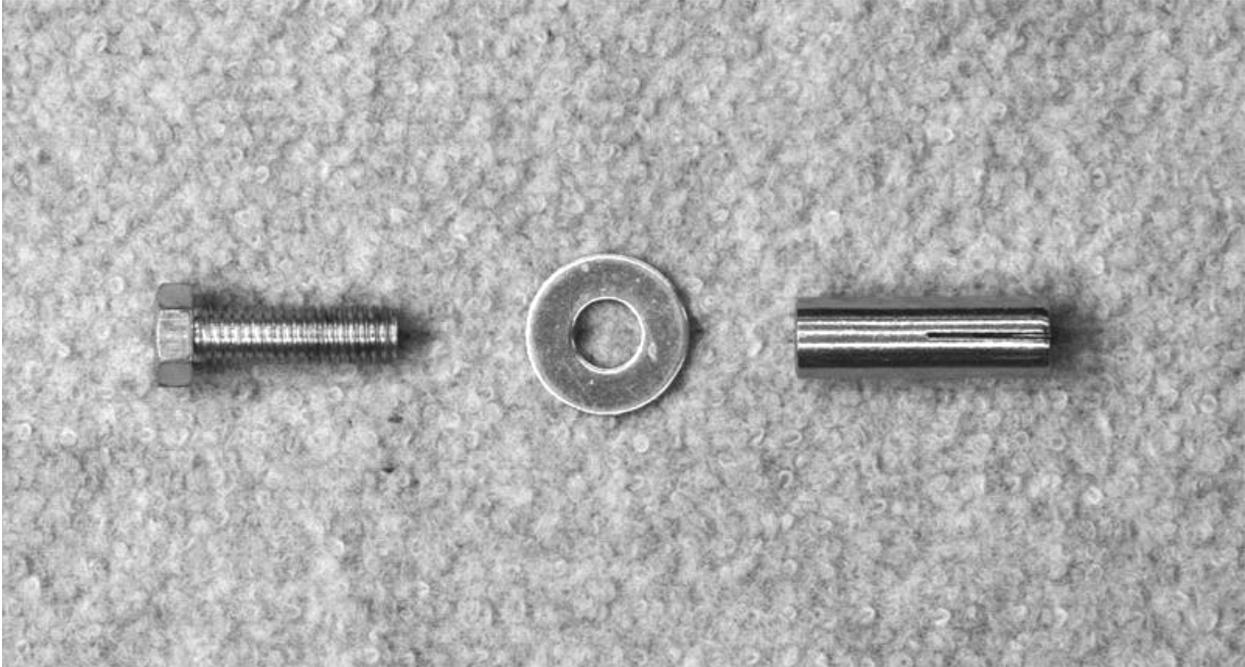
Figure 107. Photo. Concrete anchor.

Installation

1. Determine the appropriate location for the ball-joint anchor on the test pad. The FWD needs to impart a deflection of 16–24 mil (400–600 μm) at a 16,000-lbf (71-kN) load where the ball-joint will be located.

2. Using the base bar from the ball-joint anchor (B04, drawing CLRP-BJ03) as a guide, mark where the two anchors will be installed. The holes should be 6 inches (152.4 mm) apart from center to center.

3. Drill pilot holes at the anchor locations using a $\frac{1}{4}$-inch (6.35-mm) masonry bit and, if available, a hammer drill. The holes should be slightly greater than 1.5 inches (38.1 mm) deep to ensure that the anchor rests below the surface of the concrete. Ideally, the holes will be drilled about $\frac{1}{16}$ inches (1.59 mm) deeper than the height of the anchor (see figure 108).

Figure 108. Photo. Concrete anchor installation step 3.

4. Drill the final holes for the anchors with a $^1/_2$-inch (12.7-mm) bit. Do not use a hammer drill for these holes.

5. Blow out the debris from holes with compressed air.

6. Drop the anchors into the holes and gently tap on the top of the anchor with a hammer to insert it into the hole. Be careful not to damage the anchor. If the anchor does not sit flush in the hole, do not attempt to drive it in by striking the anchor itself directly because this will damage the anchor. If necessary, remove the anchor and drill a little deeper (see figure 109).

Figure 109. Photo. Concrete anchor installation step 6.

7. Once the anchors are at the correct depth in the hole, use the setting tool to expand the anchor by placing the setting tool inside the anchor and striking it with a hammer (see figure 110).

Figure 110. Photo. Concrete anchor installation step 7.

BALL-JOINT ANCHOR

Parts and Tools

Table 43. Tools and equipment for ball-joint assembly.

No.	Part/Equipment	Quantity	Notes
B01	Ball-joint	1	Techno/Sommer KG-60
B01a	Ball	1	Techno/Sommer KG-60
B01b	Socket	1	Techno/Sommer KG-60
B01c	Clamp	1	Techno/Sommer KG-60
B01d	Screw	2	Techno/Sommer KG-60
B02	Clamp	1	Drawing CLRP-BJ01
B03	Clamp base	1	Drawing CLRP-BJ02
B04	Base bar	1	Drawing CLRP-BJ03
B05	Rest stop	1	Drawing CLRP-BJ04
B06	M6 x 16-mm socket head cap screw	4	McMaster-Carr[®] p/n 91292A135
B07	M8 x 16 mm socket head cap screw	6	McMaster-Carr[®] p/n 91292A145
B08	M8 x 25 mm socket head cap screw	2	McMaster-Carr[®] p/n 91292A148
B09	Loctite[®] #242 threadlocker	1	
B10	5-mm hex wrench	1	
B11	6-mm hex wrench	1	
B12	Dow Corning Molykote G-4500 alum thickened grease, 14.1-oz, Nlgi #2		McMaster-Carr[®] p/n 4328T24

1 inch = 25.4 mm
1 oz = 28.35 g
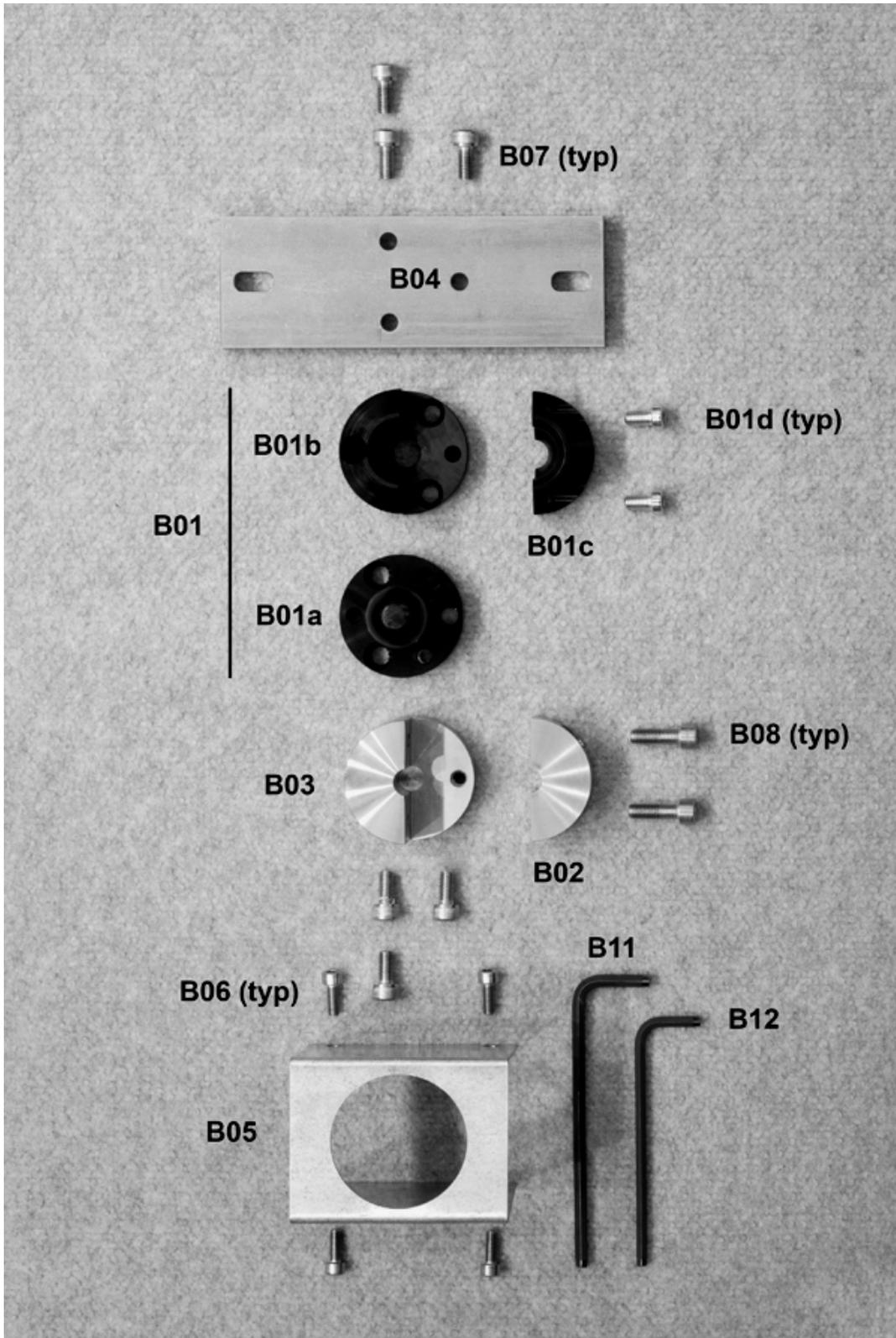
Figure 111. Photo. Parts and tools for ball-joint assembly.

Assembly

1. Attach the clamp (B02) to the clamp base (B03) with two M8 x 0.975-inch (25-mm) socket head cap screws (B08).

   Note: Do not apply Loctite® to the two screws.

2. Completely disassemble the ball-joint (B01) by removing its two screws (B01d). Thoroughly clean all old lubricant off the ball and socket and apply a thin layer of Molykote® type G lubricant (B12) on the mating surfaces.

3. Use Loctite® and three M8 x 0.624-inch (16-mm) socket head cap screws (B07) and mate the ball-joint's ball (B01a) and the clamp components assembled in step 1 through the counterbored holes in the ball.

4. Reassemble the ball-joint (B01).

   Note: Do not apply Loctite® when installing the screws (B01d).

5. Attach the base bar (B04) to the completed ball-joint assembly with Loctite® (B09) and three M8 x 0.624-inch (16-mm) socket head cap screws (B07) through the counterbored holes in the bottom of the base bar. The ball-joint screws (B01d) must be aligned along the length of the base bar for access as shown in figure 112.

6. Slide the rest stop (B05) over the ball-joint assembly and secure it to the base bar (B04) with four M6 x 0.624-inch (16-mm) socket head cap screws (B06). See figure 113 for a photograph of the assembly of the ball joint anchor.
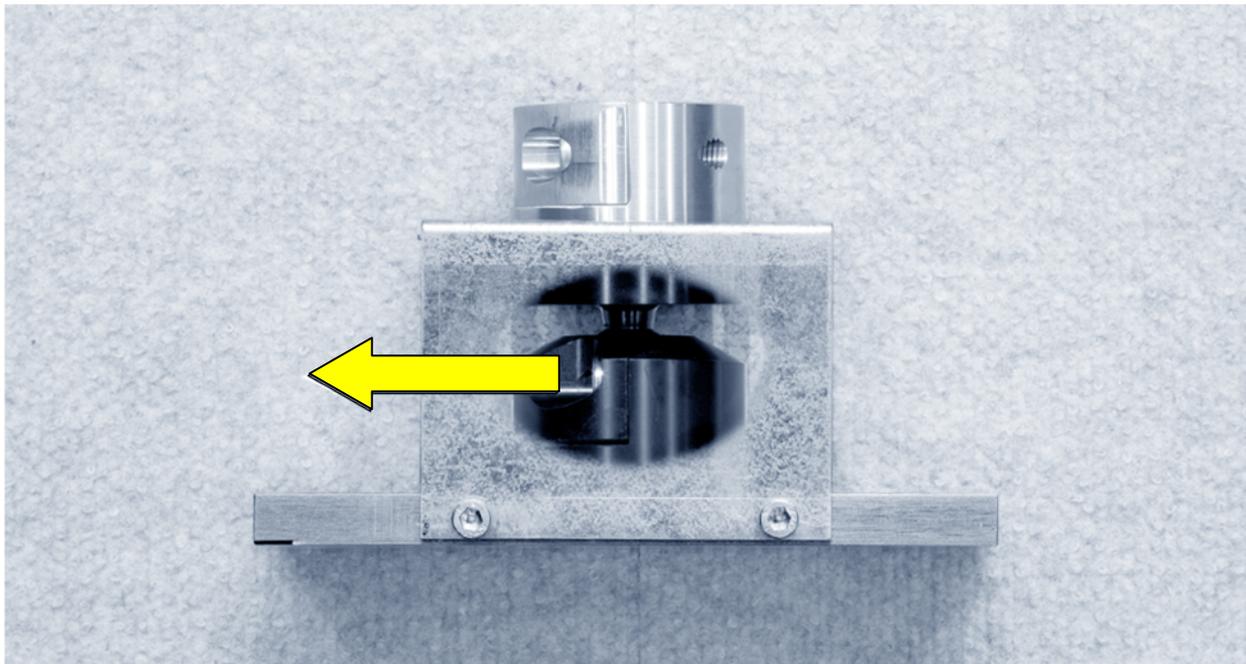
Figure 112. Photo. Proper alignment of ball-joint screws.
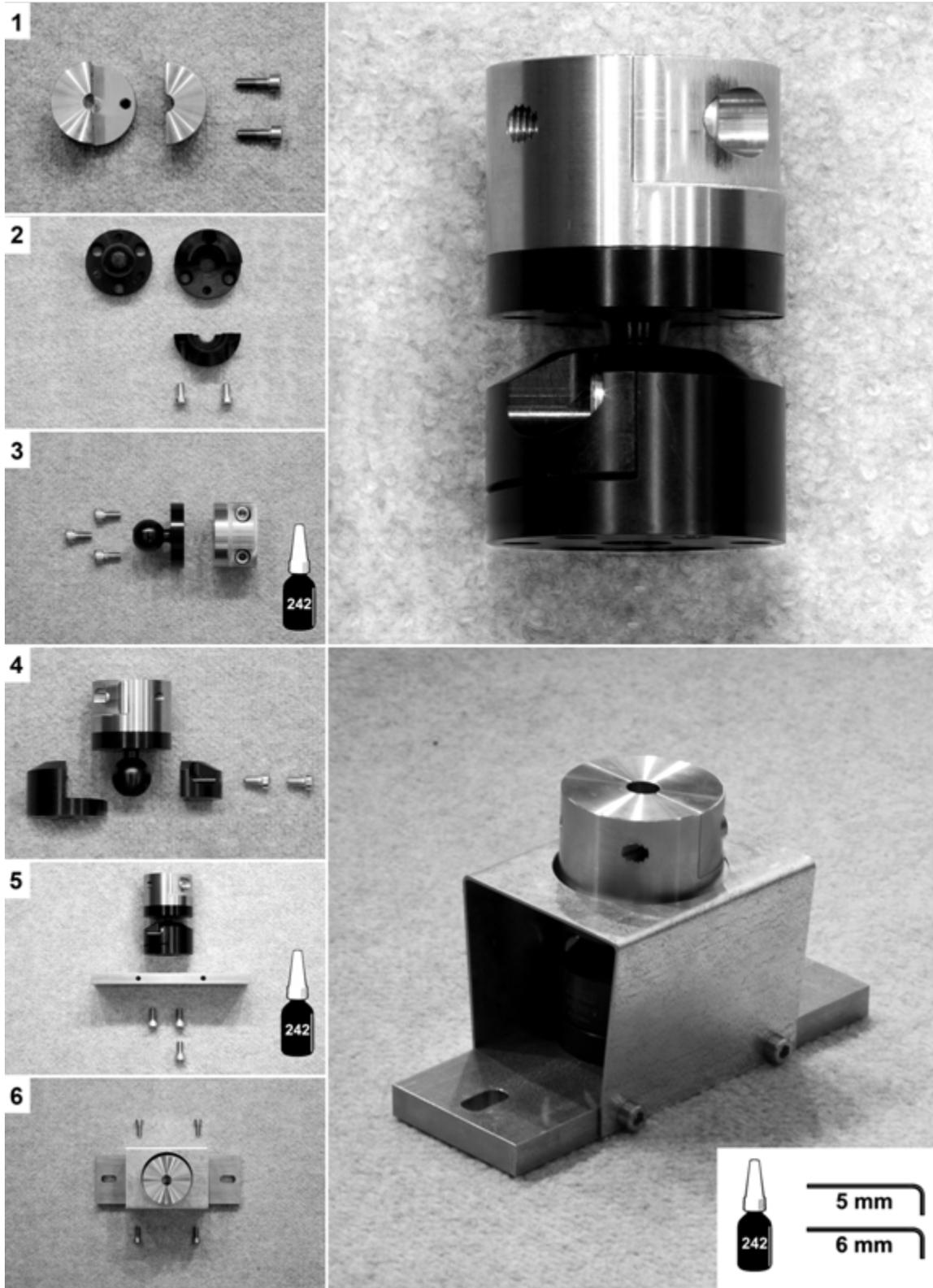
Figure 113. Photo. Assembly of the ball-joint anchor.

ACCELEROMETER BOX

Parts and Tools

Table 44. Parts and tools for accelerometer box assembly.

No.	Part/Equipment	Quantity	Notes
A01a	Accelerometer assembly	1	
A01a	Accelerometer	1	Silicon Designs model 2220-005
A01b	Amphenol PT02A-10-6P box mounting receptacle	1	Mouser p/n 654-PT02A106P
A01c	Accelerometer wiring	1	Drawing CLRP-AB05
A02	Box bottom	1	Drawing CLRP-AB02
A03	Box top	1	Drawing CLRP-AB03
A04	Calibration platter	1	Drawing CLRP-AB04
A05	#4-40 x $^3/_8$-inch flat head Phillips machine screw	4	McMaster-Carr® p/n 96877A209
A06	#4-40 x $^1/_2$-inch pan head Phillips machine screw	2	McMaster-Carr® p/n 91400A110
A07	#4 retaining washer	2	McMaster-Carr® p/n 91755A205
A08	#4-40 x $^1/_4$-inch fillister head Phillips machine screw	7	McMaster-Carr® p/n 91737A072
A09	#10-24 x $^1/_2$-inch knurled head thumbscrew	2	McMaster-Carr® p/n 91746A876
A10	Bubble level, glass surface mount	1	McMaster-Carr® p/n 2198A85
A11	Leveling mount with polyethylene base, $^3/_8$-inch 16 x 1-inch stud	3	McMaster-Carr® p/n 23015T64
A12	$^3/_8$-inch 16 locking wig nut	3	McMaster-Carr® p/n 98520A145
A13	#1 Phillips head screwdriver	1	
A14	Loctite® #242 threadlocker	1	

1 inch = 25.4 mm
Note: Blank cells indicate that no notes are available.

Assembly

1. The accelerometer is attached to the box top (A03) using two #4-40 x $^1/_2$-inch (12.7-mm) pan head machine screws (A06) with #4 nylon retaining washers (A07). The sensor element of the accelerometer must be oriented in the correct alignment. The element is marked on the casing of the accelerometer as shown in figure 114. This element must be centered on and mated to the inside face of the box top.

2. Coil the accelerometer wiring (A01c) into the box top and slide the wire through the channel in the front of the box top so that Amphenol receptacle (A01b) sits flush against the front of the box.

3. The Amphenol receptacle (A01b) is attached to the face of the box top with four #4-40 x $^1/_4$-inch (6.35-mm) fillister head machine screws (A08) and medium strength Loctite® #242 (A14).

4. The box top and box bottom (A02) are mated together with four #4-40 x $^3/_8$-inch (9.52-mm) flat head machine screws (A05) and medium strength Loctite® #242 (A14). The final assembly is shown in figure 115.
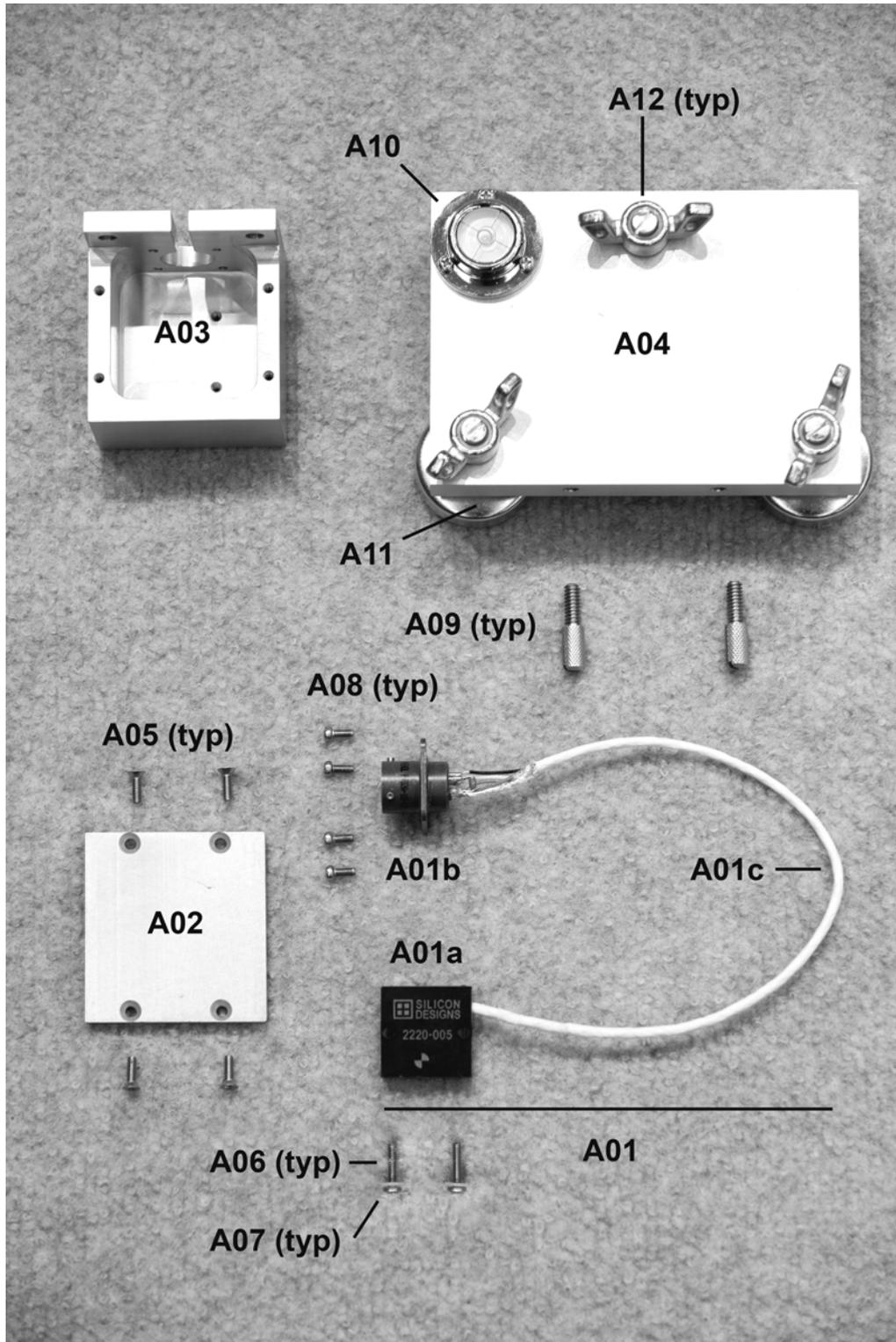
Figure 114. Photo. Parts for accelerometer box assembly.
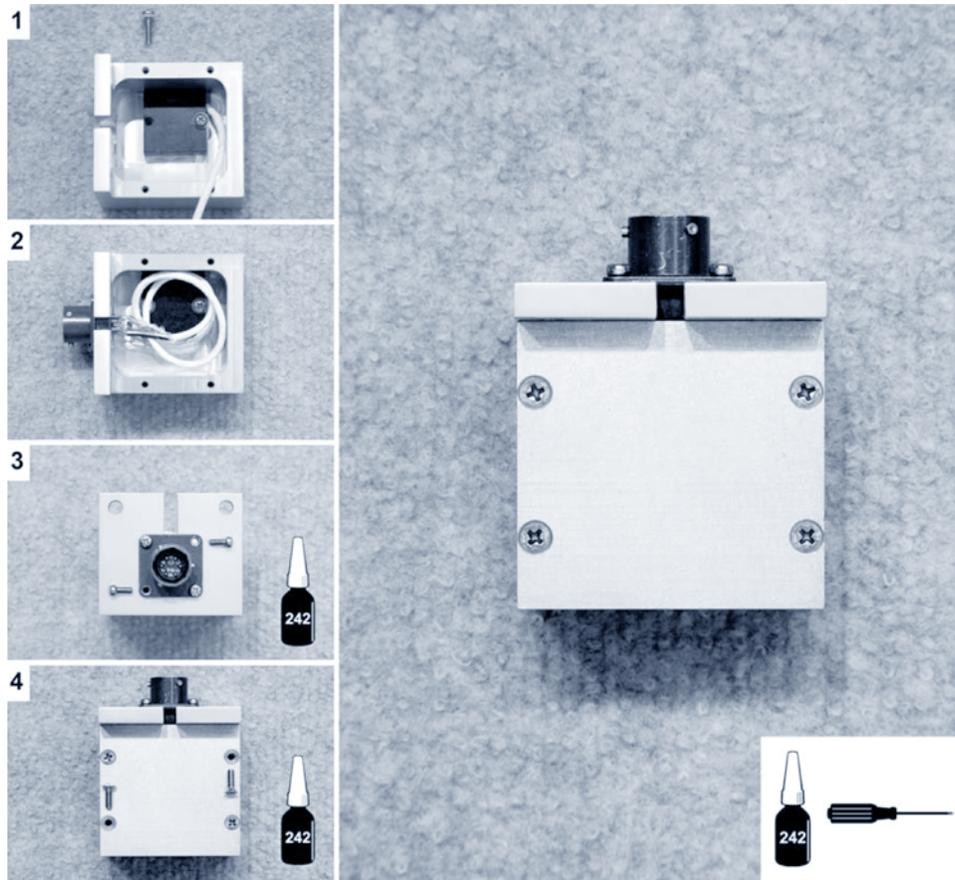
Figure 115. Photo. Accelerometer box assembly.

Calibration Platter Assembly

1. Attach the bubble level (A10) to the calibration platter (A04) with three #4-40 x $^1/_4$-inch (6.35-mm) fillister head machine screws (A08). Note that the threaded holes for the thumbscrews are not centered on the side of the calibration platter. Check for proper alignment of the accelerometer box on the platter before mounting the bubble level.

2. The three leveling mounts are threaded into the calibration platter and topped with three $^3/_8$-inch (9.52-mm) 16 locking wing nuts (A12).

3. The accelerometer box is attached to the calibration platter with two #10-24 x$^1/_2$-inch (12.7-mm) knurled head thumbscrews (A09) as shown on the left in figure 116.
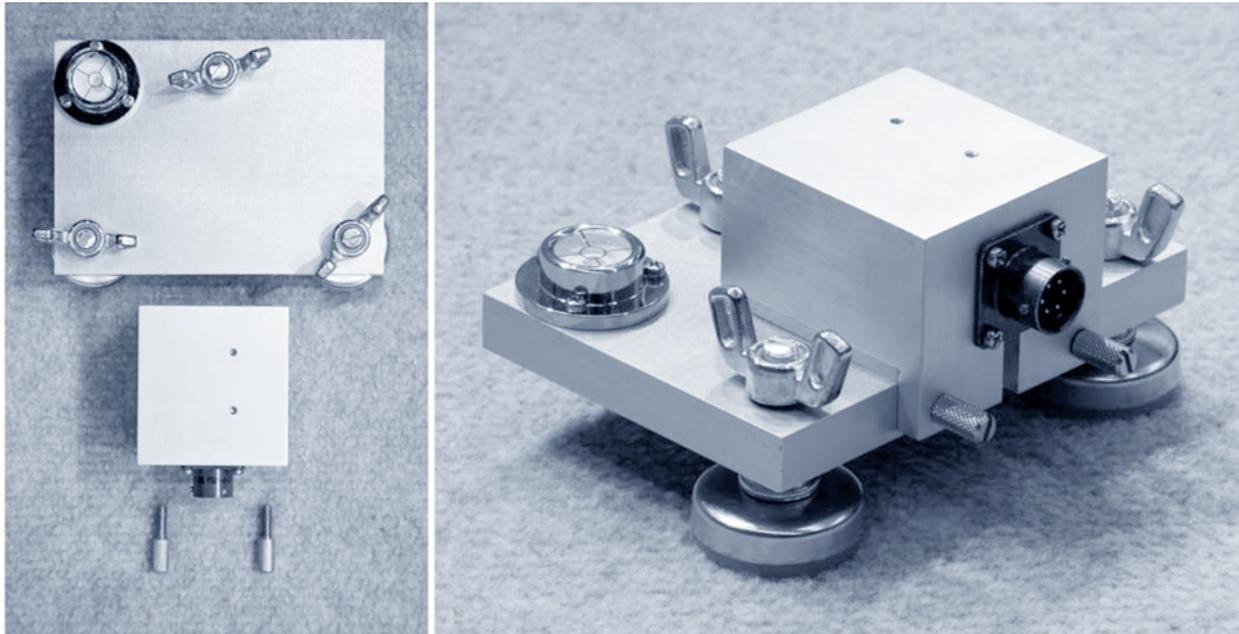
Figure 116. Photo. Accelerometer box attached to calibration platter.

Accelerometer Storage

1. When not in use, attach the accelerometer box to the calibration platter with the two #10-24 knurled head thumbscrews (A09) provided.

2. The accelerometer needs to be stored on the platter and be level for a minimum of 24 h prior to use.

Accelerometer Calibration

1. Place the calibration platter, with the accelerometer box attached, on a flat surface and carefully level the platter.

2. Remove the thumbscrews and press the accelerometer box on to the calibration platter with a finger. Otherwise, the weight of the cable may pull the accelerometer box onto the floor.

3. While following the on screen instructions from *WinFWDCal*, continue to press the accelerometer box to the calibration platter.

4. Flip the accelerometer box over when instructed.

CALIBRATION STANDS

Parts and Tools

Table 45. Equipment for calibration stand assembly.

Number	Tool/Equipment	Quantity	Notes
S01	Geophone calibration stand assembly	1	Drawing CLRP-GCS01
S02	Seismometer calibration stand assembly	1	Drawing CLRP-SCS01
S03	Phenolic handle, $^3/_8$-inch 16 x $^1/_2$-inch stud	4	McMaster-Carr® p/n 62385K65
S04	Bubble level, glass surface mount	2	McMaster-Carr® p/n 2198A85; Also No. A10 in this guide.
S05	#4-40 x $^1/_4$-inch fillister head Phillips machine screw	6	McMaster-Carr® p/n 91737A072; Also No. A08 in this guide.
S06	Carl Bro geophone adapters with M8 1 mm threaded through hole	10	Morton Machine Works p/n KK-GA02
S07	JILS geophone adapter with $^3/_8$-inch 24 threaded through hole	10	Morton Machine Works p/n KK-GA03
S08	$^3/_4$-inch inside diameter washer	10	McMaster-Carr® p/n 90126A036
S09	$^3/_8$-inch inside diameter washer	10	McMaster-Carr® p/n 94744A273 Also No. B11 in this guide.
S10	$^3/_8$-inch -24 x $^5/_8$-inch hex head cap screw	10	McMaster-Carr® p/n 92865A212
S11	#10-24 x $^1/_2$-inch knurled head thumbscrew	2	McMaster-Carr® p/n 91746A876; Also No. A09 in this manual
S12	Two-piece clamp-on shaft collar 20-mm bore, 40-mm outside diameter	10	McMaster-Carr® p/n 6063K19
S13	Magnet assembly with #10-24 button head cap screw and nut	10	McMaster-Carr® p/n 5685K26, p/n 92949A246, and p/n 90730A011
S14	Modified knurled rim knob	10	McMaster-Carr® p/n 6121K93

1 inch = 25.4 mm

Assembly

See figure 117 for a photograph of the equipment necessary for calibration stand assembly.

1. The bubble level (S04) is fastened to the handle holder of either stand (S01 or S02) with three #4-40 x $^1/_4$-inch (6.35-mm) fillister head machine screws (S05). Since there are four potential places to attach the level, the calibration center operator should determine which location is appropriate for visibility and comfort during use.

2. Two phenolic handles (S03) are screwed in place at one of the two available positions depending on the preference of the operator.

3. The pushbutton assembly (described elsewhere) should be attached with Velcro® to the stand at the same level as the handles and in a spot where it can be easily reached during use. See figure 118 for an example.

4. For both the geophone calibration stand and the seismometer calibration stand, the connector pin is fastened to the stand with medium strength Loctite® #242. Figure 125 shows the geophone calibration stand with a connector pin attached.
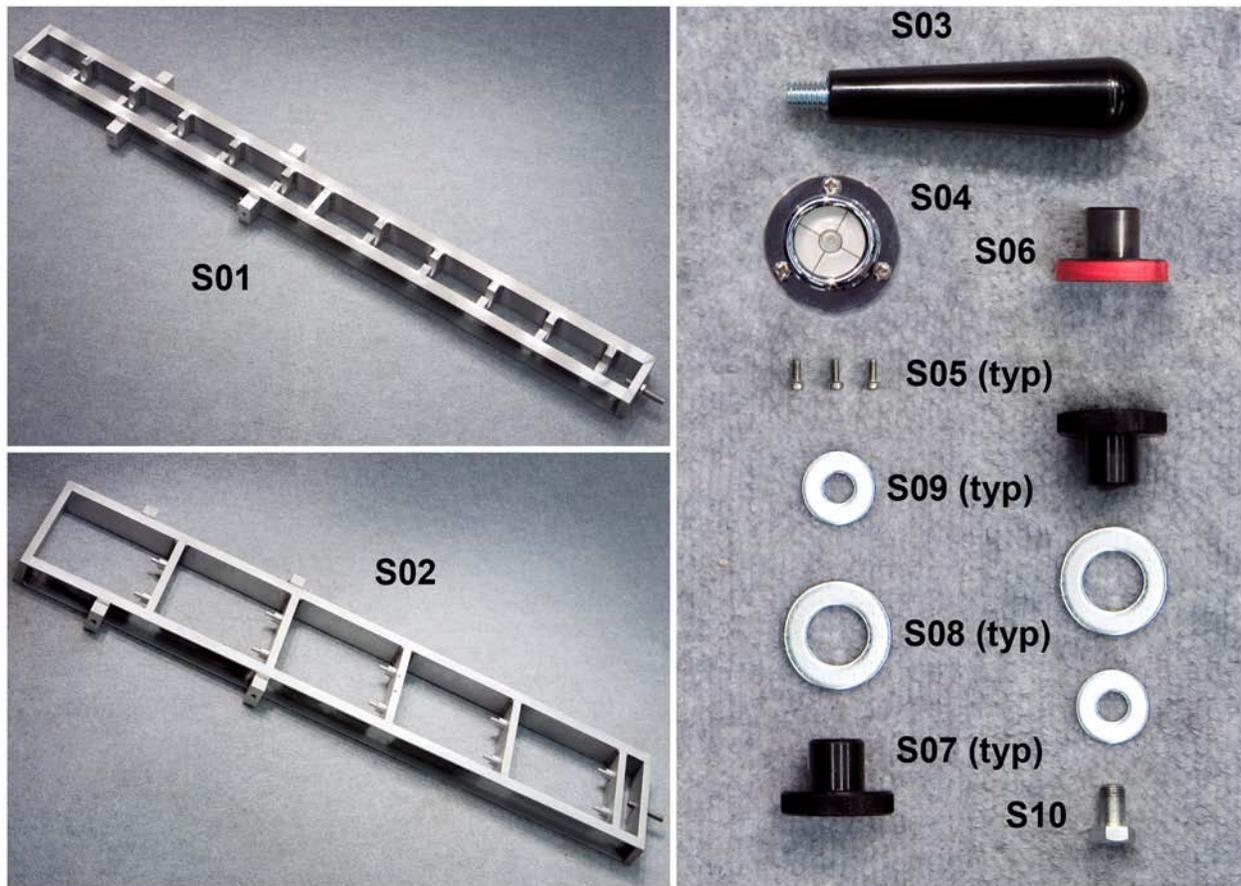
Figure 117. Photo. Equipment for calibration stand assembly.
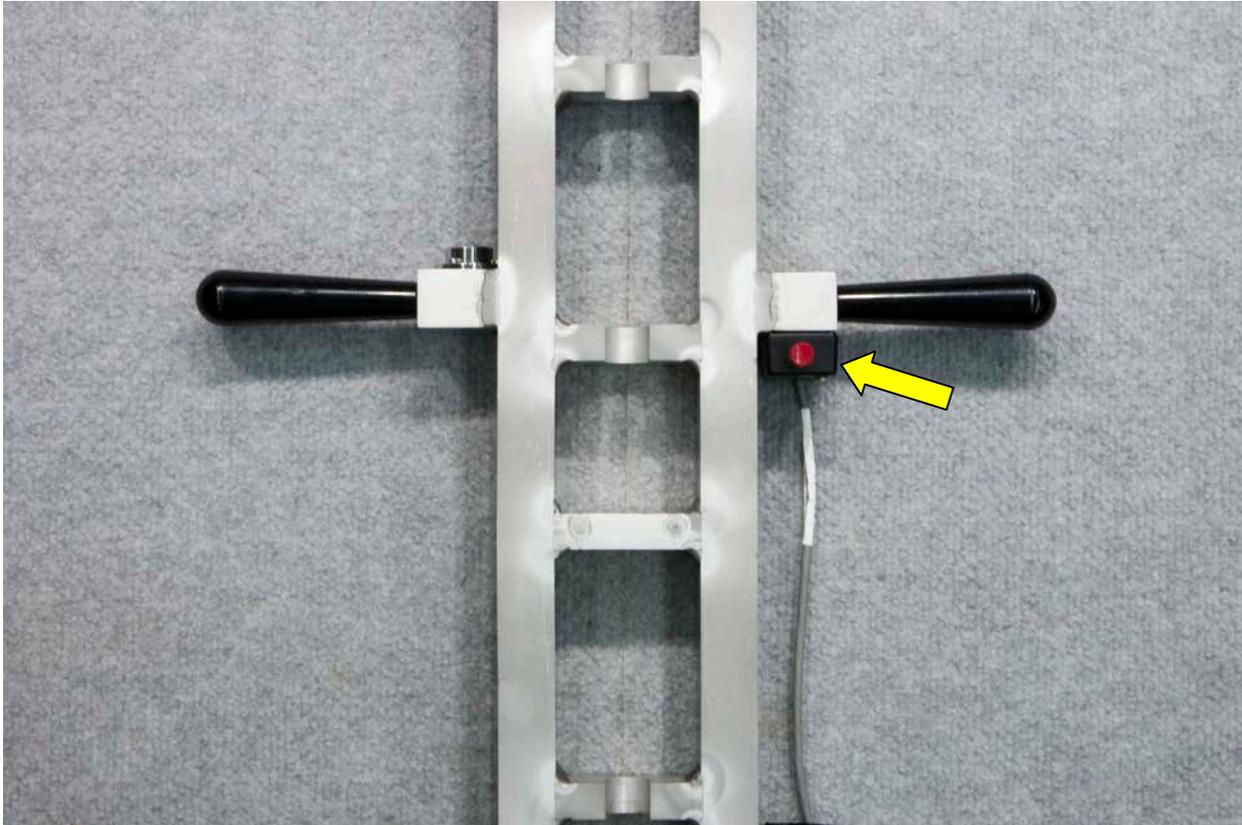
Figure 118. Photo. Calibration stand with handles, bubble level, and pushbutton.

Location of Accelerometer Box

On the geophone calibration stand, the accelerometer box is fastened to a shelf half way up the stand with two #10-24 x $^1/_2$-inch (12.7-mm) knurled head thumbscrews (S11).

On the seismometer calibration stand, the accelerometer box sits in the middle of the third shelf up on the stand and is held on with two thumbscrews (S11). The accelerometer box needs to be attached before the seismometers to ensure ease of use.

Deflection Sensors

For the geophone calibration stand, there are four different types of geophones that can be calibrated: Carl Bro, Dynatest®, KUAB, and JILS.

The Carl Bro and the JILS geophones are fastened to the stand in similar manners, though they each require their own adapters. The geophone and its respective adapter (S06 and S07) screw together with a $^3/_4$-inch (19.05-mm) inside diameter washer (S08) placed between the adapter and shelf of the stand and a $^3/_8$-inch (9.53-mm) inside diameter washer (S09) placed between the geophone and the shelf. Figure 119 shows a JILS geophone and adapter fastened to the stand. Carl Bro geophone adapters (S06) have different size threads and are painted red.

The Dynatest® geophones use a magnet to couple to the stand (see figure 120). To accomplish this, the JILS adapter (S07) is turned upside down and fastened to the stand with a $^3/_8$-inch

(9.53-mm) to 24 x $^5/_8$-inch (609.6 x 15.88-mm) hex head cap screw (S10) as shown in Figure 121. The Dynatest® geophone then sits on top of the adapter.

The KUAB geophones use a collar (S12), magnet (S13), and modified knob (S14) to attach to the stand, as shown in figure 122 and figure 123. The knobs are painted gold. The modifications to the knob are to drill and tap for a #10-24 machine screw thru the length of the knob, and to mill out a $^1/_8$-inch (3.18 mm) deep by 1-inch (25.4-mm) diameter recess at the top of the shank to allow the magnet assembly to fit inside.

Figure 119. Photo. Attachment of a JILS or Carl Bro geophone to the stand.
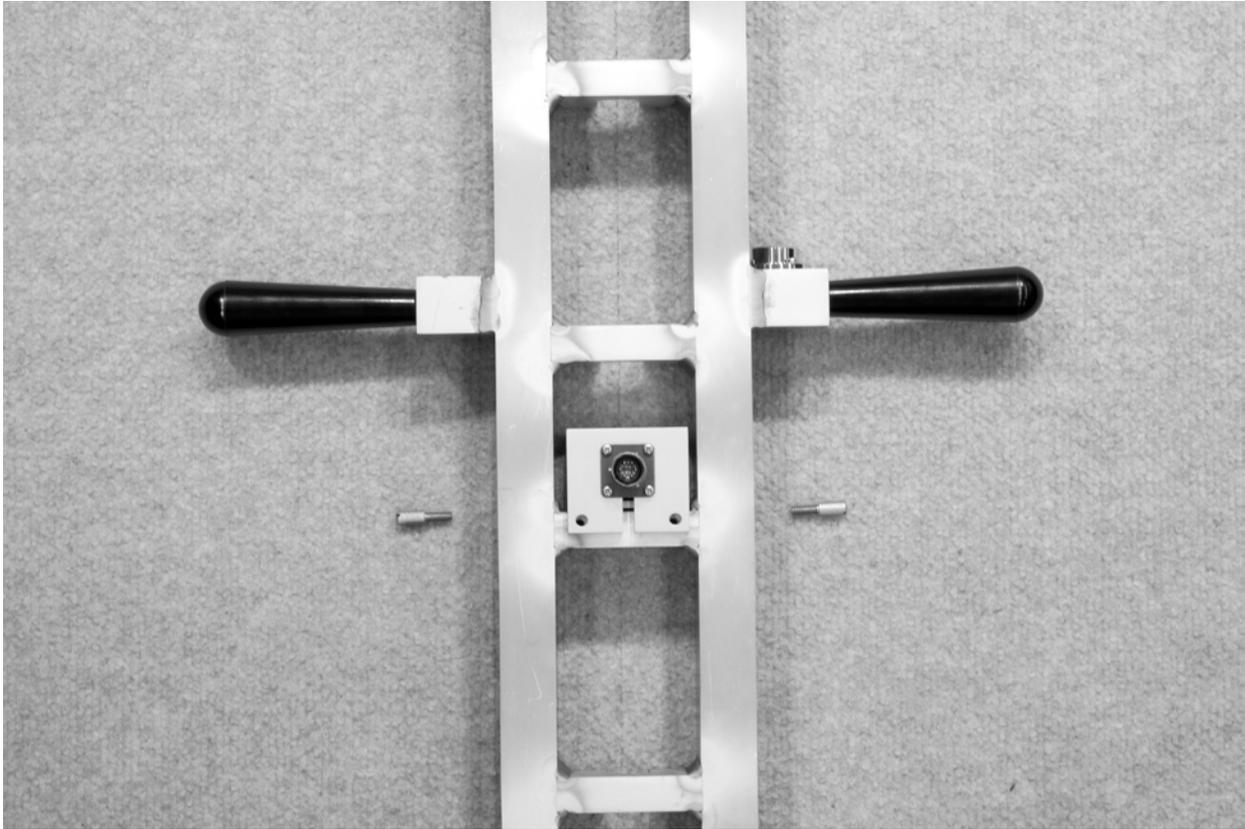
Figure 120. Photo. Placement of the accelerometer box on the geophone stand.

Figure 121. Photo. Attachment of a Dynatest® geophone to the stand.

Figure 122. Photo. KUAB geophone adapter equipment.

Figure 123. Photo. Attachment of a KUAB geophone adapter.

For the KUAB seismometer calibration stand, the seismometers are aligned in a two-column configuration as shown in figure 124. Users should tighten the setscrew at the bottom of the seismometer onto the standoffs on the stand.

Figure 124. Photo. Seismometer stand with sensors attached.

Using the Stand

During deflection sensor calibration, the calibration stand should be set up in the following order:

1. Attach the stand to the ball-joint anchor.

2. Fasten the accelerometer box to the stand after the accelerometer has been calibrated.

3. Place the deflection sensors in the correct configuration as shown on screen in the *WinFWDCal* program.

4. Use Velcro® to attach the pushbutton to the stand.

The following procedure is used when going from one trial to the next in relative and reference calibration:

*   For Dynatest® geophones, remove the sensor by tilting its casing until the magnetic force is reduced enough to pull it out of the stand. Never pull on the sensor's wiring to remove it.

*   For the Carl Bro and JILS geophones, loosen the adapter by unscrewing it to a point where the adapter/sensor combination can be slid out of the stand as a unit.

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- For KUAB geophones, remove the sensor and collar by tilting the casing until the magnetic force is reduced enough to pull it out of the stand. Never pull on the sensor's wiring to remove it.

- For KUAB seismometers, do not move the sensors in the stand. Simply rotate the stand horizontally about the connecting pin 180 degrees.

To couple the stand to the ball-joint, use the following:

- For both calibration stands, the connector pin slides into the clamp as shown in figure 125. The clamp is then tightened so that the stand cannot be removed.

- It is very important that the pin extending from the calibration stand is tightly fixed in the stand. Use several drops of Loctite® on the threads to assure that the pin does not come loose. Doing so will reduce the variability of the deflection data that is collected.

- The screws holding the pin in the clamp must be tightened firmly. The two bolts that hold down the ball-joint anchor to the floor must also be tight. However, do not use Loctite® on these connections.

- Finally, the two screws that adjust the ball-joint friction must be set so the calibration stand will stay upright when it vertical and not held, but a small tap horizontally will cause the stand to fall over easily to the rest stop.

Figure 125. Photo. Coupling the calibration stand and ball-joint anchor.

DATA ACQUISITION SYSTEM

Parts and Tools

Table 46. Parts and equipment for data acquisition.

No.	Tool/Equipment	Quantity	Notes
USB	Standard USB cable	1	
D01	Vishay to KUSB DAQ cable	1	Drawing CLRP-DAQ01
D01A	Vishay 2310B to KUSB DAQ cable	1	Drawing CLRP-DAQ01A
D01B	Vishay 2310B to DAQ cable (stock parts)	1	Drawing CLRP-DAQ01B
D02	Vishay to load cell cable	1	Drawing CLRP-DAQ02
D03	Accelerometer signal cable	1	Drawing CLRP-DAQ03
D04	Pushbutton to KUSB DAQ cable	1	Drawing CLRP-DAQ04
D05	Keithley KUSB-3108 16-bit DAQ	1	
D06	Vishay 2310 signal conditioner	1	

Note: Blank cells indicate no notes area available.

Cable Assembly

All cables should be fabricated according to their respective drawings. A full set of calibration cables includes an accelerometer signal cable (D05), a load cell signal cable (D04), a Vishay to KUSB DAQ cable (D03), and a pushbutton assembly (D06).

Connection Breakdown

Figure 126 illustrates FWD data acquisition system components and connections. The following list explains the connection breakdown:

- **Calibration center personal computer to Keithley KUSB-3108 DAQ USB:** Use a standard USB cable and plug into an available USB 2.0 port on the calibration computer.

- **Vishay to KUSB DAQ cable (D01):** Refer to drawing CLRP-DAQ01 for information on how to connect the signal cable to DAQ. The Molex® connector (serial number (s/n) 38331-5608) plugs into the output receptacle in the back of the signal conditioner.

- **Vishay to load cell cable (D02):** The Amphenol 15-pin plug (s/n PT06A-14-15P <SR>) end of the load cell signal cable (drawing CLRP-DAQ02) connects to the input receptacle on the back of signal conditioner. The Amphenol five-pin plug (s/n MS3106A 14S-5S) end of the cable connects into the receptacle on the load cell.

- **Vishay to accelerometer cable (D03):** The Amphenol 15-pin plug (s/n PT06A-14-15P <SR>) end of the accelerometer signal cable (drawing CLRP-DAQ03) connects to the

input receptacle on the back of signal conditioner. The Amphenol six-socket plug (s/n PT06A-10-6S <SR>) end of the cable connects into the receptacle on the accelerometer box.

- **Pushbutton to KUSB DAQ cable (D04):** Refer to drawing CLRP-DAQ04 for information on how to connect the pushbutton to DAQ.
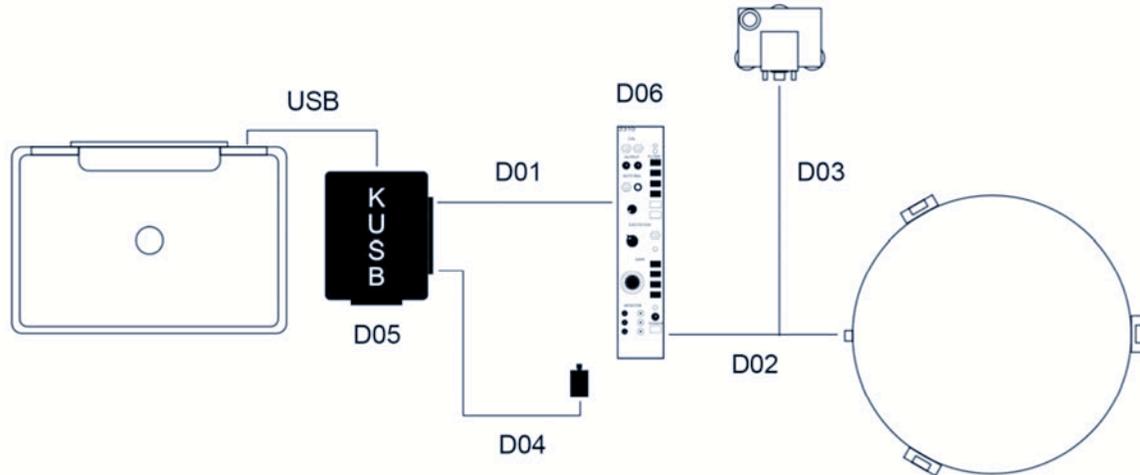
Figure 126. Illustration. FWD data acquisition system components and connections.

Vishay 2310 Signal Conditioner Settings

Table 47. Settings for the Vishay 2310 signal conditioner.

Vishay 2310 Setting	Load Cell	Accelerometer
Excitation	10 V	10 V
Filter	1 kHz	1 kHz
Gain	Load cell dependant[1]	2.0 x 1
Auto balance	Procedure dependant[2]	Always off
AC in	Fully extended	Fully extended

[1]Indicates that each calibration center is provided with the correct gain for its reference load cell from the annual calibration.
[2]Indicates that during the FWD load cell calibration, *WinFWDCal* provides instruction for when to use the auto balance switch on the Vishay signal conditioner.

COMPUTER

Table 48 presents the minimum requirements for a calibration computer. A laptop is recommended for portability.

Table 48. Minimum requirements for computer hardware.

Item	Requirement
Operating system	Microsoft Windows XP® SP3 or later (not including Windows 7®)
Physical memory (RAM)	1 GB
Hard disk space	At least 25 GB free space
Video adapter	DVI/VGA
Display	17-inch external color monitor (15-inch liquid crystal display on laptop)
Optical drive	CD-RW (DVD ±RW preferred)
Removable storage	3.5-inch floppy disk drive and 256 MB USB flash drive
USB 2.0 ports	At least four
Printer	Inkjet or laser

1 inch = 25.4 mm
Note: The USB flash drive, 3.5-inch floppy drive, and CD writer are used for transferring data between the FWD computer and the calibration computer.

APPENDIX G. SOFTWARE FLOW CHARTS

The following flow charts show the general outline of *WinFWDCal* Version 2.0.[11] The Microsoft Visual Basic® source code is available upon request from FHWA or CLRP.
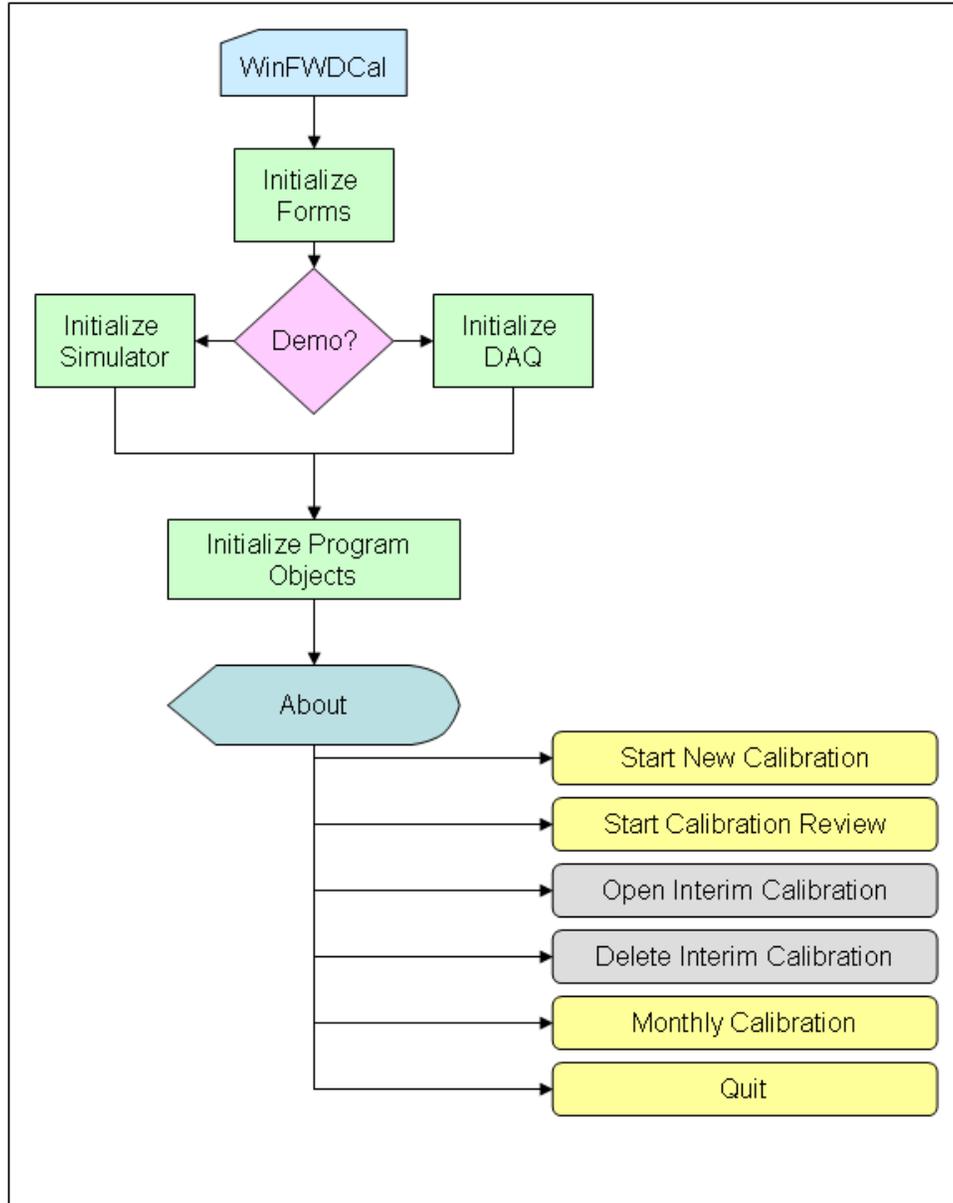
Figure 127. Illustration. *WinFWDCal* startup flowchart.
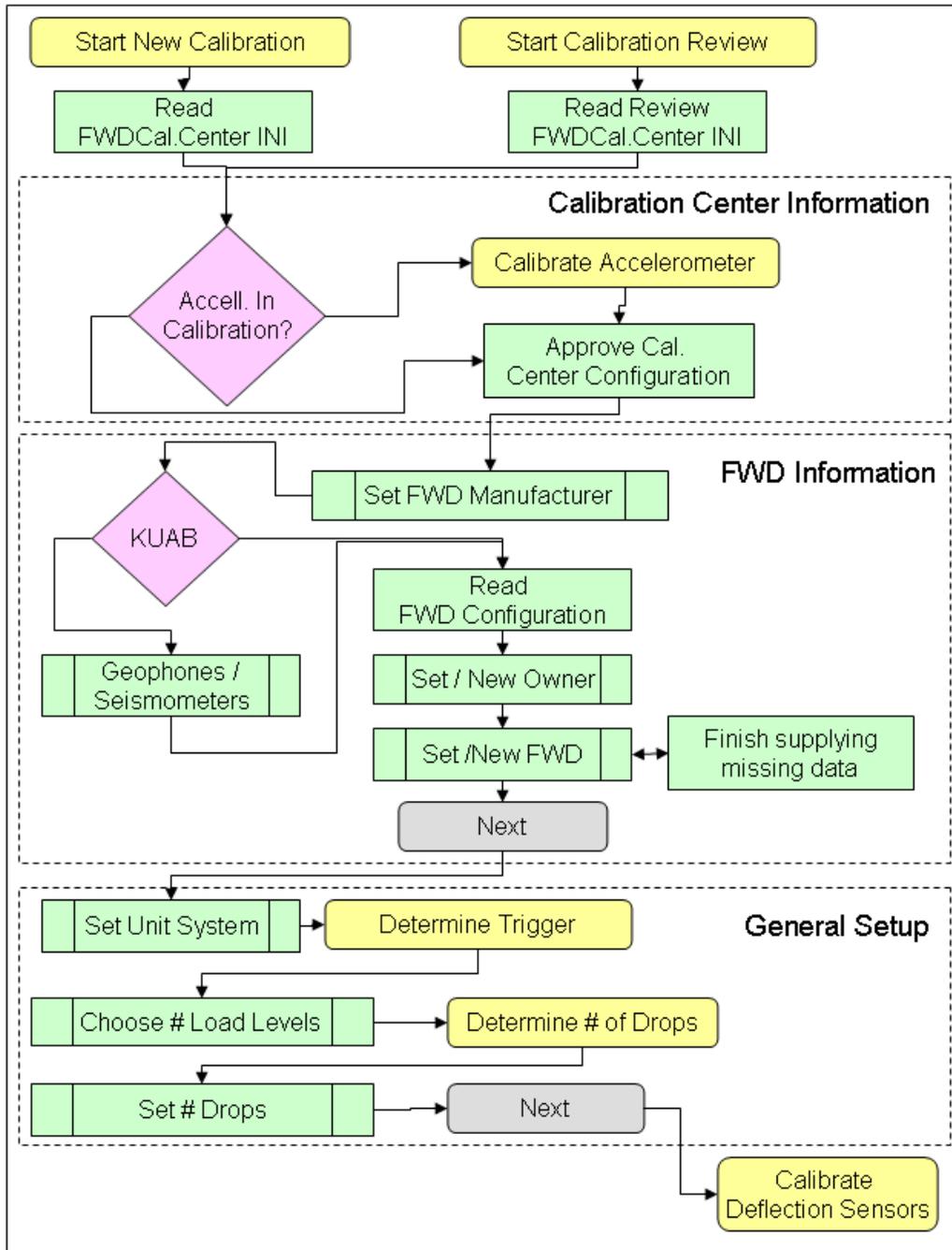
Figure 128. Illustration. *WinFWDCal* **start new calibration flowchart.**
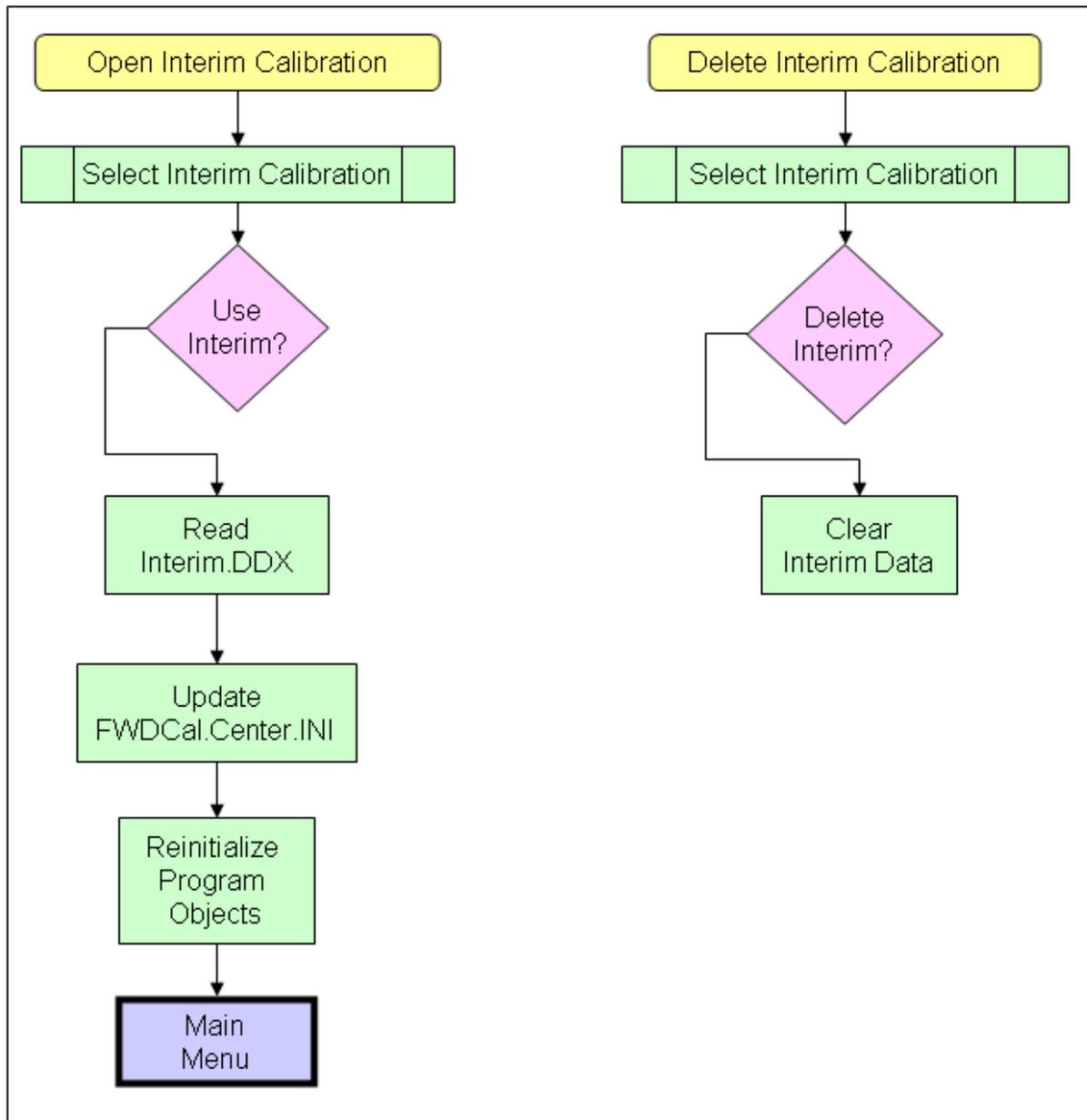
Figure 129. Illustration. *WinFWDCal* **open and delete interim calibrations flowchart.**
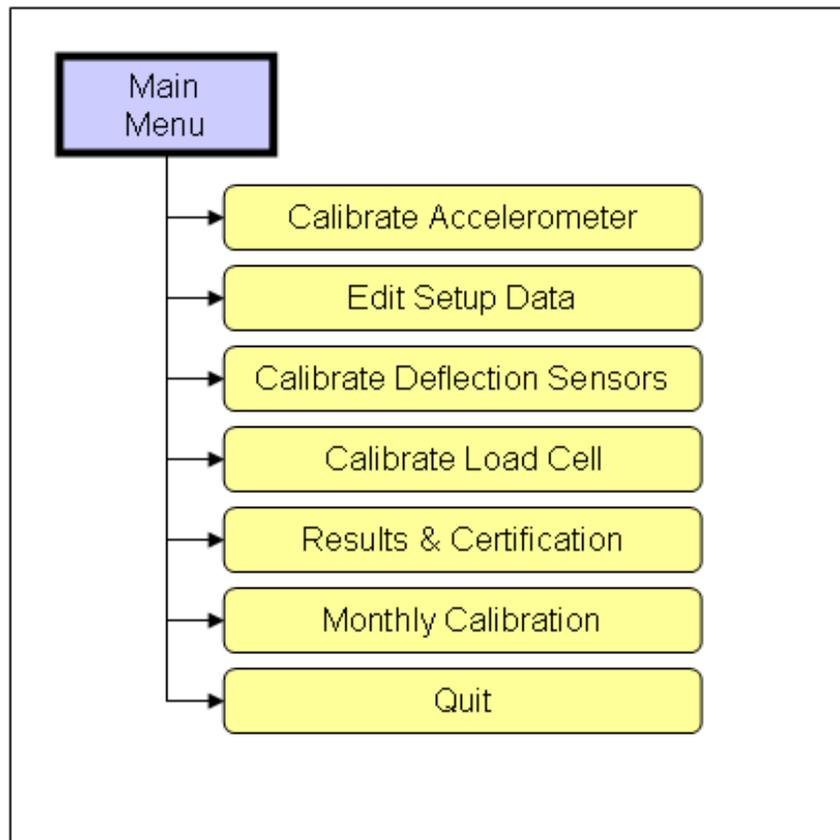
Figure 130. Illustration. *WinFWDCal* **main menu flowchart.**
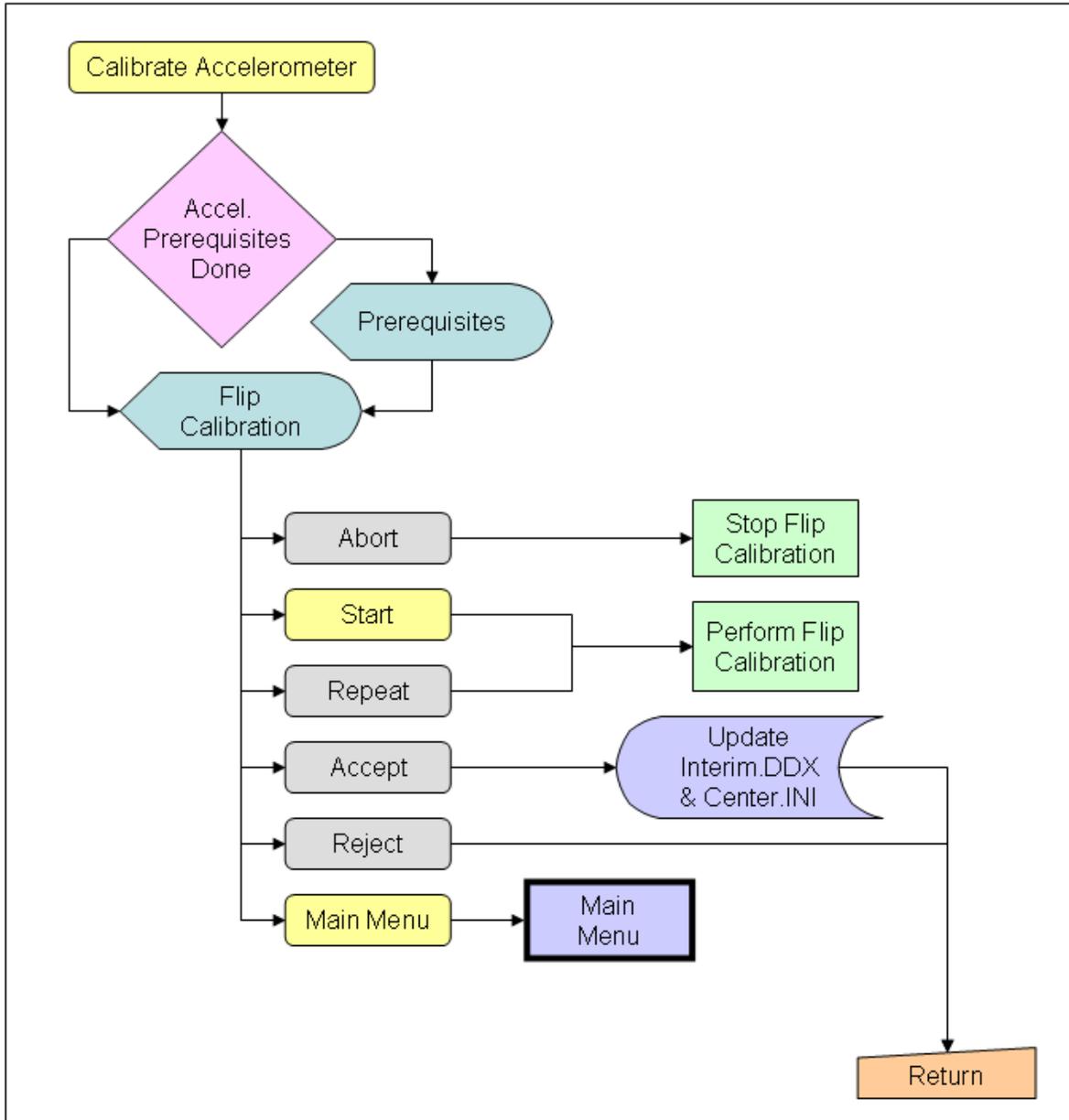
Figure 131. Illustration. *WinFWDCal* **calibrate accelerometer flowchart.**
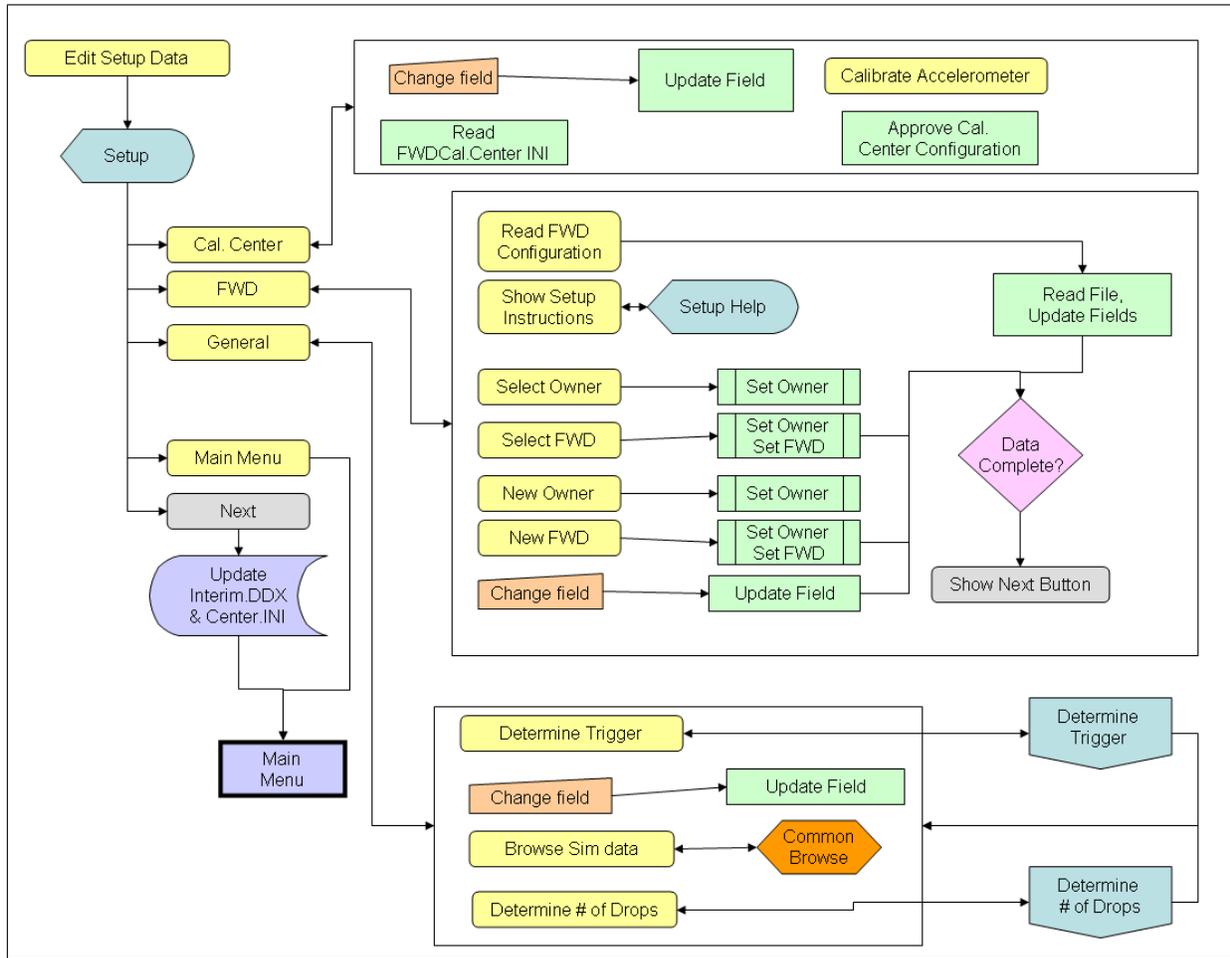
Figure 132. Illustration. *WinFWDCal* **edit setup data flowchart.**
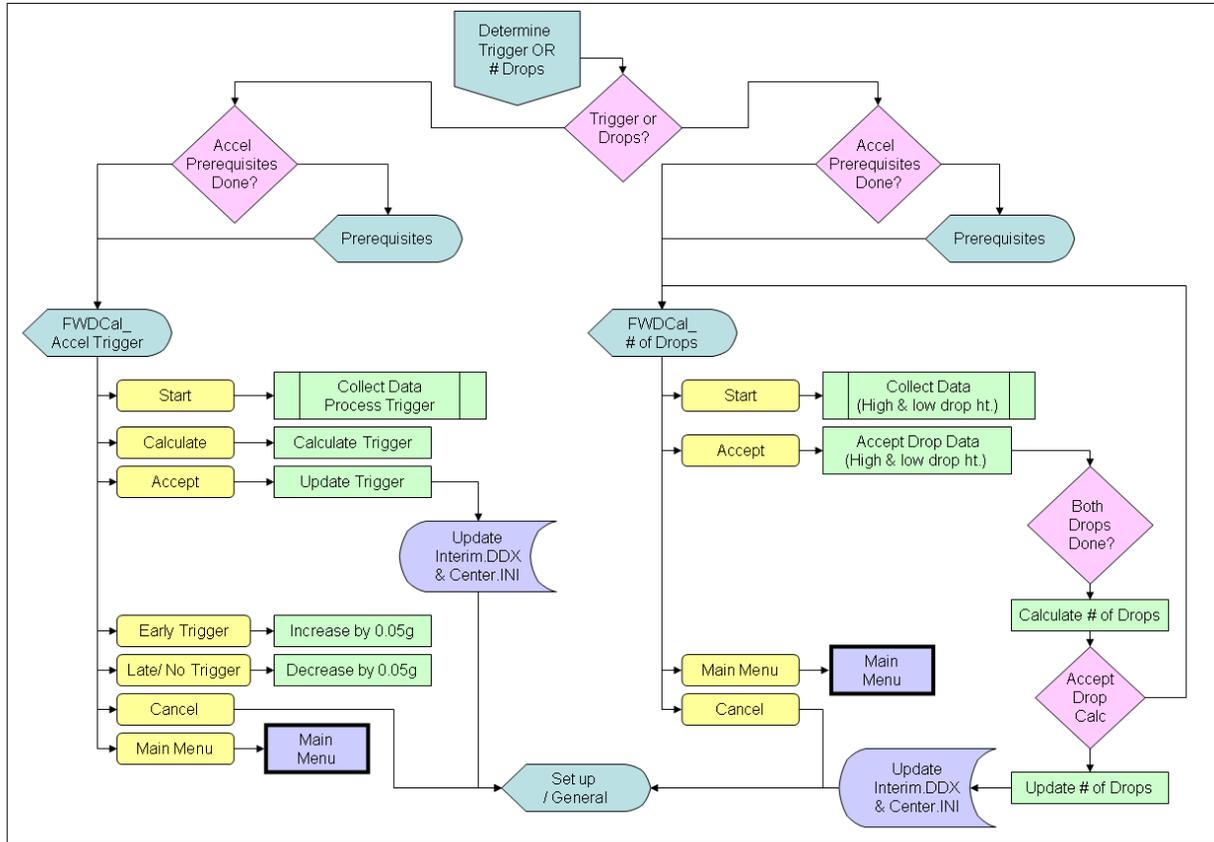
Figure 133. Illustration. *WinFWDCal* **determine trigger and number of drops flowchart.**
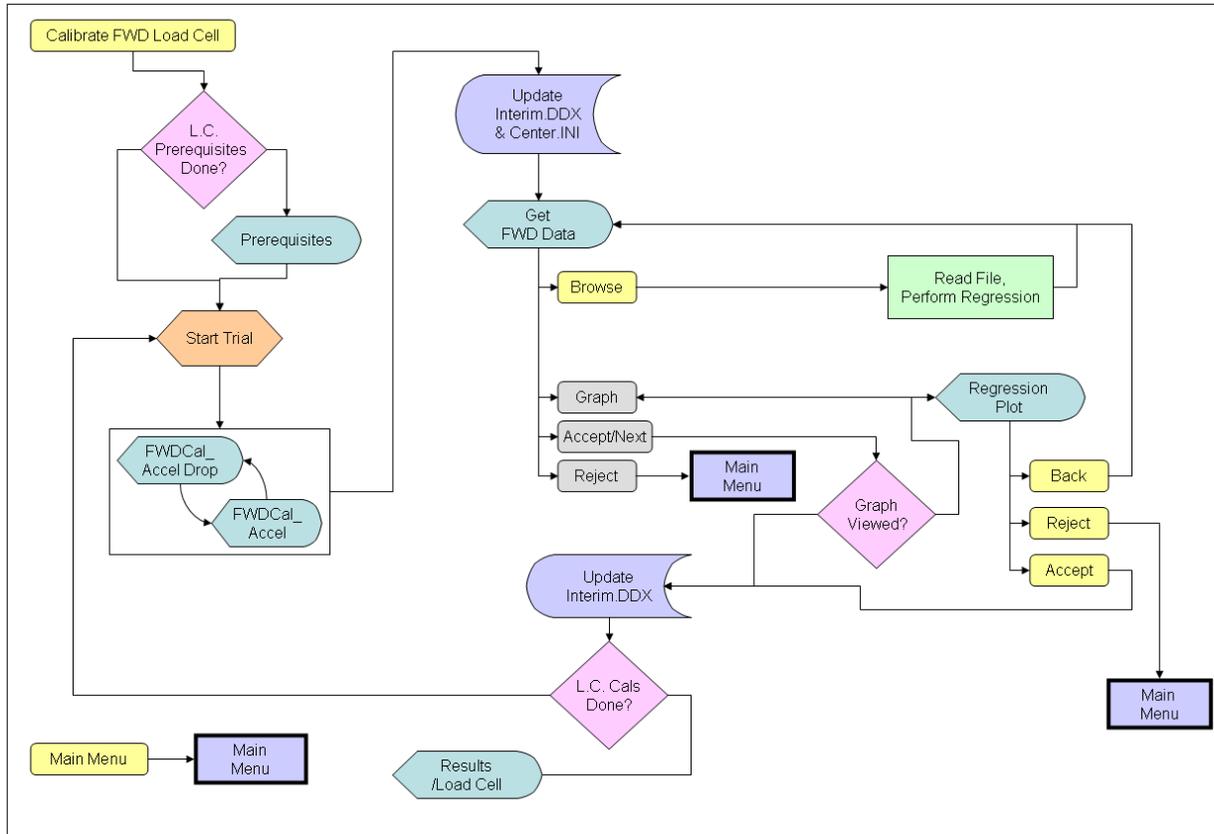
Figure 134. Illustration. *WinFWDCal* **calibrate FWD load cell flowchart.**
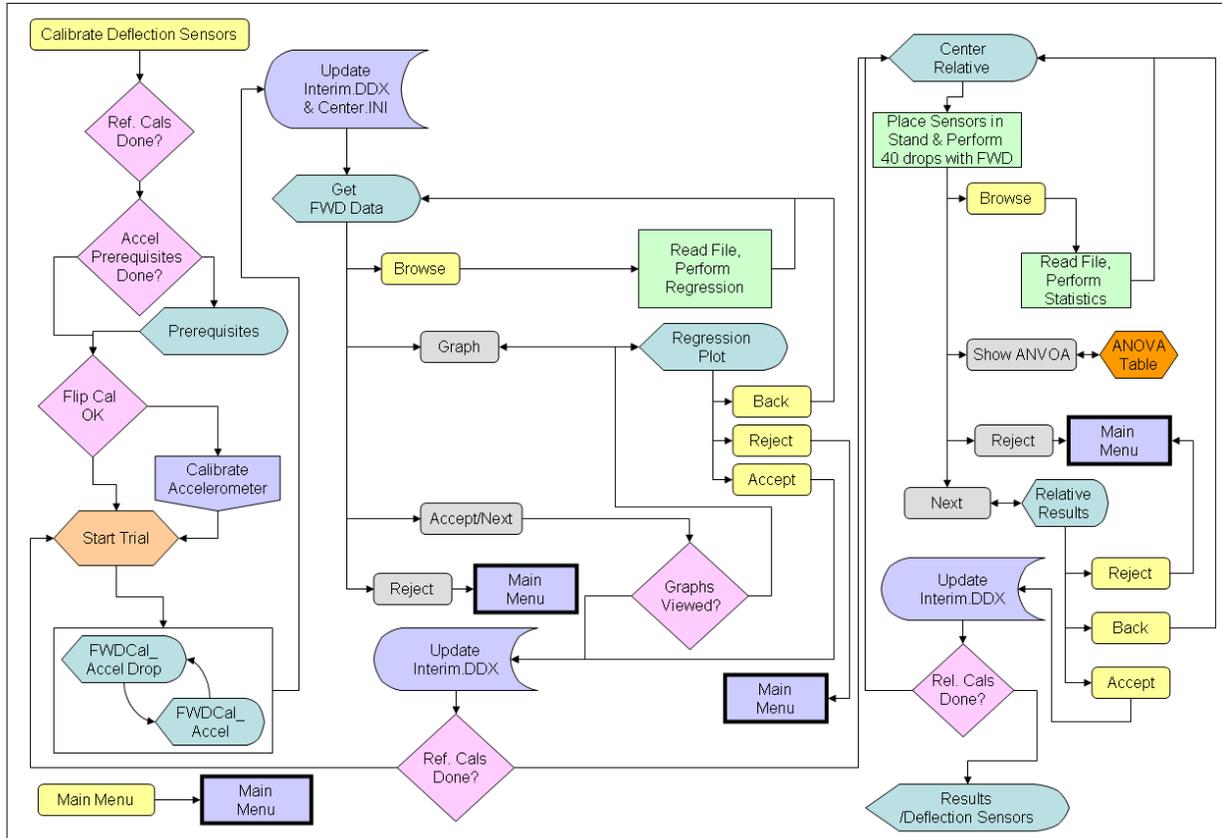
Figure 135. Illustration. *WinFWDCal* calibrate FWD sensors flowchart.
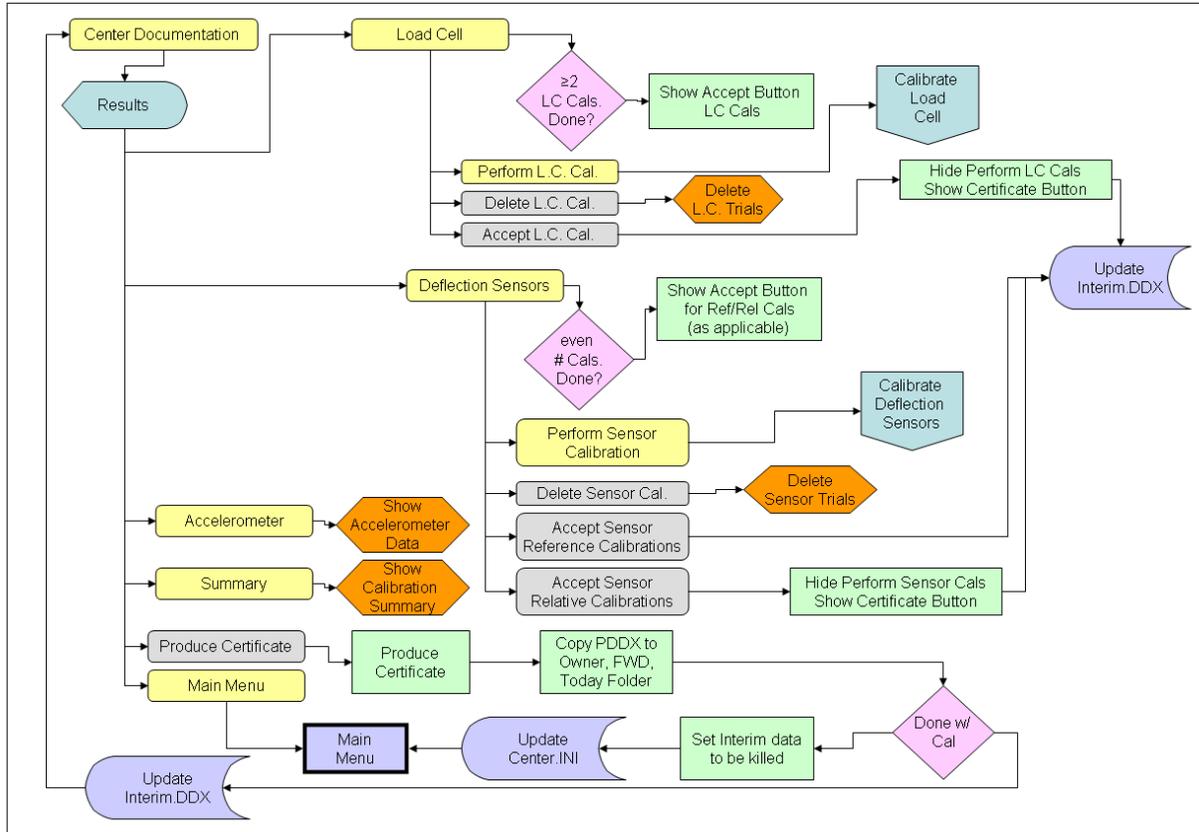
Figure 136. Illustration. *WinFWDCal* **center documentation flowchart.**
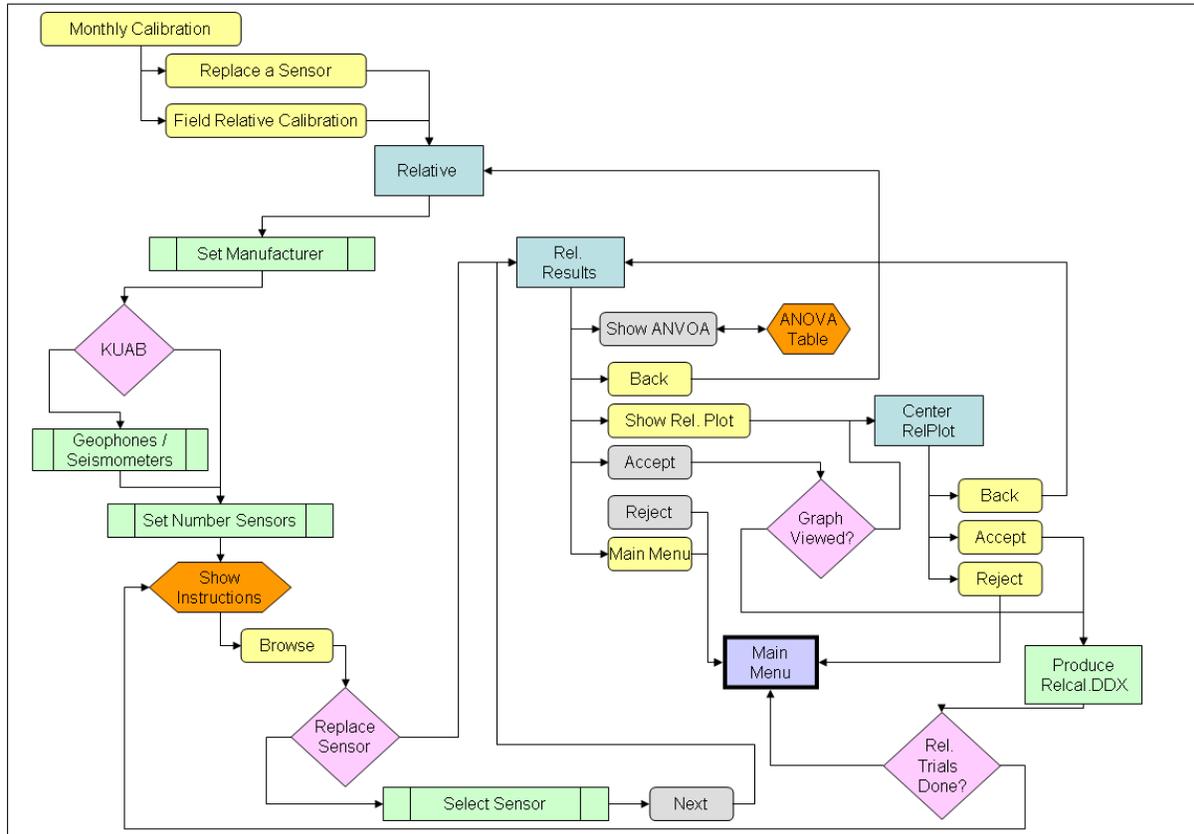
Figure 137. Illustration. *WinFWDCal* monthly calibration flowchart.
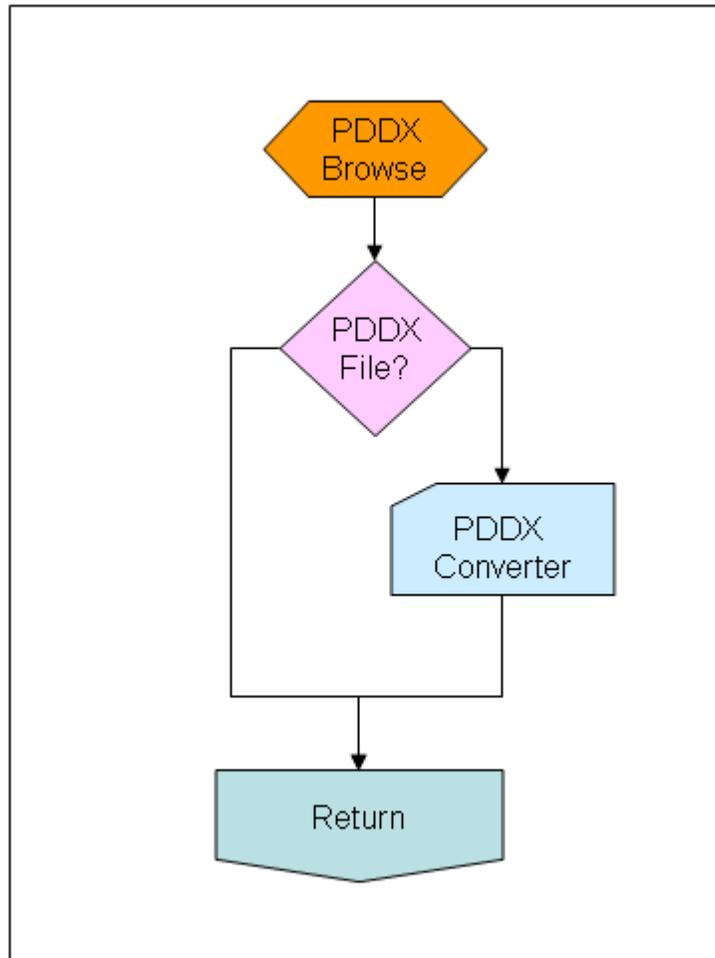
Figure 138. Illustration. *WinFWDCal* search for file and convert to PDDX input flowchart.
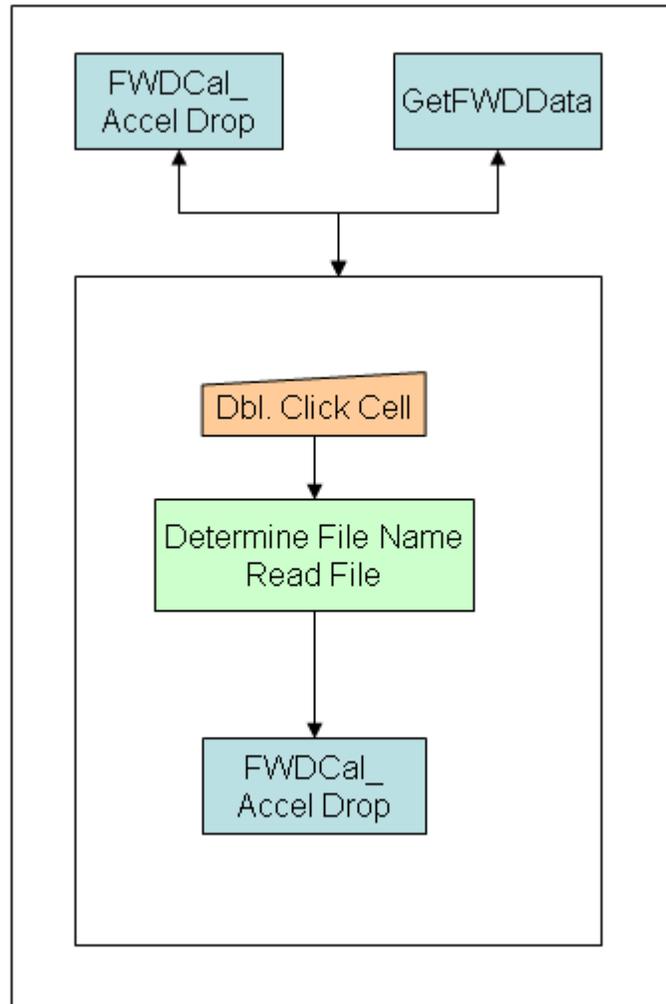
Figure 139. Illustration. *WinFWDCal* **review time history by clicking on drop cell flowchart.**
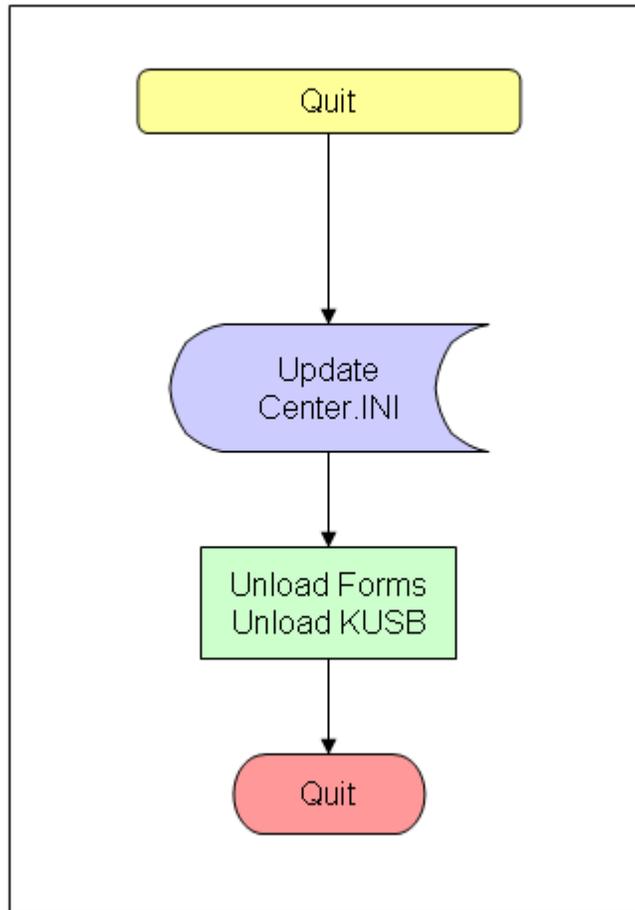
Figure 140. Illustration. Quit *WinFWDCal* flowchart.

- South Carolina Department of Transportation.

- South Dakota Department of Transportation.

- TxDOT.

- Washington Department of Transportation.

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