FWD Calibration Center and Operational Improvements:

Redevelopment of the Calibration Protocol and Equipment

Publication No. FHWA-HRT-07-040 **February 2009**

U.S. Department of Transportation
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FOREWORD

The *FWD Calibration Center and Operational Improvements: Redevelopment of the Calibration Protocol and Equipment* outlines the updates and improvements to the SHRP FWD calibration procedure. It provides information on how to calibrate an FWD according to the new procedure. It explains the basic improvements to the procedure and provides details about the critical updates. The report also provides, in the appendices, the updated protocol for FWD calibration, the drawings and specifications of the hardware needed for FWD calibration, an updated specification for the Pavement Deflection Data Exchange protocol, and a flowchart for the new calibration software, *WinFWDCal*. This report will be of interest to engineers who do structural evaluation of pavements. This is a final report covering the initial two-year Phase I and the subsequent Task Order 1 of the pooled fund study TPF-5(039).

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16. Abstract

The objective of this study is to upgrade the existing FWD calibration system to make calibration sustainable for the next decade without a loss of quality while ensuring 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 advantages of improvements in technology. The primary result of the FWD calibration procedure is to obtain "gain factors" used to correct FWD load cell and deflection sensor data to agree with the calibration instrumentation.

Changes incorporated in the new FWD calibration procedure include: replacing the reference LVDT with an accelerometer for deflection sensor calibration, development of a multiple sensor stand to allow calibration of all deflection sensors simultaneously, updating the calibration software to a modern programming language with the ability to read native data formats from each brand of FWD, and the use of modern data acquisition techniques to eliminate sensitivity problems from the older SHRP 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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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 AND MEASUREMENTS

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
CD	Compact Disk
CLRP	Cornell Local Roads Program
COTR	Contracting Officer's Technical Representative
DAQ	Data Acquisition Board
DOT	Department of Transportation
DVD	Digital Versatile Disk
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
HRTS	Office of Research and Technology Services
HWD	Heavy Weight Deflectometer
LTAP	Local Technical Assistance Program
LTPP	Long Term Pavement Performance (Program)
LVDT	Linear Variable Differential Transducer
micron (µm)	one millionth of a meter or 0.0039 mils
mil	one thousandth of an inch or 25.4 microns
NIST	National Institute of Standards and Technology
PDDX	Pavement Deflection Data Exchange
QC/QA	Quality control/quality assurance
SHRP	Strategic Highway Research Program
TFHRC	Turner-Fairbank Highway Research Center
TRB	Transportation Research Board
USB	Universal Serial Bus
USDOT	United States Department of Transportation
ISA	Industry Standard(s) Architecture
PCI	Peripheral Component Interconnect
DOS	Disk Operating System

CHAPTER 1—INTRODUCTION

SOURCES OF ERRORS IN FWD MEASUREMENTS

Deflection data from the falling weight deflectometer (FWD) are used for structural evaluation of pavements. Calculations can be made of remaining pavement life, load-supporting capacity, and the required thickness of structural overlays. The results can be used for project-level or network level pavement systems management.

Various mechanistic models of pavements are used in the analysis, including elastic layer theory, finite element theory, discrete element theory, etc. The analytical methods all need the moduli of elasticity of the pavement layers as an input. Pavement deflections, together with backcalculation methods, can provide the layer moduli. However, the precision of the deflections has a major influence on the accuracy of the backcalculated moduli and subsequent analyses.(12)

The FWD data have three 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. Random and bias errors are also illustrated in the figure.

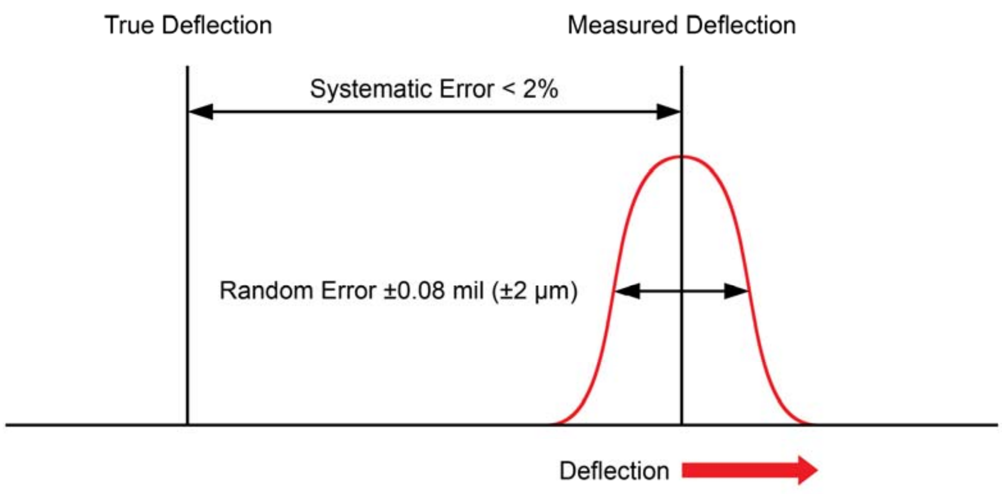

Figure 1. Chart. Random error and bias (systematic) error.

Seating Errors

When the FWD first occupies a new test point, seating errors come about from the mechanical placement of the sensors (geophones or seismometers) on the pavement. Because of roughness and loose debris on the road surface, the sensors are not always seated firmly when they are placed down. The deflection sensors can be seated fairly easily by doing several initial drops of the FWD mass, without recording the data. It is seldom necessary to do more than two or three drops to achieve good seating. However, extensively cracked pavements, such as alligator cracking, may pose a seating problem regardless of how many seating drops are done.

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 need to digitize 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 provided by the FWD manufacturer, the digitized signal is converted to displacement in engineering units (mils, microns, and so on). Digital conversions include a small amount of error, typically one or two least significant bits. The equipment manufacturers state that the random error is on the order of 1 to 2 microns (0.04 to 0.08 mils) per reading. This is independent of the peak amplitude.

Thus each deflection reading has a small component of random error in it. Because they are *random*, some of the errors are positive and some are negative. It is not possible to know for any individual drop whether the random error is positive or negative, or what its magnitude is. But 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 $X / n^{0.5}$. That means 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. So, for example, by doing four drops and averaging them, we can reduce the random error by half (since $\sqrt{4} = 2$).

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

Bias Errors

Bias errors occur due to limitations in the calibration of the sensors. The errors are directly proportional to the reading. If the deflection doubles, the bias error will be twice as big in magnitude, or nearly so. The bias error can come about for any number of reasons, but the FWD manufacturers generally state that the bias error will be no more than ±2 percent of reading. So the bias error could be zero, or a little bit positive, or a little bit negative, but unlike the random error it will be constant (as a percentage of the reading) for a given sensor from one reading 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 that is outlined in this report. The procedure involves using a reference sensor (a reference load cell for load calibration, and a reference accelerometer for deflection calibration) that is independently calibrated to a high degree of precision and reliability. The peak result from the FWD is compared to the peak recorded by the reference sensor. The ratio (reference device divided by FWD reading) becomes the *calibration factor* (also called the gain factor).

Deflections must be fairly large to be able to detect the bias error. Referring to Figure 1, if the measured deflection is close to the true deflection, the random error will mask the bias error. For example, if a measured deflection was 50 microns (2 mils) and the bias error was two percent, the bias error would be only 1 micron (0.04 mils). With a random error of 2 microns (0.08 mils) the bias error would be nearly impossible to detect using statistical methods.

Similarly, there are limits on how small the bias error can be reduced to, even with a large deflection. In the calibration procedure we typically have an average deflection around 500 microns (20 mils). When the bias error is down to 0.3 percent, the difference between the measured deflection and the true deflection is only about 1.5 microns (0.06 mils). Again, this is getting into a range where it is difficult to reliably detect the bias error and, effectively 0.3 percent is a practical lower limit that FWD calibration can achieve.

Significance of Errors

At the 1988 ASTM Conference on Backcalculation, Irwin, et al [(12)] reported on the effect of random deflection errors on backcalculated layer moduli. They found that random error alone, 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 100 microns (4 mils), a two percent bias error in an uncalibrated FWD will be larger than the ±2 micron (±0.08 mil) random error. Thus the combined effect of random error and bias error together could be substantially more detrimental to the backcalculated moduli than random error alone.

DEVELOPMENT OF THE SHRP CALIBRATION PROTOCOL

The dramatic effect of FWD errors on backcalculated moduli led the Strategic Highway Research Program (SHRP) in 1988 to begin the development of an FWD calibration procedure with the stated goal of reducing the bias error as close as possible to 0.3 percent. This goal was achieved by the 1994 SHRP FWD Calibration Protocol.[(16)] By reducing the bias error to 0.3 percent, a 2 micron (0.08 mil) random error would be larger than the bias error for deflections up to 667 microns (26 mils). The deflections measured on most good quality roads are seldom that large, especially at the outer sensors. Thus random error, which is not preventable, would control the accuracy of backcalculated layer moduli in most circumstances.

Four regional FWD calibration centers were established by SHRP in 1992. The State Departments of Transportation (DOTs) in Pennsylvania, Texas, Minnesota, and Nevada operated them. The western center in Nevada was later moved to Colorado. Since their inception, the demand for FWD calibration services has risen steadily,[(15)] and in August of 2001, the AASHTO

Subcommittee on Materials adopted a resolution supporting the continued operation of the calibration centers.

Due to changes in technology, the original calibration hardware and software had become obsolete. There was a particular need for updating of the *FWDREFCL* software [16] which was originally written as a DOS program and utilized a Metrabyte DAS-16G data acquisition board. DOS has been replaced by Windows, and the ISA bus used by the Metrabyte board has been phased out by the computer industry.

Orr and Wallace [15] reported that the 1992 SHRP calibration procedure had several shortcomings:

- The procedure was not well adapted to all types of FWDs.
- It was a slow process, requiring nearly a full day to complete.
- Movement of the inertial block holding the LVDT was sometimes a problem.
- Manual data entry was time-consuming and could lead to possible typing errors.
- The procedure was not field portable; hence the FWDs had to go to a calibration center. The need for out-of-state travel posed a problem for some agencies.

REDEVELOPMENT OF THE PROTOCOL

Pooled Fund Study Tasks

To overcome the problems noted above, in 2002 a pooled fund study, TPF-5(039), was initiated by the FHWA with the financial support of 17 State DOTs (see the Acknowledgements section). *Overall, the primary goal of the study was to modernize and streamline the calibration procedure, without reducing the accuracy and precision of the results obtained, compared to the earlier SHRP approach.*

In order to meet this goal, the various FWD manufacturers and FWD Calibration Centers were contacted for suggestions and ideas. Based upon the suggestions received from the Calibration Centers, manufacturers, and those received at annual meetings of the FWD Users Group, a series of tasks was developed. The tasks performed during the pooled fund study are listed below:

- **Develop a universal calibration protocol.**
  The redesigned equipment and software must work with all four brands of FWDs currently sold in the North American market. *This was accomplished.*
- **Expedite the calibration process.**
  A goal was established to reduce the time to perform a calibration to under three hours. *This was accomplished.*
- **Develop new hardware and procedures to overcome or correct for beam/block movement issues and equipment obsolescence.**
  New hardware was designed that sped up the process and overcame the beam movement issue. The old procedure used an LVDT as the reference deflection sensor. At certain times of the year movement of the inertial system holding the LVDT was a problem. The LVDT

was replaced with an accelerometer whose signal is double integrated to obtain deflection. *The goal was accomplished.*

- **Develop Windows-based software to perform all activities of FWD calibration.** The entire FWD calibration procedure is controlled by the new software, *WinFWDCal*. The new software provides a dual-unit option in metric and U.S. customary units. Quality control of the data is built into the software. Electronic data transfer speeds up the calibration process. *WinFWDCal* also provides a mechanism for the storage of data for historical review. *The goal was accomplished.*

  Software updates have been issued quarterly since the original release in November 2006. A major new release is expected in mid-2009.

ADDITIONAL ACCOMPLISHMENTS OF THE POOLED FUND STUDY

The four original SHRP calibration centers have been outfitted with new equipment, and the personnel have been trained and certified. In addition, two new calibration centers have been established, operated by Montana DOT and Caltrans. Both new centers expect to be fully operational by summer 2009. The calibration center operated by Indiana DOT has been updated and is currently operational. While not a part of the pooled fund study project, calibration centers have been set up at the manufacturing facilities of 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, WA has been updated, and a new calibration center has been established at the Australian Road Research Board in Melbourne, Victoria.

The new equipment and procedure is fully portable. On site calibrations, conducted by certified technicians, have been made in Hawaii and Chile, and nine different FWDs have been calibrated at remote locations in Australia. Three agencies are currently offering on site calibrations, and others have expressed an interest in doing so.

A spin-off product of the project came from the need to electronically transfer the 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 led to the development of *PDDXconvert*, a software program that converts each native FWD data file to the PDDX standard. It is used integrally with the *WinFWDCal* program to seamlessly transfer FWD to the calibration computer. The *PDDXconvert* can also be used in a stand-alone mode in support of other software, such as that used for backcalculation. For example the *MODTAG* backcalculation program uses *PDDXconvert* so that data for all types of FWDs can be processed to determine pavement layer moduli.

Quality assurance procedures have been developed for the purpose of annual recertification of the calibration center operators. The procedures and checklists have been applied successfully and updated following two cycles of QA visits. Currently, all FWD calibration centers are operated by certified technicians.

Adoption of the Calibration Procedure by AASHTO

The SHRP FWD Calibration Protocol was originally adopted by AASHTO as Recommended Practice R 32-03.[2] The AASHTO procedure has recently been revised to reflect the changes brought about by the pooled fund project. In January 2009 the AASHTO Subcommittee on Materials approved and adopted the revised procedure. In summer 2009 the revised procedure will be published as R 32-09. [3]

Revision of the PDDX Standard

In April 1998 AASHTO adopted a standard for pavement deflection data exchange (PDDX). [1] The 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 Users 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 decided to use the PDDX standard output as the means for electronic exchange of FWD calibration data. However, several problems quickly became evident:

- The DDX file input requirements for *DARWin* were not fully compliant with the AASHTO PDDX standard.
- The AASHTO PDDX standard did not provide a placeholder for all of the FWD identification data that is needed for FWD calibration.

To overcome these problems and move the project forward we wrote the *PDDXconvert* computer program. In addition, as an appendix to this report, a revised version of the PDDX standard has been promulgated that will assure compatibility of the DDX files and satisfy the original intent of the AASHTO PDDX standard.

Development of an Informational Video

To familiarize FWD owners with the new calibration procedure, and also to encourage the State DOTs to utilize the calibration facilities, a brief 11-minute video has been produced. It is available at the LTPP website, and hard copies in CD format can be obtained from FHWA.

CHAPTER 2—OVERVIEW OF THE NEW FWD CALIBRATION PROCEDURE

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

- Independently calibrated reference transducers are used to calibrate the load and deflection measurement systems on the FWD. This is called reference calibration.
- After reference calibration, relative calibration *of the deflection sensors* is used to refine the calibration factors (also known as gain factors).
- The gain factors are checked for acceptability, and then entered into the FWD operating system (i.e., the "field program") in the FWD computer.
- The gain factors are used as multipliers to the internal results from the FWD.

Very few changes have been made in the load system calibration procedure. It is done in a manner that is similar to the old SHRP protocol. However, more flexibility than before is allowed in the number of load levels used.

The deflection sensors are calibrated simultaneously by placing them in a very rigid columnar stand along with a reference accelerometer. This greatly expedites the procedure, as the old SHRP protocol did reference calibration one sensor at a time.

Relative calibration is carried out in the same stand as reference calibration. The procedure provides a check of the quality of the calibration. The sensors are rotated once to remove any bias due to position in the stand. Only one rotation is required, which also helps to speed up the procedure.

The new protocol requires two people, the FWD system operator and the calibration system operator. It takes less than three hours to perform provided the FWD is in good working condition. The detailed FWD Calibration Protocol is contained in Appendix I.

WINFWDCAL

The new protocol is conducted using a new software program, *WinFWDCal*.[7] The program reads input from the FWD computer and produces all required outputs. The Windows user interface is graphically oriented, showing the time history data for each drop during reference calibration. Typical screens are shown in Figure 2.

Data from the FWD are transferred electronically to the calibration computer. A flash drive or a floppy disk or a CD can be used. This enhances the accuracy of the data transfer, and it also speeds up the calibration process. *WinFWDCal* utilizes an FWD data file format conversion program called *PDDXconvert*.[6] It reads the data files from all types of FWDs in their native format and converts them to an AASHTO standard DDX format.

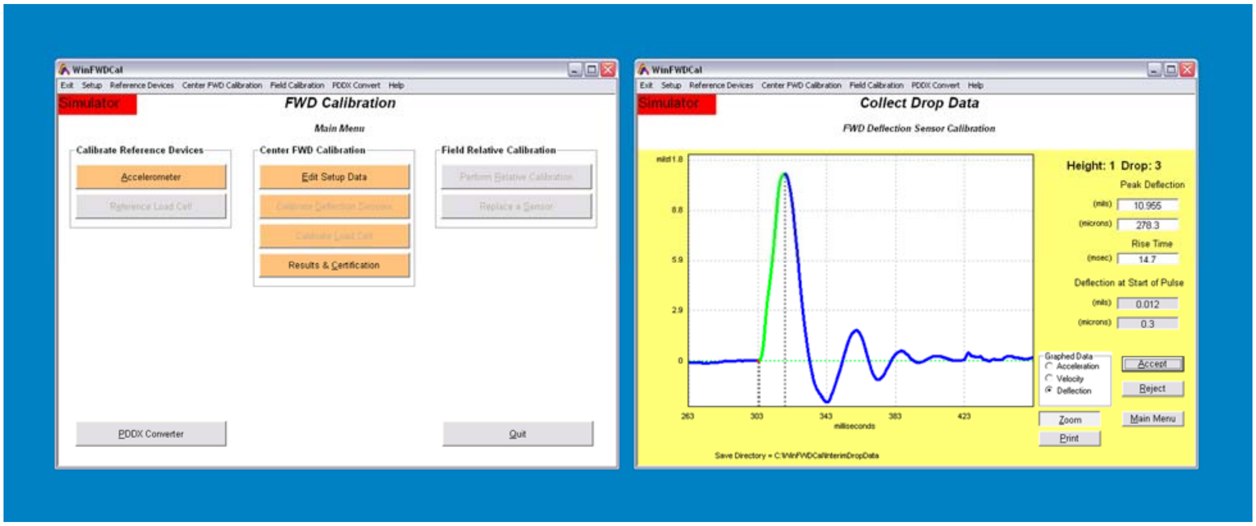

Figure 2. Photo. Screenshots from the *WinFWDCal* software program.

The data are checked during acquisition to assure that accurate, high quality results are obtained. A calibration certificate is produced, and where prior calibration results are available for a particular FWD, the history is reviewed as part of the acceptance process.

At the end of the calibration the data are retained for historical and forensic analyses.

CALIBRATION OF THE REFERENCE DEVICES

The calibration of the two reference calibration devices (load and displacement) is done versus independent reference systems:

- The reference load cell is calibrated with a NIST traceable universal testing machine on an annual basis. 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. Accuracy approaching 0.1 percent of full scale is achieved for the reference load cell.

  The calibrated range of the reference load cell was increased from 89 kN (20,000 lbf) to 107 kN (24,000 lbf) to accommodate a higher pre-load force from the FWD. A study performed by Orr and Wallace in 2002 confirmed the need for annual calibration of the reference load cell.[15]

- The reference accelerometer is calibrated on a daily basis using Earth's gravity field. Daily calibration accounts for temperature, hysteresis, and other known variations in the response of the reference accelerometer. Non-linear characteristics of the accelerometer are corrected using factors provided be the manufacturer.

  Gravitational differences between the regional calibration centers could result in a small difference in the results of the daily calibration. The maximum difference in gravity constants between the Pennsylvania and Colorado calibration centers (at the lowest and highest elevations) would result in a difference of about 0.1 percent or less than 0.5 microns (0.02 mils) for a deflection of 500 microns (20 mils).[14]

SIGNAL CONDITIONER AND DATA ACQUISITION SYSTEM

The Vishay model 2310 signal conditioner is still used. The major change is the use of a Keithley model KUSB-3108 USB data acquisition board (DAQ), rather than the ISA-bus Metrabyte board. The USB DAQ is an improvement since it is small and it 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.

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

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

CALIBRATION OF THE FWD

The new protocol provides for two types of FWD calibration: Annual Calibration and Monthly Calibration. Annual Calibration, which historically has been done at calibration centers, can also be done on site, wherever the FWD is located. The equipment is sufficiently portable that it can be taken to the FWD to do an annual calibration. Whether it is done at a center or on site, a Certified Technician must perform the annual calibration.

Monthly Calibration is used to verify that the FWD is working correctly. It is done by the FWD Operator at any suitable location. *WinFWDCal* can assist with the data evaluation.

The Annual Calibration of the FWD is done in four steps. *WinFWDCal* must be used in the process.

Setup

Setup involves inputting the information about the FWD and its current calibration settings. Details about the calibration are input by the FWD Calibration Operator. 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 daily calibration of the reference accelerometer is done 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 (five drops at four load levels). The required number of drops was based on having a 400-micron (16-mil) deflection at the largest load level used in the calibration. Many of the existing FWD calibration centers cannot achieve this deflection during various times of the year due to 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. This 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.

FWD Deflection Sensor Calibration

The FWD deflection sensors are calibrated in two sequential procedures. The first, 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 an inversion of the sensors relative to the accelerometer to eliminate a small bias in the stand.

In the case of KUAB seismometers, there are two columns rather than one. The calibration stand is rotated 180° in the ball joint anchor to eliminate the bias in the stand.

As with the FWD load cell calibration, the slope of the regression line is used to define an interim calibration factor. 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 FWD.

In relative calibration, forty drops are performed in each of the two sensor arrangements used during reference calibration. This eliminates the bias in 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. The relative calibration is also a means of detecting any anomalous behavior of the deflection sensors.

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 the drop sequence are used to determine a relationship between the reference load cell and the FWD load cell. The slope of the regression line driven through zero is used to modify the existing gain of the FWD. The process is repeated at least twice to ensure repeatability and improve precision.

Documentation

The final step is to review the data and provide documentation of the calibration. A series of quality assurance data checks are performed. *WinFWDCal* alerts the user to perform additional tests or repeat the calibration, if that is needed.

A certificate of calibration is produced 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 for reading the electronic file.

RELATIVE CALIBRATION OF THE DEFLECTION SENSORS

The major difference in relative calibration in the new Annual Calibration protocol is the elimination of full rotation of 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 the bias due to position in the stand. This is a relatively small time savings, but is much easier to perform than the old full rotation needed in the SHRP procedure.

Monthly Calibration of the Deflection Sensors

Frequent relative calibration of the deflection sensors will ensure the FWD is operating properly. It should be done at the home base on a monthly basis. A relative calibration stand provided by the FWD manufacturer is used for this purpose. This involves multiple drops and full rotation of all sensors in all positions in the stand. By having all of the sensors in all positions, any bias due to position in the stand is removed. If a sensor needs to be replaced then the relative calibration procedure can be used to determine a temporary gain factor for the new sensor by performing a comparison to the remaining sensors.

SETTING UP NEW FWD CALIBRATION CENTERS

The pooled fund study provided for the creation of two new FWD calibration centers. These have been located in Helena, MT and Davis, CA where they will be operated by Montana DOT and Caltrans/University of California Davis. New equipment and training has been provided at both locations. Both centers expect to be fully operational by summer 2009.

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

The site of a new FWD calibration center must meet certain minimum specifications. Based upon experience gained from the first fifteen years of FWD calibration, the needs of a calibration center are well known. Appendix VI—Hardware Use and Installation Guide gives the details about setting up the equipment shown in Figure 3, but there are certain basic operational issues that must be discussed prior to ordering equipment and installing a test pad.

The calibration of an FWD at a center is done to control or eliminate as many variables as possible, while calibrating using the actual ground wave created by the FWD. A test pad is recommended in order to provide consistent deflections. If built well, the deflections will be consistent from season to season. The test pad can also be designed to provide larger deflections than might be found on normal industrial floors.

The preferred size of the test pad is 4.0 m wide by 4.5 m long (12 ft x 15 ft), but 4.0 m by 4.0 m (12 ft x 12 ft) is acceptable if space is limited. There should be sufficient space around the test pad for personnel to move, and to allow maneuvering of the FWD. A larger area is better, and at least 2.5 m (5 ft) clear space is recommended on all sides. The slab needs to be accessible by all

Figure 3. Photo. Calibration system hardware set.

brands and models of FWDs. It should be possible to place the FWD and the tow vehicle entirely indoors during calibration, to allow FWD calibrations to be performed year around.
Once a site has been chosen, the test pad can be installed. A trailer mounted FWD should be driven into the facility, if possible, prior to the construction to help locate the test pad.

Table 1 lists the estimated cost for a new FWD calibration center. In addition to the space needed to meet the needs of the FWD calibration, there should be 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.

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

Component	Notes	Cost*
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	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 & 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**

* Prices current as of February 2009. Does not include shipping, installation, or training.

Figure 4. Photo. Calibration center locations in the U.S.

UPDATING THE EXISTING SHRP CALIBRATION CENTERS

The pooled fund study provided support for the upgrading of all of the existing calibration centers in the United States. These included the centers operated by Colorado DOT, Indiana DOT, Minnesota DOT, Pennsylvania DOT, and Texas DOT (Figure 4). Installation and training has been provided to all centers. In addition, but not part of the pooled fund study, the calibration center operated by Dynatest in Starke, FL and the center operated by Main Roads Western Australia were upgraded. The only existing center that has not yet been upgraded (as of February 2009) is the center that is operated by the South African Bureau of Standards.

The old beam and concrete block was removed, and the new hardware equipment listed in Table 1 and described in Appendix V—Specifications and Drawings was installed. The existing test pad continued to be used, with the new ball joint anchor located close to the rear edge. At most locations a new laptop computer was provided. A three-day training program was given during which the operators demonstrated their proficiency with the new procedure and were certified.

TRAINING, AND OPERATOR CERTIFICATION

Training is needed to use the equipment and software. Training and certification only takes three days, but it is recommended that a new Calibration Operator perform several trial calibrations prior to the first calibration for a client.

At the conclusion of the training the operators demonstrate their proficiency at carrying out the protocol that is detailed in Appendix I—FWD Calibration Protocol. This is the same as the AASHTO R 32 procedure.[(3)] A certificate is issued to each operator who passes this review. The certificate must be renewed annually by conducting a quality assurance (QA) visit. The procedures and checklists used during the QA visit are included in Appendix IV—Quality Assurance Reviews. All FWD calibrations should 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 for the updated calibration protocol is universal compatibility for the four brands of FWD used in North America. Interviews conducted with the FWD manufacturers, FWD Calibration Operators, some FWD owners, and other FWD experts determined what problems have been encountered during calibration with the old SHRP procedure.

The following sections discuss the four brands of FWDs and known issues associated with their calibration. Additionally, other problems commonly encountered during FWD calibration are explored. Table 2 at the end of this section provides an overview of the technical specifications for all four brands of FWDs.

Figure 5. Photo. Dynatest model 8000 trailer-mounted FWD

Dynatest

The first Dynatest FWD was manufactured in Denmark in 1976, with the first one coming to the United States in 1981.[8] Dynatest manufactures two varieties of FWD, the model 8000 FWD and the model 8081 HWD. Both systems are trailer mounted, have loading plates of 300 mm (with an optional 450 mm plate available), and can have between seven to fifteen deflection sensors. Figure 5 shows a model 8000 FWD. A truck-mounted FWD unit has recently been developed.

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 placed along a raise/lower bar. The raise/lower bar runs frontward from the load plate toward the tow vehicle. Optionally, 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.

During FWD calibration, the HWD normal load levels exceed the normal 27, 40, 53, and 71 kN (6000, 9000, 12000 and 16000-lbf) range specified in the original SHRP calibration procedure. In order for the HWD to achieve the required loads, all attached weights are removed. The leads to some concern about whether the calibration is valid for the HWD, since it is not normally used with all weights removed.

Figure 6. Photo. JILS-20T truck-mounted FWD

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. Currently work is underway to design an improved reference load cell, with a greater load capacity that could be used with HWDs.

JILS

The first JILS FWD was made in 1987 in the United States.(10) JILS manufactures four varieties of FWD:

- JILS-20C, a single-axle trailer mounted FWD
- JILS-20, a two-axle trailer mounted FWD

- JILS-20T, a truck mounted FWD
- JILS-20HF, a trailer mounted, high force model designed for airports

All of the JILS FWD use a 305 mm (12 in), rigid steel loading plate, and have an optional 305 mm (12 in) segmented or an 457 mm (18 in) rigid loading plate. The JILS FWD have seven deflection. The deflection sensors are velocity transducers, and their response is single integrated to determine the deflection. A unique feature of the JILS FWD is the different programs used for collection of data in the field and for calibration of the FWD.

The lack of a swivel on the load plate has made calibration difficult in some locations. The calibration operator must make special effort to assure that the load plate is firmly seated on the test pad and on the reference load cell, with no gaps around the perimeter.

Since the standard JILS load plate is slightly larger than the 300 mm (11.81 in) diameter of the reference load cell, adjustments have been made to the original design of the reference load cell. We have adjusted the guide fingers to accommodate the JILS load plate.

Figure 7. Photo. Carl Bro FWD

Carl Bro

Carl Bro manufactures both a double-axle trailer-mounted and a vehicle-mounted FWD.[11] The two loading plate options are a four-segmented 300 mm (11.8 in) diameter plate or a 450 mm (17.7 in) plate. A single mass is used and controlled hydraulically. The minimum number of deflection sensors is nine, with the maximum being eighteen. 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 towards 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.

Using the SHRP protocol, it was difficult to trigger the data acquisition system. This was mainly due to the large distance between the FWD load plate and the LVDT. The use of about triggering in the new protocol has solved that issue.

KUAB

KUAB has been manufacturing FWDs since 1976, with the first one coming to the United States in 1988.(9) KUAB makes both trailer mounted and vehicle mounted FWDs of the single-mass and dual-mass designs. 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 standard.

The sensors can be aligned going towards the tow vehicle (Figure 8) or away from the vehicle. KUAB has the option of either a four-part segmented load plate at 300 mm (11.81 in) or 450 mm (17.72in) diameter, or a rigid load plate at 150 mm (5.91 in), 300 mm (11.81 in), or 450 mm (17.72 in) diameter.

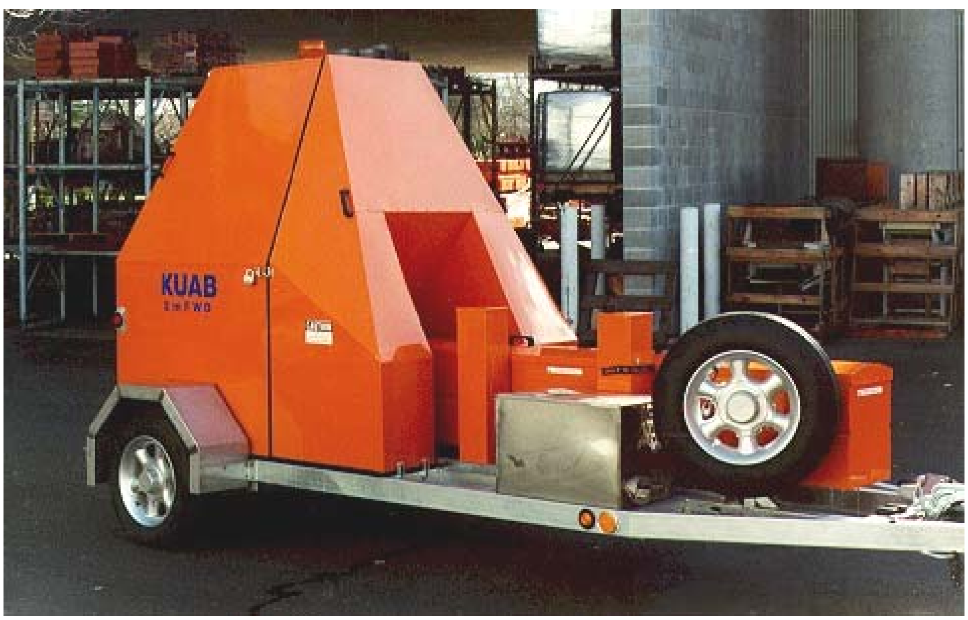

Figure 8. Photo. KUAB FWD with sensors aligned toward the tow vehicle.

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 rather difficult. This made it difficult to trigger the data acquisition system and to achieve the desired deflections during geophone reference calibration. About triggering has reduced that issue.

Table 2. FWD manufacturers' 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)
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 msec	20–30 msec	25–30 msec	23 msec [1]
Typical Maximum Deflection	80 mils (2,032 microns)	87 mils (2,200 microns)	78 mils (2,000 microns)	78 mils (2,000 microns)
Optional Maximum Deflection	None	None	98 mils (2,500 microns)	197 mils (5,000 microns)
Deflection Sensor Types	Geophone	Geophone	Geophone	Geophone, Seismometer
Typical Number of Deflection Sensors	7	9	9	7
Max. 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 inch (305 mm)	11.81 inch (300 mm)	11.81 inch (300 mm)	11.81 inch (300 mm)
Optional Load Plate Diameter	18 inch (457 mm)	17.72 inch (450 mm)	17.72 inch (450 mm)	17.72 inch (450 mm)
Data Taking Trigger Type	About triggering [2]	Proximity sensor	Proximity sensor	[3]
When Trigger Occurs	At peak load [2]	Just before mass strikes	Just before mass strikes	[3]

[1] The KUAB specifications are for rise time, not for 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. They are; data recording at all times, an end switch activated between 10 and 30 mm before the buffers strike the load plate, an end switch activated about 10 mm after the weight is released, and activation when the magnet holding the weight turns off.

Issues Encountered with the SHRP FWD Calibration Protocol

In addition to the FWD-specific issues cite above, there were several more general problems encountered while using the old SHRP procedure and equipment. These included excessive beam movement, triggering difficulty, and difficulty in getting sufficiently large enough deflections. Electrical problems included excessive noise in the signal, and insufficient power supplied by 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 9 shows the beam and block combination used in the SHRP protocol. After the reference calibration of each deflection sensor, the beam movement was determined from the FWD time histories. If the beam movement was 3 microns (0.12 mils) 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, and hence it was seasonal. It was frustrating because the FWD owner would have to come back for another calibration attempt at a later date. This caused some of the calibration centers to shut down for periods of time, particularly in the spring.

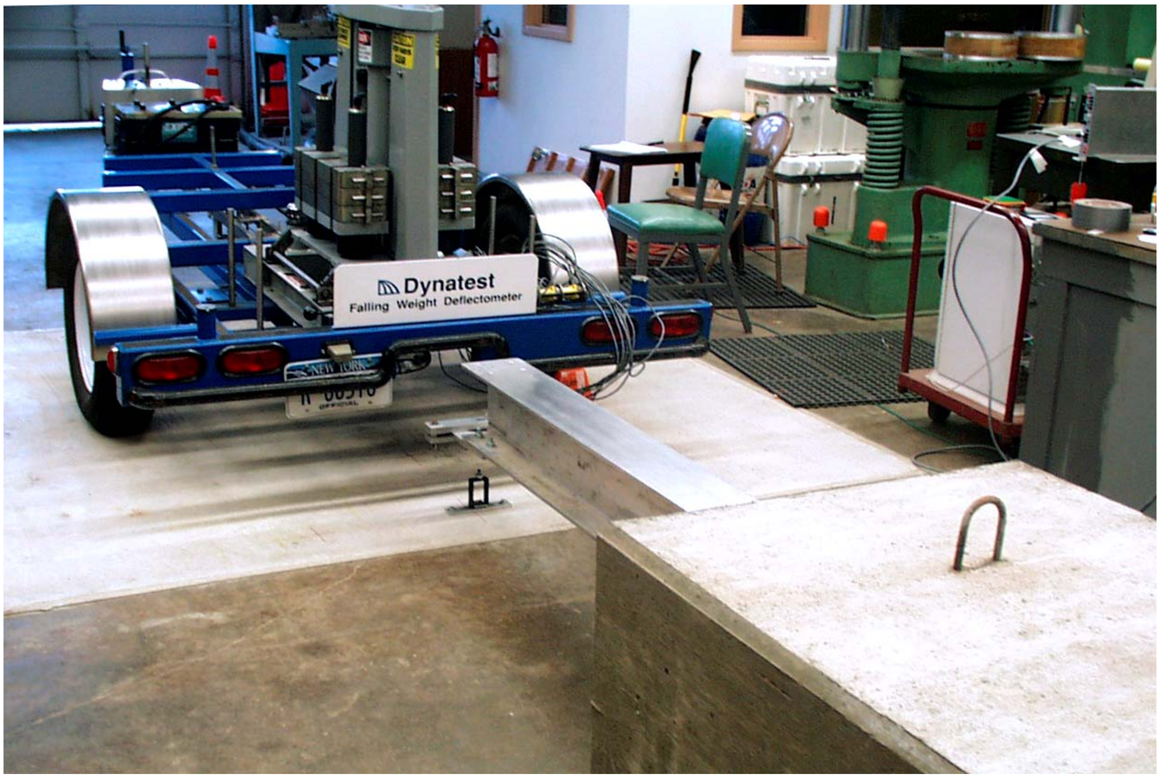

Figure 9. Photo. FWD Calibration Beam and Inertial Block.

The SHRP calibration protocol required at least 400 microns (16 mils) of deflection at the 71.2 kN (16,000 lbf) load level during deflection sensor calibration. This means 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 two categories: FWD brand specific problems, and general data problems.

The KUAB and JILS FWDs had a triggering problem, especially at the low load level. 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 take data. The KUAB FWD, due to the nature of its mass release system, did not cause a measurable vibration at the time of release, and often the data acquisition system failed to initiate data taking as a result. The JILS, on the other hand, produced a lot of vibration when the mass was released, and this often triggered the data acquisition too early.

Data transfer from the FWD was a considerable problem with the old SHRP method. The calibration system software collected and stored the data from the reference calibration instrumentation, but the data collected from the FWD had to be printed and hand typed into the calibration system. This led to possible transcription errors as well as it took a considerable amount of time.

FWDCAL 4 is a program written to perform the relative calibration data analysis. It could only read output from some Dynatest FWDs. A spreadsheet with macros was written to work with additional data formats, but it did not cover all FWD types and system configurations.

The lack of a common data file format was at the heart of the problem. Each brand of FWD outputs its data in a different format. This required the Calibration Operators to be experts in reading the FWD data. It occasionally required manual calculations to convert the 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.(1) All FWD manufacturers have promised to provide that output option. Some FWDs use a separate converter program to change their normal data format into the PDDX format. Unfortunately the original AASHTO standard format did not provide all of the data that is needed for FWD calibration.

Other Known Problems

Legislative and financial restrictions kept some Departments of Transportation from traveling out-of-state to one of the FWD calibration centers. So they could not get their FWD calibrated to the SHRP/LTPP standard. Included in this group were FWDs from other countries, such as Canada.

EQUIPMENT AND PROCEDURAL UPDATES

In this section we will discuss the research that led to the development of the new FWD calibration protocol. The detailed procedure is included in Appendix I—FWD Calibration Protocol. Specifications for each item of equipment mentioned are in Appendix V—Specifications and Drawings

Data Acquisition

The Keithley KUSB-3108 data acquisition board 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 having USB 1.0 or 2.0 ports and does not require the now obsolete ISA bus.

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

A feature specific to the chosen model was the availability of drivers compatible with the Visual Basic language in which the *WinFWDCal* software was written. Thus there was no need for us to develop custom drivers. Keithley supplies a driver set that is compatible with Windows XP and Windows Vista.

About Triggering

Modern data acquisition equipment allows the use of a technique called *about triggering* to determine when an event has occurred. About triggering allows the collection of data *before and after* a user specified threshold value is reached. This means the data are taken *about*, or around, the point in time when the trigger level is reached. The readings are continuously stored in buffers by the *WinFWDCal* software. Currently *WinFWDCal* uses 50 buffers, each with 300 readings per buffer.

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 data set. If not, the oldest data are discarded and a new set of data is collected and reviewed.

In the case of FWD calibration, a full second of data is saved for analysis; one-third of a second before the trigger and two-thirds after. With a reading rate of 15,000 Hz, this means 5,000 readings are taken before and 10,000 after the trigger. That includes data from before the release of the mass to the bounces after the main pulse.

The incoming data are read as voltages. To convert the voltages to engineering units requires the sensors to be calibrated. The procedures for sensor calibration will be discussed in following sections.

A*bout triggering* has streamlined the data taking process and eliminated the need to have separate hardware to detect the trigger point. It also eliminated the triggering problem mentioned previously that we experienced 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 ten consecutive readings exceed the trigger level, the about trigger point is set. Using ten readings assures no false triggers due to a voltage spike.

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

The acceleration trace is very different from the load cell trace and so is the trigger level that needs to be used. A high frequency, high acceleration, wave pulse occurs upon the release of a JILS FWD mass, that can cause a premature trigger.

Several different techniques were tested to overcome this difficulty. The successful concept came from Foundation Mechanics, the JILS manufacturer, and it is used in *WinFWDCal* for all types of FWDs. The duration of the pulse due to the mass striking the load plate is much longer than the noise surrounding the release of the mass. A trigger level, in g's, is defined that must be exceeded a preset number of times in a row. This avoids false triggering when the mass is released. Currently, the number of consecutive readings above the threshold value is set at ten. At 15,000 readings per second it takes less than a millisecond to collect ten readings.

To set the appropriate acceleration trigger level requires finding an optimum between the pulse peak from the lowest load level and that from the highest load level. Our research has shown that this must be tailored for each type of FWD. The pulse duration, and thus the accelerations, differ from one type of FWD to another. The position of the FWD load plate vis-à-vis the accelerometer in the calibration stand is variable, and thus so are the peak accelerations. The response characteristics of the test pad can vary from one day to another at the same location, so the trigger level must be determined for 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. The *WinFWDCal* software does the analysis.

It is very important that the trigger level be determined for each FWD calibration. There is no guarantee that the trigger level that worked last week with a JILS will work this week with a KUAB, etc. With the help of the software, it only takes a minute or so to determine the required trigger level. Doing so will avoid complications and frustration.

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 twenty 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 instance the JILS uses a heavier mass and a shorter drop distance, and the lowest load level (26 kN, 6,000 lbf) has a much shorter free fall time than the Dynatest FWD. Vibration associated with the release of the mass does not have enough time for damping before the mass strikes the load plate. The Calibration Operators reported problems with "excess noise" messages showing up routinely at the low drop height.

We were able to overcome this issue by relying on the experience from doing hundreds of FWD calibrations over the previous 15 years. Rather than work with a single, fixed drop sequence, we were able to allow some flexibility depending on the daily response of the test pad. The solution involves a trade off between the number of load levels used and the number of replicate drops that are required to achieve a certain, 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. The *WinFWDCal* software determines the required number of replicate drops per load level. The number of drops must be the same at *each* load level to simplify the data collection and analysis. We also recommend that the same drop sequence be used for both load and deflection sensor calibration.

We have a goal that the standard error of the final calibration factors should be no more than 0.003 (i.e., 0.3 percent). Experience over 15 years with all types of FWDs has shown that the expected random measurement error for one drop is seldom more than ±2 microns (±0.08 mils) deflection and ±0.09 kN (±20 lbf) load. Deflection is the more critical of the two to achieve the desired standard error, so it will control 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 the minimum number of drops that are needed to achieve the desired precision of the calibration factor. The *WinFWDCal* software does the analysis. At least eighteen total drops are required to ensure the minimum statistical power. This requires at least six replicate drops at three load levels or five replicates at four levels.

Ten replicate drops per load level were found to be a practical upper limit. If the required number of replicates exceeds ten, 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 being needed. So switching from three to four load levels will reduce the required number of drops.

It is very important that the drop sequence be determined for each FWD calibration. This is a simple routine to perform. It takes only a minute or two. It 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 in. The dynamics of the FWD load pulse are considered, so that excess noise messages should be less likely to be encountered. The ability of the software to determine the drop sequence based on the local, daily conditions provides a great deal of flexibility.

Recommended Peak Deflection

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

We have found that a test pad built with a 125 mm (5 in.) thick fiber-reinforced concrete surface, a 150 mm (6 in.) aggregate base, and a 3 to 5 m (120 to 200 in.) deep soft clay subgrade will achieve the target deflection level. The deflection profile near the edge of the test pad is not constant, and the deflections generally increase near the edge of the pad. The calibration stand will need to be placed somewhere between 300 mm (12 in.) and 450 mm (18 in.) from the edge of the test pad. It is important that the perimeter of the test pad concrete *not* be bonded to the surrounding floor. To maintain a near constant deflection over long periods of time, it is recommended that the clay subgrade be completely wrapped in neoprene or heavy polyethylene sheeting to resist drying of the material.

It is no longer required that a special test pad be built to carry out the FWD calibration procedure. Any good quality pavement that will provide a peak deflection that does not require more than ten replicate drops per load level is sufficient. This allows the calibration procedure to be portable so it can be done by a qualified technician at any suitable location. *It is the limit on the required drop sequence and not the minimum amplitude of the peak deflection that determines whether a certain site can be used for FWD calibration.*

The *WinFWDCal* software will also check each drop to assure that the maximum acceleration does not exceed five g's. If this limit is exceeded the data are invalid.

Choosing and Using an Accelerometer in FWD Calibration

After review of many accelerometers currently in manufacture, we found an accelerometer with excellent frequency response and shock resistance. Peak accelerations experienced during the development phase showed that the accelerometer needed a range of at least 3g. The Silicon Designs model 2220-005 ±5g accelerometer was chosen. The device offers an optimum combination of low-noise, high sensitivity, and excellent shock resistance. It is quite small, only one inch square and a few millimeters thick. The accelerometer is housed inside a shielded aluminum box (Figure 12).

Figure 10. Photo. The Silicon Designs model 2220 accelerometer.

Most accelerometers are not very shock resistant. Dropping them is usually fatal. Specifications for the Silicon Designs accelerometer say the 5 g unit is resistant to a 2000 g shock. While it was unintentional, during the research an accelerometer box was dropped onto a concrete floor from a height of 760 mm (30 in.), and it survived without any measurable effect on its calibration.

A Vishay model 2310 signal conditioner is used to power the accelerometer. The signal conditioner has a six-pole, low-pass Butterworth filter which is set at 1000 Hz to protect against aliasing and remove unwanted high-frequency electrical noise. The same signal conditioner is also used with the reference load cell, thereby saving on hardware costs.

The Silicon Designs accelerometer is a MEMS device, and thus it produces a signal due to the acceleration of Earth gravity. This is termed the "zero bias" by the manufacturer. It is advantageous because it allows us to use Earth gravity (at one g) to calibrate the accelerometer.

Calibration of the Accelerometer

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

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

Figure 11. Equation. Nonlinear conversion of voltage to acceleration.

where g = measured acceleration in g's

V = accelerometer output in volts

a_i, b = coefficients of polynomial from manufacturer's calibration at 50 Hz

We use this relationship to convert the accelerometer response (in volts) to engineering units (in g's). The second and third order terms contribute a relatively small amount to the conversion.

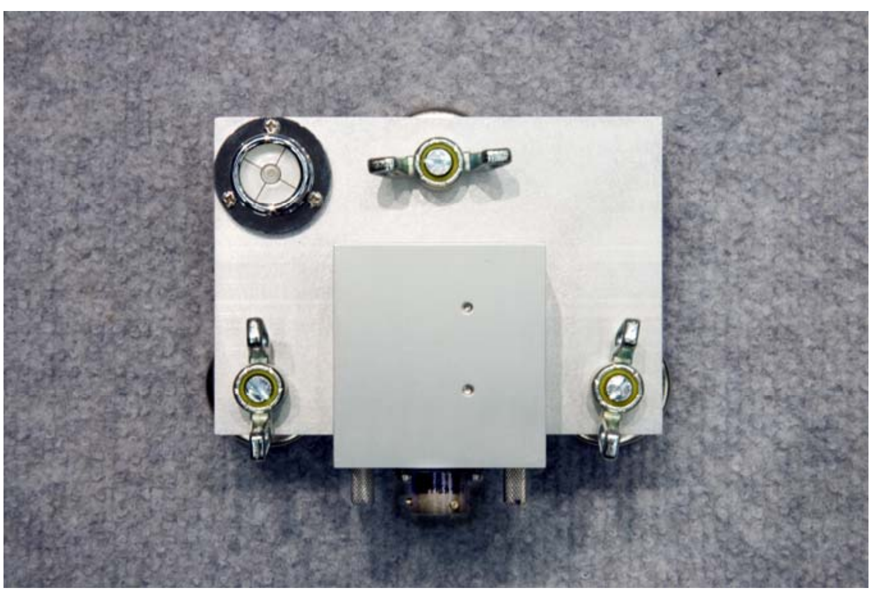

Figure 12. Photo. Accelerometer box on calibration platter.

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 gravity, is used to calibrate the output and determine the bias and slope a_1 at whatever the current ambient temperature is.

The daily accelerometer calibration is straightforward. The accelerometer is calibrated on a flat, level plate that is also used to store the accelerometer when it is not being used (Figure 12). First, a full second of accelerometer readings (15,000 readings) is taken in a +1g gravity field. This is repeated ten times. Then the accelerometer (in its protective box) is inverted, and ten more sets of readings are taken in a -1g field. The accelerometer is immediately inverted back into the +1g field and ten 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 stable during the test. The results are also compared to historical data for the accelerometer to assure that the results are typical.

The data from the calibration are used to determine a daily value for the zero bias, b, in g's, and the slope, a_1, in g's per volt. These results include the effect of the gain setting in the signal conditioner, temperature effects, hysteresis effects, aging of the accelerometer, etc.

Data Checks During Accelerometer Calibration:

Several data checks are made during the daily calibration of the accelerometer. Some are done to assure the device is working within normal parameters, and others are used to look for changes from one accelerometer calibration to the next.

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

- **Change in slope**
  The slope of voltage versus acceleration (the inverse of a_1) should be relatively constant over time even with temperature changes. Based on our research, 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*. This limit will be reviewed after a practical limit on the change can be determined.

- **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. This limit will be reviewed after a practical limit on the change can be determined.

- **Temperature change**
  The KUSB DAQ board has a temperature measurement system. The temperature at the time

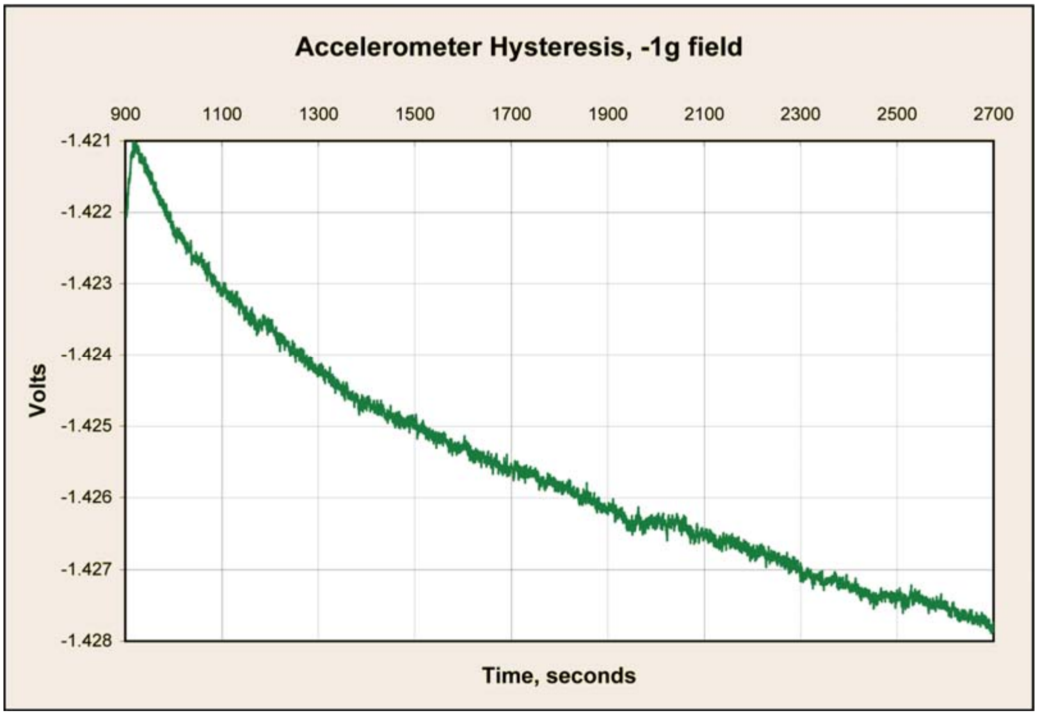

Figure 13. Graph. Hysteresis effect in a -1g field.

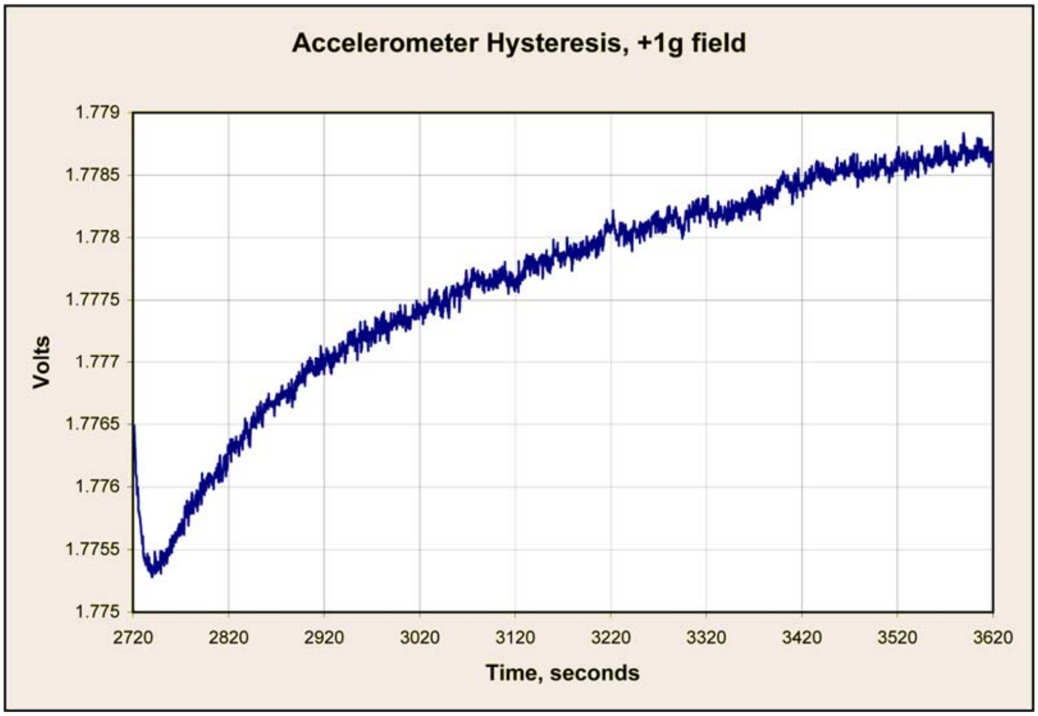

Figure 14. Graph. Hysteresis effect in a +1g field.

Note: Accelerometer was inverted from the condition in Figure 13 and the time scale is continued.

of accelerometer calibration is recorded. The temperature thereafter is monitored. A temperature change of less than 10°C (18°F) during calibration is allowed. Normally the temperature will be very constant in the calibration facility.

- **Overall temperature**
  In a temperature sensitivity study we examined the behavior of the accelerometer over a range of temperatures well within the expected range in service and the allowable range of the device. A range from -15 to +55 °C (5 to 131°F) is allowed.

Hysteresis of Silicon Designs Accelerometer

The Model 2220 accelerometer has an issue with hysteresis. Every time the accelerometer is inverted in Earth gravity, the zero bias gradually changes. The change occurs exponentially with time, whether the accelerometer is powered or not. It is a materials science problem rather than an electrical one. This accelerometer drift could present a biased, non-random error.

If not accounted for, hysteresis can lead to a calibration error in excess of one 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 +1g gravity field as much as possible. It should only be "flipped" upside-down during the daily calibration. By keeping the time for flip calibration short, the effect on the overall daily calibration is very small.

Hysteresis does not affect the *dynamic* response of the accelerometer because it stays in a +1g overall gravity field. Since Earth 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 13 and Figure 14 show the effect hysteresis has on the accelerometer response. An accelerometer was left in a +1g condition overnight. Readings were taken for 15 minutes (900 seconds) and were very stable (not shown). Next, the accelerometer was inverted into a -1g condition, and the voltage output was recorded every second for 30 minutes (from 900 to 2700 seconds - Figure 13). The accelerometer was then returned back to a +1g gravity field and additional measurements taken for 15 minutes (from 2700 to 3600 seconds - Figure 14).

Each figure shows an immediate change in one direction, with a signal change on the order of 1 to 1.5 millivolts. This is followed by a slower, long-term change in the opposite direction. Our research showed that if the inversion time (during daily flip calibration) was kept to under 20 seconds, the effect on the accelerometer voltage would be less than 0.035 percent (about 0.5 mv).

The rate of drift due to hysteresis diminishes as the period of time gets longer. After six days at room temperature the accelerometer is completely stable. If the accelerometer was stored upside down for a long period, it would take about 24 hours 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 +1g gravity field at all times.

As a general rule of thumb, if the accelerometer is inverted for a brief period of time (say, a few minutes) it should be left in the upright position for an equal length of time to re-equilibrate it.

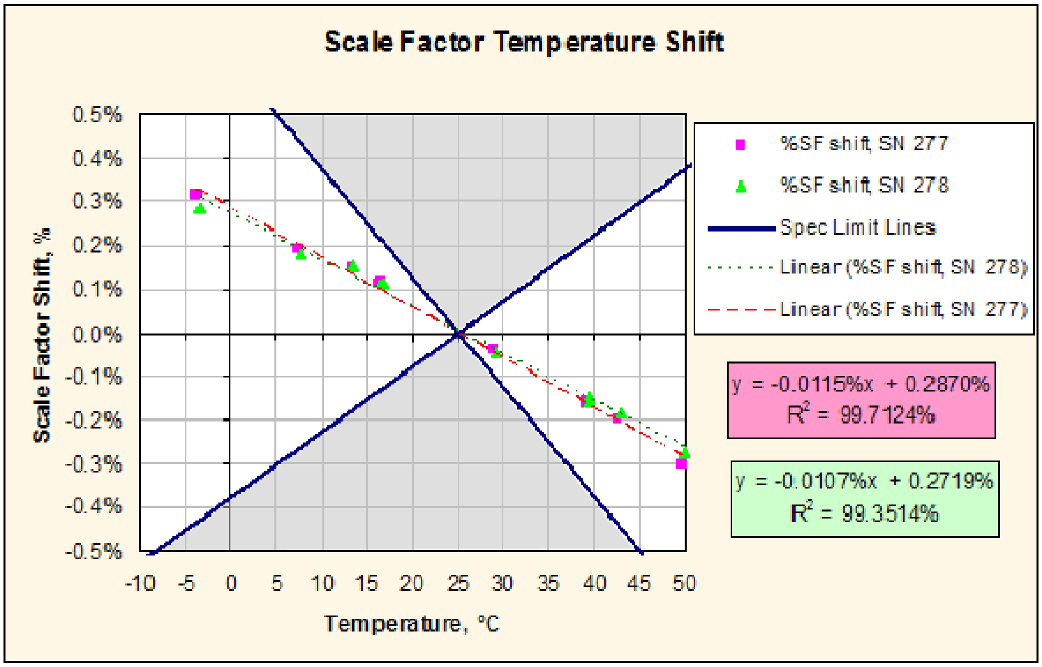

Figure 15. Graph. Scale factor temperature shift for accelerometer.

Temperature and Electromagnetic Interference (EMI) Sensitivity

The feasibility of using an accelerometer as a reference device for calibrating FWD deflection sensors depends in part on the effects of environmental factors on their function. Should the device be too greatly affected by temperature or by interference from electromagnetic fields, then the accuracy of 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 the model 2220-005 (Figure 15). We calibrated two accelerometers (serial numbers 277 and 278) over a range of temperatures, and the change in the output voltage was determined. Results of our research showed that if the maximum allowable error due to temperature change is 0.1 percent, the maximum acceptable temperature shift is 10°C (18°F).

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 EMI on the accelerometer, an aluminum box showed good results in fields above 0.0001 tesla (1 gauss). Aluminum was deemed sufficient. Even large magnetic fields had 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 to insulate the accelerometer from temperature effects. Temperature measured at the DAQ board can be expected to move more rapidly than inside the box, provided the aluminum box is not in direct sunlight.

Double Integration of Accelerometer Signal

Use of an accelerometer as a reference sensor in deflection measurement requires that we double integrate the output from the accelerometer to convert to displacement. This sounds simple, but it is actually a very challenging problem. It is difficult, in part, because release of the FWD mass a couple of hundred milliseconds before the mass strikes the load plate can leave a legacy of on going, damped vibration in the pavement at the moment when the mass strikes.

When considering integration for any purpose, one must 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: $\iint A\,dt = \frac{1}{2}At^2 + Bt + C$, where A, B, and C are constants, and t is time. In instrumentation engineering terminology, the ramp is "drift," and the parabola is "nonlinear drift."

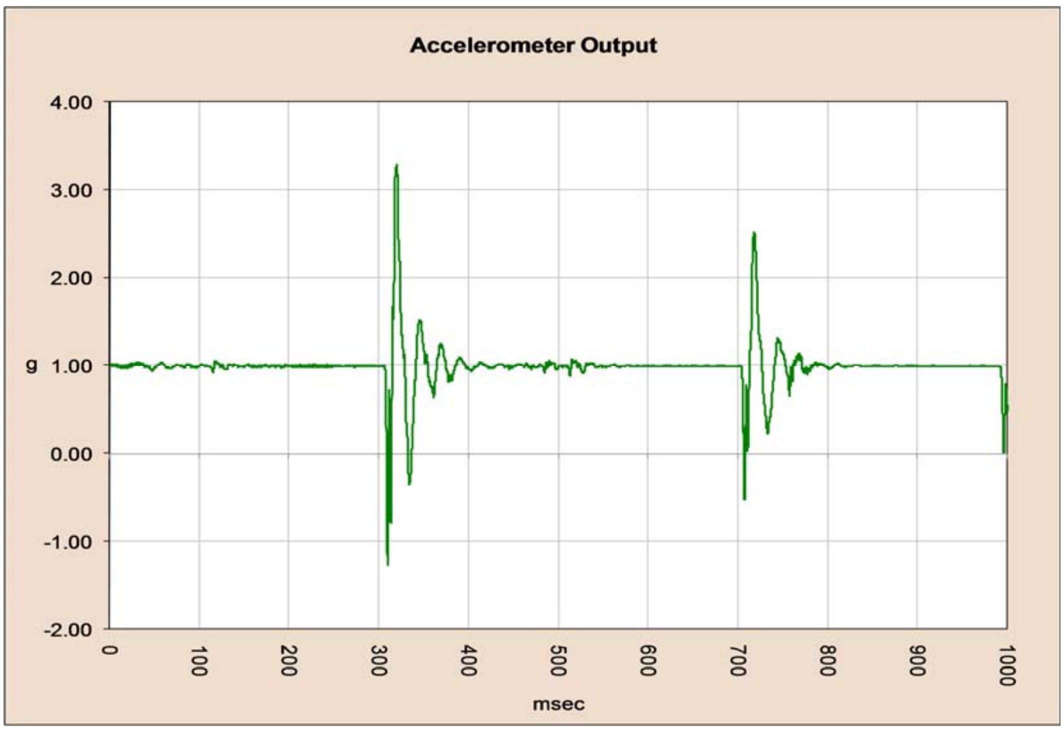

Figure 16. Graph. Raw accelerometer output from a Dynatest FWD load impulse.

Before performing the integration calculations, several boundary conditions and assumptions must be defined. Figure 16 shows the acceleration trace from a Dynatest FWD impulse, after converting from volts to g's. The release of the mass occurs at t_r around 40 ms, and the strike of the mass on the load plate occurs at t_i just after 300 ms.

The baseline in Figure 16 is on +1.0 g's because the mems accelerometer responds to Earth gravity. This zero bias can be measured by taking a burst of readings before the FWD mass is released. The readings are examined to assure that there are no unwanted vibrations occurring just before the drop. The subsequent acceleration data can be corrected to remove the zero bias before any integration is performed. Further details on this process are given in the next section. Figure 17 and Figure 18 show the resulting integration of the accelerometer trace, first to velocity and then to displacement.

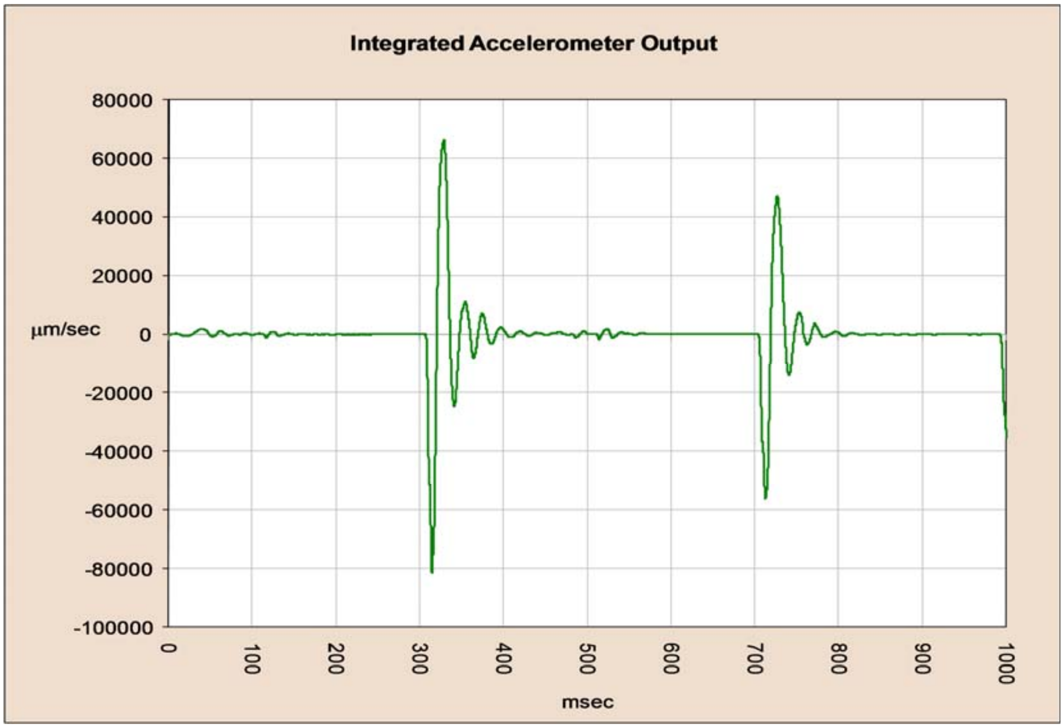

Figure 17. Graph. First integration (velocity) from a Dynatest FWD load impulse.

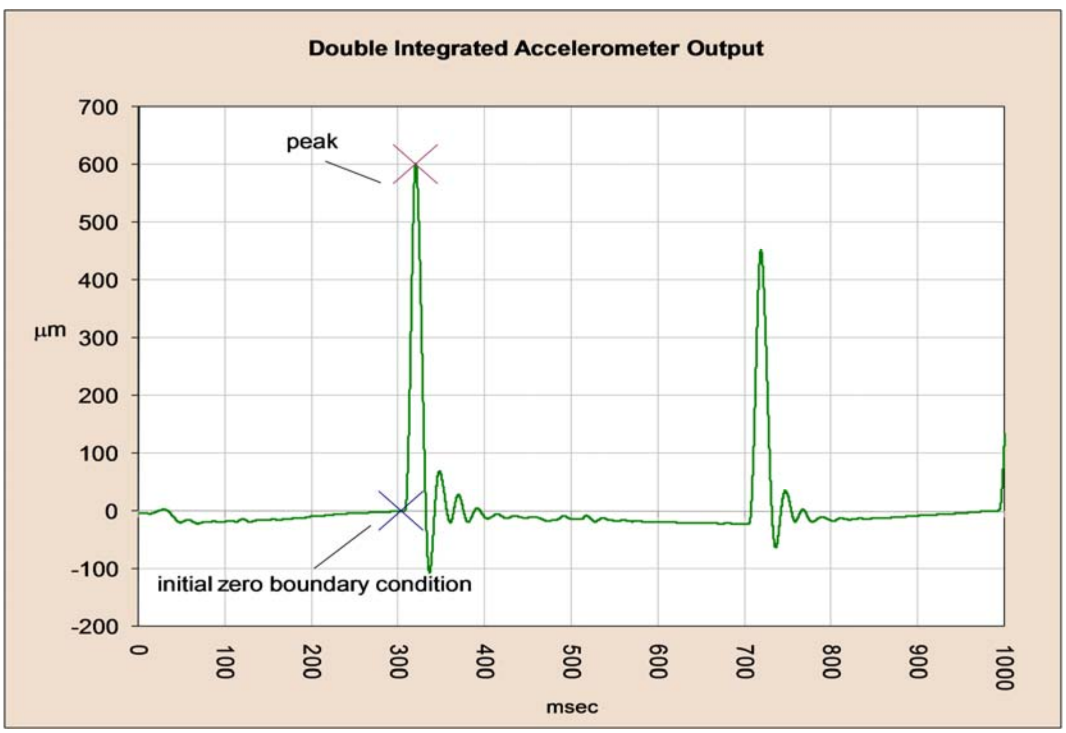

Figure 18. Graph. Second integration (deflection) from a Dynatest FWD load impulse.

Figure 19 through Figure 21 show a similar set of results for a JILS machine. The peak force for both examples was about 70 kN (16,000 lbf). It is evident that different types of FWDs have different vibration characteristics both before and especially after the falling mass strikes the load plate. This provides quite a challenge to accommodate in the integration routines. A small, but acceptable amount of baseline drift is evident in Figure 18 and Figure 21.

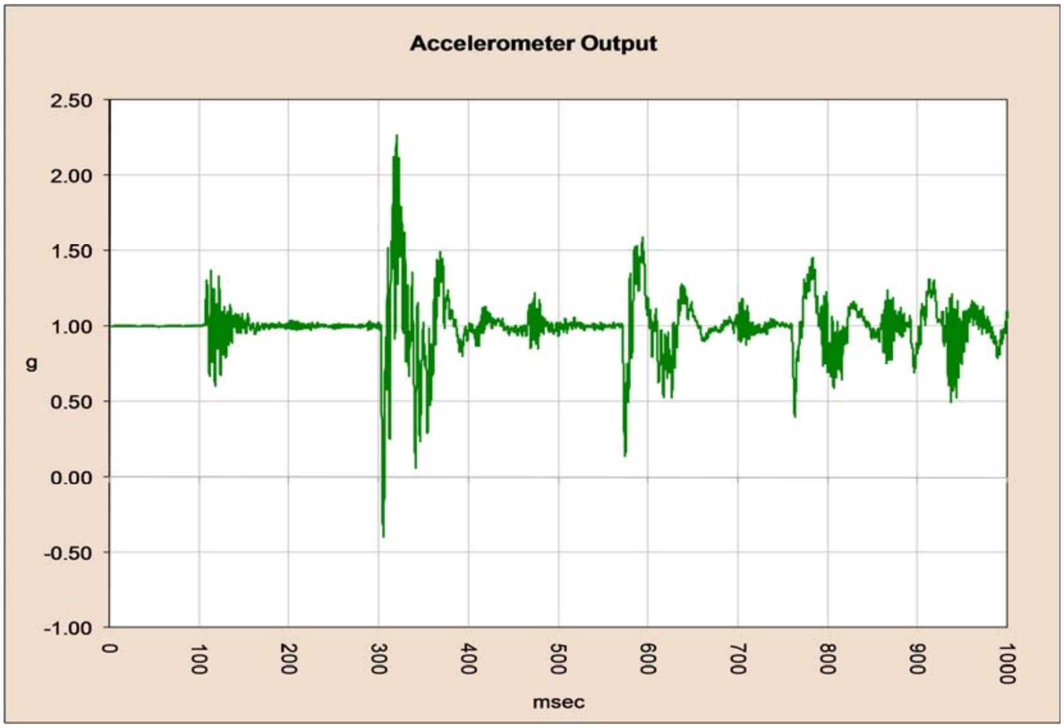

Figure 19. Graph. Raw accelerometer output from a JILS FWD load impulse.

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 gravity, and a variable acceleration a'(t) due to the impact of the falling mass.

As has been noted, the mass is released at time t_r, and the time of impact of the mass is at t_i, which occurs after the release of the mass. The peak deflection z_{peak} is at t_{peak} (marked in Figure 18 and Figure 21) which occurs after the mass strikes the load plate. Thus, $t_r < t_i < t_{peak}$. Our 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 a small amount. The KUAB has an outrigger system that supports the mass, and hence there is no change of force at the load plate. The JILS FWD uses a pair of air bags to apply a very large preload on the load plate. The JILS 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 21).

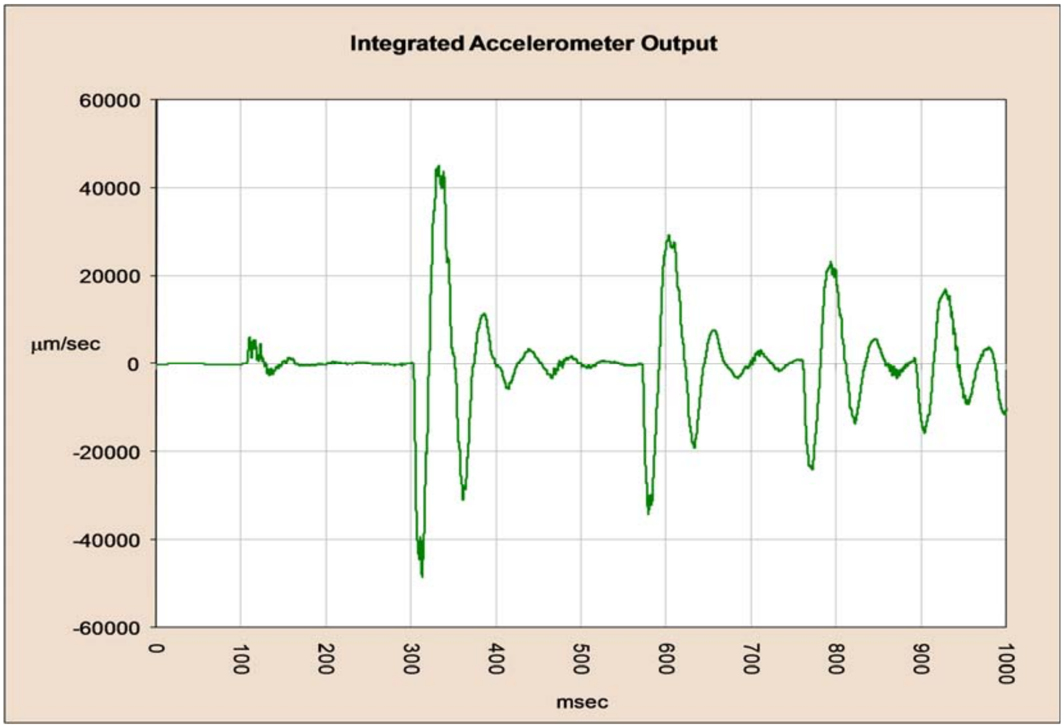

Figure 20. Graph. First integration (velocity) from a JILS FWD load impulse.

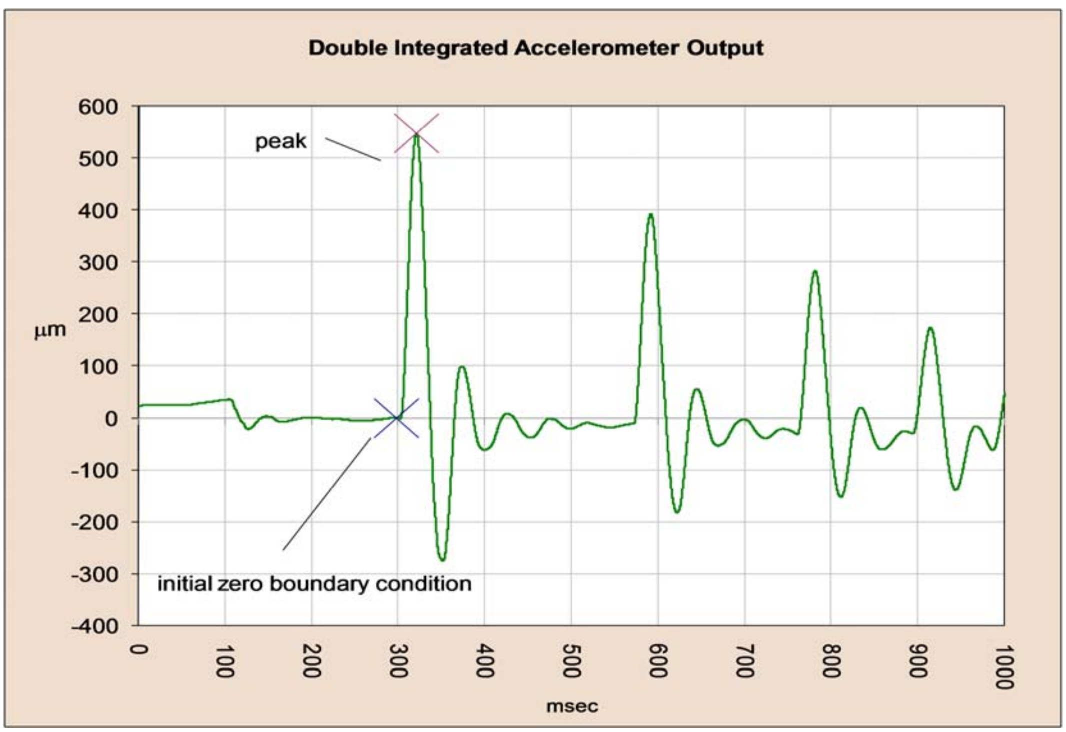

Figure 21. Graph. Second integration (deflection) from a JILS FWD load impulse.

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

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

Figure 22. Equation. Acceleration due to gravity and the FWD load pulse.

where $a(t)$ = acceleration over time, t
a_o = constant acceleration due to Earth gravity
$a'(t)$ = acceleration due to the FWD mass strike at t_i

The constant a_o is measured by averaging a burst of 3000 readings taken immediately *before* the mass is released (at that time $a'(t) = 0$). Thus if the calibration stand is not exactly vertical or if the temperature has changed since the accelerometer was last calibrated, the constant a_o includes 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, leaving us with a *relative acceleration*, $a'(t) = a(t) - a_o$. Thus the equation in Figure 22 becomes

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

Figure 23. Equation. Relative acceleration after removing Earth gravity.

We can integrate the relative acceleration in Figure 23 to find the velocity v(t) as a function of time.

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

Figure 24. Equation. Velocity as a function of time.

By examining the data we can choose the starting point of the integration 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…

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

Figure 25. Equation. Deflection as a function of time.

Again we choose $t = 0$ in Figure 25 so that $v(t) = 0$ and if $z(0) = 0$ then constant $c_2 = 0$. The starting point for integration in Figure 24 and that in Figure 25 will most likely not be at the same reading number in the data file.

If at the start of integration 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) then Figure 24 becomes …

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

Figure 26. 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 $a(t) = a_o + a_o(t) + a'(t)$. We can still measure a_o at a time when $a_o(t) + a'(t) = 0$. We can also choose a starting point 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 very difficult to solve the equation in Figure 26. It is even more complicated and difficult to define $z(t)$.

If there is vibration present at t_i but we still assume that Figure 24 and Figure 25 are applicable, the constants c_1, c_2 and c_3 will be nonzero. It is not be 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 staring 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. But if, when the falling mass strikes the load plate at t_i, the vibrations are renewed and enhanced, then $v_o(t)$ and $a_o(t)$ may be quite significant, the drift may become quite large, and so will the error in z_{peak}.

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 (4) will contain little, if any, drift. To assure that condition is met we can analyze the accelerometer signal during each drop for a short period before t_i, and reject all drops that show excessive vibration.

Our research has shown that it is important for the FWD to be seated squarely on the pavement in order to minimize the undesired vibrations. Several seating drops should be done before any data collection to establish good contact of the load plate. With the Dynatest and Carl Bro FWDs, it is necessary that the load plate swivel be recently lubricated and free to rotate. With 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 done using a sheet of paper, and the procedure for checking this is explained in more detail in Appendix I, Annex C.

Implementation

The *WinFWDCal* software is used to implement the data acquisition and double integration. It also provides several quality control checks during the data processing. Setting the trigger level has been discussed in an earlier section. The following steps are taken when the Calibration Operator decides to initiate an FWD drop during reference calibration.

Measuring a_o:

Before the computer screen turns green, thereby signaling the FWD operator to release the mass, the computer takes a burst of 3000 readings at 15,000 Hz (e.g., 200 ms read time). The average (i.e., a_o) and the standard deviation are computed. If the standard deviation is larger than 0.005 volts, a popup message provides an alert that the pre-drop vibration exceeds the acceptable level.

The 3000 readings are converted to g's. The vector is checked to assure that all readings are between 0.98 – 1.02. According to NIST [(17)] the acceleration of gravity (1 g) is exactly 9.80665 m/s^2. Locally in Minneapolis, MN gravity is 9.80585 m/s^2, in Denver, CO it is 9.79615 m/s^2, and in College Station, TX it is 9.79324 m/s^2. None of the locations are less than 0.9985 g. So if the data are out of range this is an indication that the accelerometer is not working correctly. A popup message provides an alert to the Calibration Operator.

The data are saved in the time history file for the drop.

Finding the trigger point:

The incoming readings from the accelerometer are continuously scanned for the trigger level. When ten consecutive readings are over the trigger level, the trigger is satisfied. This 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. Then the accelerometer readings in volts are transferred from the buffers to a program array such that the trigger point is the 5000th reading out of 15,000. Thus there is 0.333 s of data ahead of the trigger, and 0.666 s after the trigger.

The raw data in volts, the absolute acceleration in g's, and the relative acceleration in g's are saved in the time history file for the drop.

Finding t_i:

The time of impact, t_i, is determined by working backward from the trigger reading. We seek to find the transition point from where the time history trace is steep to where it is level. To do this we examine the standard deviation of sets of 25 readings.

Starting at the trigger point, we calculate the standard deviation of the previous 25 readings and place that value in an array. Moving back one point, we calculate the standard deviation of the next set of 25 readings. Similarly, the running standard deviation of consecutive sets of 25 points is tabulated. When the standard deviation falls below 0.020 g that is 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 we continue to work back until both criteria are satisfied.

The pulse rise time can be calculated by subtracting t_i from t_{peak}. The rise time is reported on screen 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 the time of impact, t_i.

Working back from t_i we find the first set of three consecutive readings where the acceleration is within ±0.0030 g. 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 done is a similar manner, using the velocity data array. Working back from t_i we find the first set of three consecutive readings where the velocity is within ±30 µm/s. 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.

It is generally the case that the two starting points occur at different reading numbers.

For both the acceleration and the velocity data arrays, if we cannot locate a starting point within 50 ms ahead of t_i, a popup error message provides an alert that there is excessive vibration before the strike of the mass. 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. The 15,000 readings are taken over a period of one second, so the readings are 0.0667 ms apart. The digital integration is done 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 speeding up the calibration process and creating a universally compatible procedure. Time is saved using a multi-sensor stand, eliminating the need to reference calibrate deflection sensors individually. The design of the stand made it possible to easily position the stand close to the load plate for all brands and models of FWD.

In the new calibration protocol, the sensors need only to 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 results in removing the effect of the two columns of the stand.

Photos of the two stand designs are provided in Figure 56 (page 153) and Figure 65 (page 163). Details about the installation and use of the stands are given in Appendix VI—Hardware Use and Installation Guide.

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 proved stiff enough to ensure consistent deflections for all positions in the stand. Our research showed it was the least affected by the rolling motion of deflection waves.

For the new protocol it was necessary to develop two different stands, one for geophones and another for the seismometers used by KUAB FWDs. Ten geophones or seismometers can be simultaneously calibrated using the new stands. The same stand is used for both reference and relative calibration.

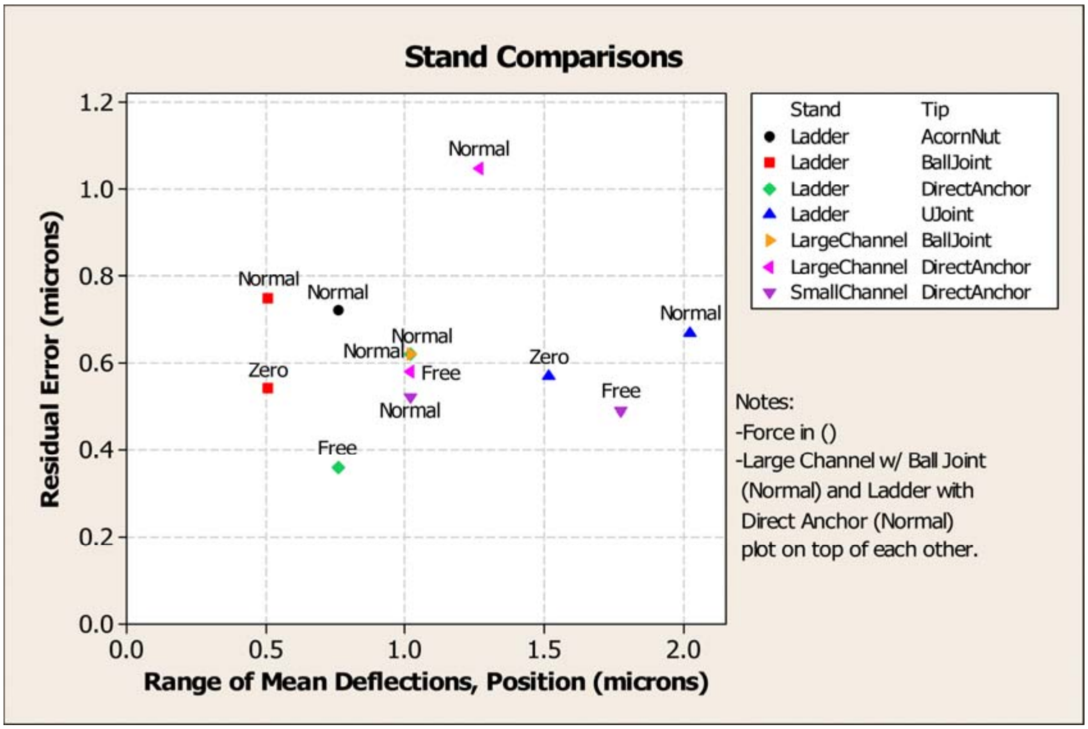

Figure 27. Graph. Comparison of sensor stand performance.

Ball Joint Anchor

To assure accurate measurement with the columnar stand design, we found 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 a person could not provide enough downward force to keep the stand in contact with the test pad and produce consistent results. The graph in Figure 27 shows the results of the tests.

This 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, and the other was to connect the stand through a ball joint clamp bolted to the pad (Figure 50, page 146).

The single-hole direct anchor was shown to be acceptable in terms of unattributed (or residual) error and range of deflections, as was the ball joint anchor. Yet despite the efficacy of both, we selected the ball joint anchor over the direct anchor for several reasons:

- The ball joint makes it possible to keep the stand vertical during testing.
- We found that having a person hold the stand acts as a dampener to vibration. With the direct anchor, it is possible for the stand to be used without being held, and this increased the variability of the results.
- Direct anchored stands would be more prone to damage if hit by the FWD.

Reference Load Cell

The reference load cell (Figure 98, page 205) has been modified in two ways. The thickness of the lid was increased from 16 mm (5/8 in.) to 25 mm (1 in.) to better resist bending and permanent deformation. The guide fingers were moved back slightly, from a 300 mm (11.9 in.) diameter to a 305 mm (12 in.) diameter, to accommodate the larger load plate on the JILS FWD.

When calibrating the reference load cell, the maximum load has been increased to 107 kN (24,000 lbf) (versus 89 kN (20,000 lbf) used in the SHRP protocol). This change was made to accommodate the higher preload pressure that is used by the JILS FWD. The calibration should be done by a qualified agency in accordance with AASHTO R 33.

A new design for the reference load cell is currently being studied. It will have a higher maximum load capacity around 310 kN (70,000 lbf). This will allow HWDs to be calibrated without the need to take off the removable masses. The new design is expected to offer the same, or nearly the same, precision as the current reference load cell.

Software Redevelopment

One task was to update the existing software to a modern, Windows-based graphical user interface (GUI) 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 Visual Basic 6. It was chosen because the older *FWDREFCL* program used the QuickBasic language and Visual Basic would not require a complete rewrite of the code, and also because the KUSB data acquisition card already had drivers for Visual Basic 6.

The update of the program started in June 2005 with the conversion of the *FWDREFCL* code to Visual Basic. 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 (October 2005). The computer programming team added support for these devices in a skeleton version of the new program and built the graphical interface around that.

A draft Visual Basic program that performed some of the basic data acquisition functions and analysis was used during the visits to the FWD Calibration centers in April and May 2006. The visits allowed us to try out the concepts with all four types of FWDs. Comments by the Calibration Operators and other people who participated were incorporated into the program, and a list of suggestions and bugs in the program was developed to track upgrades and changes.

Initially the calculations were done with spreadsheets, Minitab statistical software,[13] or by hand to confirm their validity. The validated procedures were then provided to the software developers and incorporated into the software in late summer 2006.

The beta version of the *WinFWDCal* was vetted at Cornell prior to its release to the four regional calibration centers in late November and early December 2006. During the installations at the regional centers additional upgrades were made.

Periodic updates of *WinFWDCal* have been issued on roughly a quarterly basis. Version 2.0 of the software is expected to be released by summer 2009.

Electronic Data Transfer

We experienced a problem with transferring the data from the FWD to the *WinFWDCal* program. Each type of FWD had a different native file format, and several manufacturers have many different formats. We chose the AASHTO PDDX file standard[1] as the preferred format for data transfer after discussion with the FWD manufacturers, Calibration Operators, and other FWD users. This led to development of a self-standing program, *PDDXconvert*. *WinFWDCal* uses *PDDXconvert* as an intermediary for all data transfers.

At the FWD, a data file is copied in native format onto a USB flash drive or a floppy disk to transfer data to the calibration computer. This eliminates the manual entry of values 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 consistent format that *WinFWDCal* can read and use.

One spin-off advantage of developing *PDDXconvert* as a stand-alone program is it can be used for other applications, such as backcalculation programs.

The *PDDXconvert* computer program 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 our experience working with various FWD file formats and many user needs, is offered in Appendix III—Pavement Deflection Data Exchange (PDDX) Standard, Version 2

Each FWD manufacturer has a different way of storing this important information. For example, one FWD operating system includes the operator's name, all of the sensor serial numbers and the current gain factors in the header of every data file. Another manufacturer disperses the same information among three different files. And the file naming scheme is not consistent either.

Currently no FWD operating system stores the last calibration date for each sensor.

Several of the FWD operating systems provide a PDDX output option. If they were formatted correctly, these file could be read directly by *WinFWDCal*. However, these files are created for use by AASHTO's *DARWin* pavement design program, and unfortunately *DARWin* does not adhere to the AASHTO standard for PDDX files. Further, the AASHTO standard does not provide a place for the current load cell calibration factor, which is important information for FWD calibration.

This problem could be easily overcome if the FWD manufacturers would adopt Version 2 of the PDDX standard that is defined in Appendix III.

Two FWD calibration data exchange file formats are described in Appendix III (page 114). One provides a suggested file name and contents for exchange of information from the 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. All of these 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 the FWDs.[(15)]

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

Thus stability, in terms of the constancy of a sensor's gain over time, is more important than whether the gain factor falls between 0.98 and 1.02. Evaluation of the historical database showed that a reasonable expectation that an individual gain factor would not change more than one percent from one calibration to the next (typically one year apart). We use this result as the first criterion in evaluating and accepting the results of an FWD calibration.

When data for a particular FWD are available for a period of four years or more, the long-term data can also be used as part of the calibration acceptance criteria. From the historical database a tentative finding is an individual gain factor should change no more than 0.1 percent per year, provided that at least three calibrations were done in the four-year period.

The long-term allowance for change (0.1 percent) is less than that for a single year (1.0 percent) because our research showed that the short-term change is usually more than is found over a longer period of time. Being mindful 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, for several reasons it will be difficult to implement the long-term acceptance criterion until the new procedure has been in use for four years or longer. First, 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. Second, there was only a small number of FWDs that had four years of calibration history. Third, essentially all of those machines were Dynatest FWDs.

We must wait until the new calibration procedure has been used for several years, and look carefully at the data that are collected, before we can implement the long-term acceptance criterion.

COMPARATIVE ACCURACY OF THE OLD AND NEW PROCEDURES

Our objective was to make procedural 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 was using the older SHRP protocol and the other using the newly developed method.

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 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 sets of calibrations of the nine sensors were completed with each protocol. The overall average gain obtained with the new 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.

A dotplot in Figure 28 compares the results for the two protocols. The upper half of the graph shows the final gain with the old SHRP protocol. The lower half shows the results with the new protocol.

Influence on Load Cell Gain Factors

Twenty load cell calibrations were completed with the old SHRP protocol, and 17 with the new procedure. Figure 29 shows the load cell final gains for the SHRP (old) and new protocols. The average final gain increased by 0.4 percent. The 95 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.

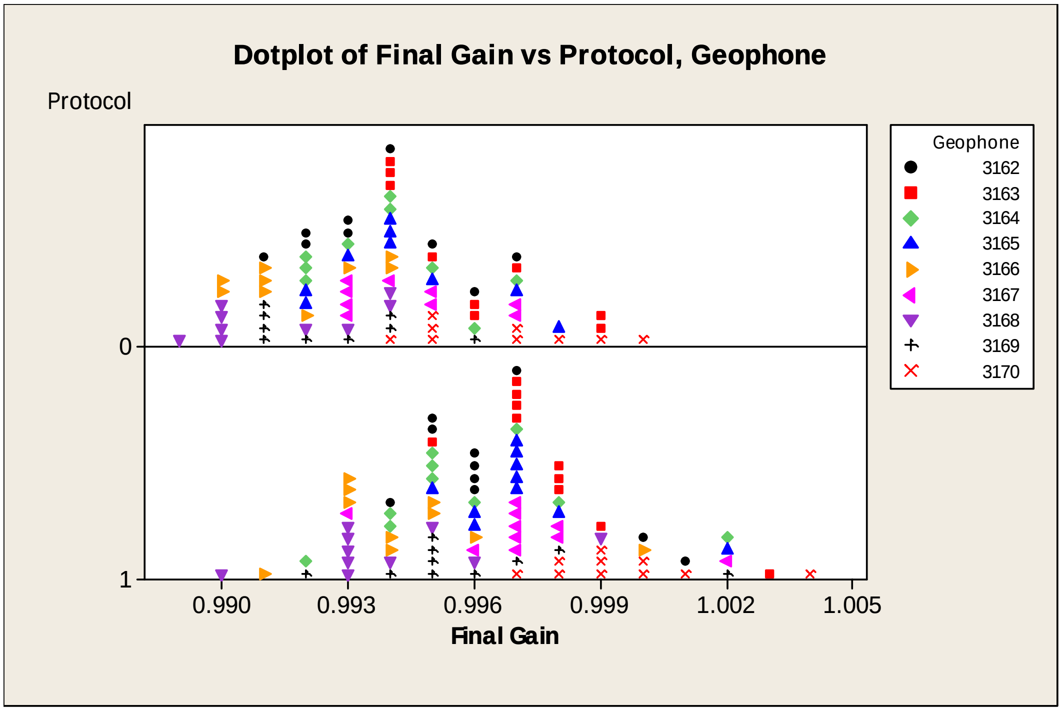

Figure 28. Graph. Comparing deflection sensor final gain values produced with the old (upper panel) and new (lower panel) protocols.

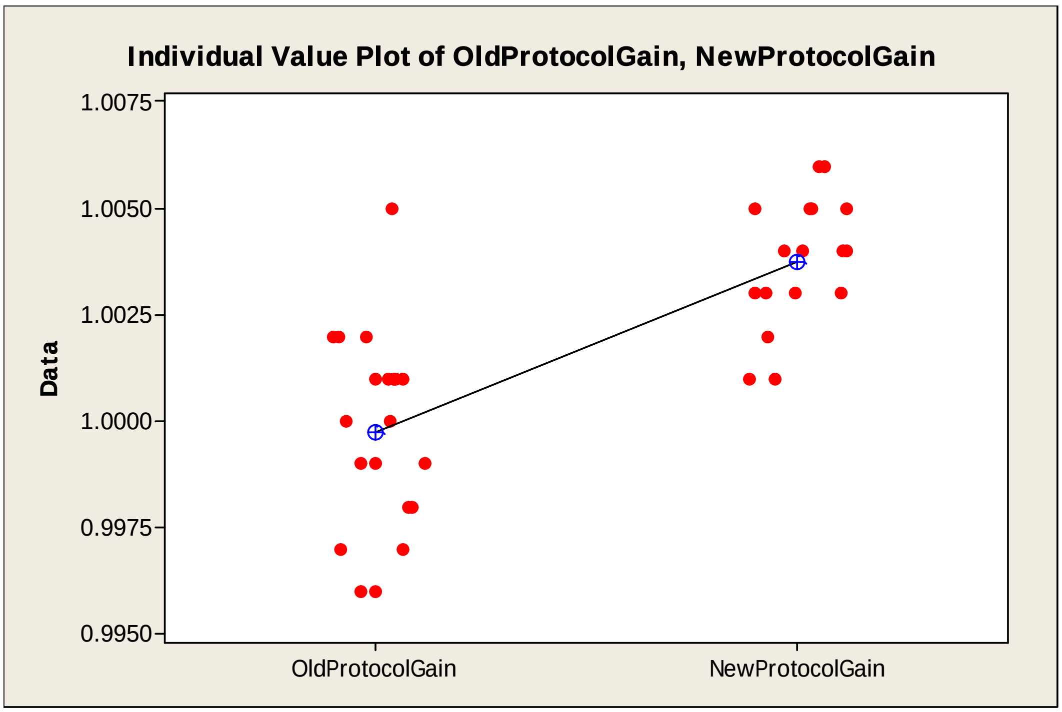

Figure 29. Graph. Individual value plot of load cell final gain values from the old and new protocol.

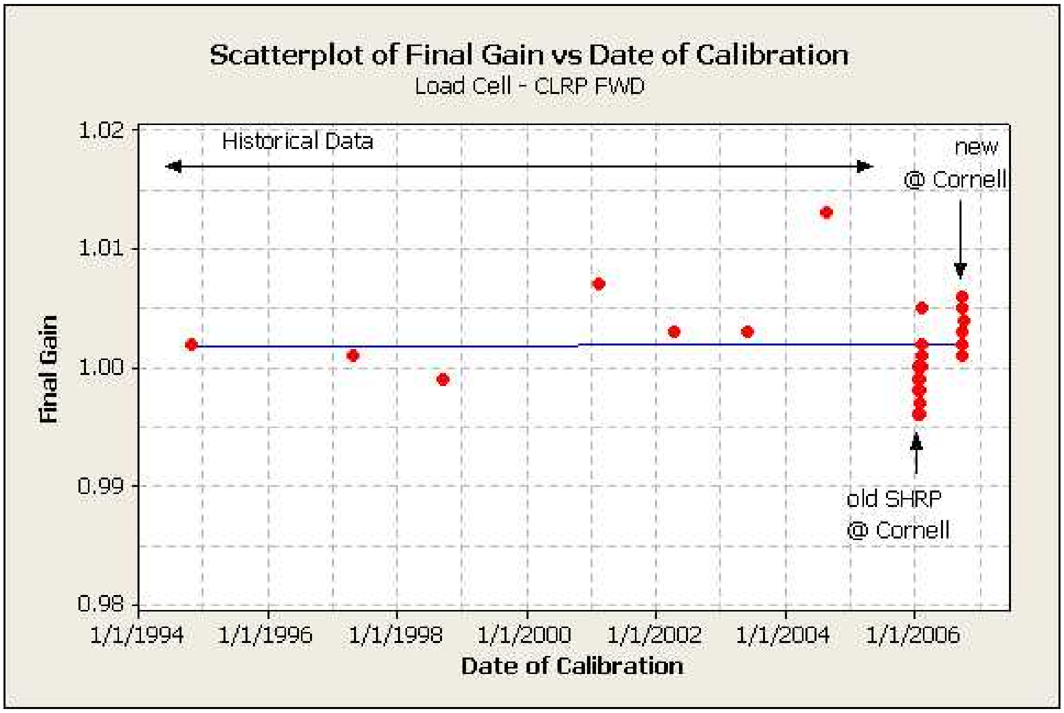

Figure 30. Graph. Load cell calibration history 1994-2006.

The change was more than we 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. We wondered why, then, had the gain changed by 0.4 percent? We looked at the long-term history of the load cell calibrations for the FWD, going back to 1994, to see if there was any explanation.

The gain factor history is shown in Figure 30. The year-to-year changes are much more volatile than the long-term trend, and that is normal. The (calculated) trend line is essentially flat. The set of calibrations in early 2006, using the old SHRP procedure, tend to fall mostly below the trend line. The data for the new procedure tend to fall mainly above the trend line.

We conclude that *both protocols may have accurately reported the gain factors that were applicable at the time*. That is, we believe the response of the FWD load cell actually changed during the course of the year. The magnitude of the change in 2006 was consistent with the changes that have been observed in earlier years. Other interpretations of the data are possible, but we feel 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 might conclude from this that the new protocol yields different results than the SHRP protocol, but in practical terms the differences are small. For example, for a deflection of 500 microns (20 mils), the average difference in the two protocols is only 1.3 microns (0.05 mils). It is questionable whether such a small difference has practical meaning, even if the statistics indicate it is significant.

- Beam movement up to 3 microns (0.12 mils) was tolerated using the old method.
- The new method completely eliminated that problem.
- That fact alone could account for the difference in the two methods.
- The standard deviation for multiple calibrations is on the order of ±0.3 percent.
- In addition, some real change in the sensor response could have occurred over the course of the year.

It is entirely 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. **So, from a practical perspective, we believe the small differences are not a concern.**

PRECISION AND BIAS STATEMENTS FOR FWD CALIBRATION

The pooled fund study was focused on removing any possible bias error in the gain factors. Our research found that no meaningful bias comes from either the load or deflection calibration procedures. We used the data cited in the previous section to formulate a precision and bias statement according to ASTM E-177. [(4)]

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

The series of calibration trials using the new procedure were used to define the precision and bias. Our 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 three weeks or so) to minimize possible changes in the FWD.

Since this testing was on a single Dynatest FWD at one location, the results cannot be applied directly to all brands of FWDs or to multiple centers. However, the historical information about FWD calibration collected by Orr and Wallace [(15)] and reviewed as part of this research shows that similar results can be expected for most Dynatest FWDs.

Load Cell

Seventeen load cell calibration trials were done by three FWD Calibration Operators. No differences between operators were found. The overall standard deviation of the final calibration factor was 0.00152. The 95th percentile repeatability using a Student's t-test uses a multiplier of 2.11.

Precision and Bias Statement for Dynatest Load Calibration

The 95% repeatability of the final gain factor: 0.321%
No reproducibility statement is available at this time.

There is no bias expected in the final gain factor.

Geophone Calibration

Nine geophone calibration trials were done 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% repeatability of the final gain factor: 0.480%
No reproducibility statement is available at this time.
There is no bias expected in the final gain factor.

QUALITY ASSURANCE PROCEDURES AND OPERATOR CERTIFICATION

A key support function is the annual quality assurance and certification reviews at each center. These visits help to keep each operator informed about the changes in the protocol, equipment and software. They also assure everyone, Calibration Operator and FWD owner alike, that the calibration procedures are being carried out correctly.

The Certificate of Compliance that is issued to the Calibration Operator is valid for the following year. It conveys that the person doing the calibration has been observed to be knowledgeable about the procedure. The annual visits also promote communication and feedback, helping to identify needed improvements in the software and the protocol based on operator experience.

Beginning with the Strategic Highway Research Program in the early 1990's, quality assurance procedures were developed to be used annually at the calibration centers. Those procedures were reviewed and updated as part of the support function of the pooled fund study. During March and April 2008 the first quality assurance visits were conducted. A report for each separate visit was sent to the calibration center and copied to the FHWA. Each Calibration Operator received a Certificate of Compliance.

Two checklists have been developed for use during the quality assurance 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 IV—Quality Assurance Reviews.

CHAPTER 4—CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

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

The new procedure works well with all brands of FWDs. It is expected, however, that there will continue to be a need for improvements as changes occur in FWDs. For example, the new Dynatest truck-mounted FWD did not exist when the new protocol was developed. And we had very limited access to the Carl Bro FWD during the development stage.

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 is developed. The major changes are the use of the self-referencing accelerometer, the updated data acquisition system and *WinFWDCal* computer program, and the new multi-sensor deflection sensor calibration stands.

RECOMMENDATIONS

- **Review and update the calibration acceptance criteria.**

  There are many places in WinFWDCal where the internal quality control criteria are not satisfactorily defined. Using our best judgment, we had to choose initial values to get the procedure into use. Over time, continued use of the new protocol provides additional data that can help to refine the critical criteria. Listed below are some of the criteria that should be reexamined:

  - The allowable change for daily accelerometer calibration.
  - The allowable change in gain factor from one calibration year to the next.
  - The allowable rate of change per year in gain factor for FWDs with at least 4 years of calibration history.
  - 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 preceding the impact of the falling mass.

  Additional criteria may be encountered that require review as we gain experience with applying the *WinFWDCal* program.

- **Continue to provide support and quality assurance for the calibration centers.**

  The Calibration Operators need on going support. When they are having a problem calibrating an FWD they need a person to talk to who can help them overcome it. They need to know whether their equipment is working properly and their results are believable. They need someone who can fix the software problems they encounter and a person to offer suggestions for procedural improvements who can implement them.

The annual quality assurance reviews 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 to identify problems that the centers are encountering.

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

  Over the 28 months between the first public release of *WinFWDCal* and now (November 2006 until February 2009), several major releases of the software have gone out and numerous small "bug fixes" have been made. While the rate of problem identification coming from the users has slowed down, there are still a number of software improvements that are planned.

  With any software package there will be 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.

- **Develop procedures and equipment that are better suited for calibrating HWDs.**

  The current calibration procedures are well suited for calibrating FWDs. They also work with HWDs, but in order to calibrate the load cell on the HWD all of the removable mass must be taken off the machine. The HWD is capable of forces up to 300 kN (65,000 lbf) or so, but the current procedure only calibrates up to 71 kN (16,000 lbf). A high capacity reference load cell will enable HWDs to safely be calibrated over their full load range, and without the hassle of removing the weights.

  The consequence of using full-mass deflection sensor calibration on the calibration test pads needs to be studied. One possibility would be to establish suitable calibration test points on other, more substantial floor areas.

- **Provide a mechanism to transfer the results (gain factors) of the calibration into the FWD computer automatically.**

  The new calibration procedure provides the means for electronic transfer of data *from the 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.

- **Improve the electronic data transfer procedures.**

  The program *PDDXconvert* only partly meets the needs for FWD calibration. Some of the necessary input data (from the FWD) must still be entered manually or left out entirely. And several types of FWDs have their input data scattered among several different files.

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

APPENDIX I—FWD CALIBRATION PROTOCOL

INTRODUCTION

This document describes the procedure for calibrating Falling Weight Deflectometers (FWDs). It updates the original protocol developed by the Strategic Highway Research Program.(16) The original software and hardware have been revised for this procedure.

This protocol is written for use with the four types of FWDs currently manufactured or sold in the United States of America. It is *not* applicable to the calibration of lightweight deflectometers (LWDs) 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, described in the annexes.

This protocol does not cover the calibration of other parts of the FWD including temperature probes and the distance measuring instrument (DMI) of the FWD. Use the manufacturers' recommended procedures to calibrate these devices.

This protocol contains two procedures: *Annual Calibration* and *Monthly Calibration*. The deflection sensors must be removed from their holders on the FWD for either procedure.

Annual Calibration can be performed at a FWD Calibration Center or on site where the FWD is located. The same equipment and procedures are used at either location. A certified technician shall 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.

For Monthly Calibration only relative calibration is done, at any suitable location, using equipment supplied by the FWD manufacturers. A certified technician is not required. It is done periodically for verification of the accuracy of the deflection sensors and occasionally when a sensor must be replaced. The procedure used for Monthly Calibration is different than for Annual Calibration.

Either procedure results 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 that there be 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 on the FWD.

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

Personnel

Annual Calibration requires two people to perform the procedure. One person is the *FWD Operator*. The FWD Operator is responsible for assuring that the FWD is in proper working order for the calibration. During the calibration this person operates the FWD and removes and replaces the sensors in their holders.

The other person is the *Calibration Operator* (a certified technician). This person makes sure the calibration equipment is maintained and calibrated as needed. During the calibration this person is responsible for operation of 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 shall 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 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 the calibration, the moving of sensors and operation of 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.

After completion of the procedure, the Calibration Operator shall 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 shall enter the Final Gain Factors in the FWD computer. The FWD Operator should maintain a cumulative history of calibration results in the FWD computer. The Calibration Operator shall also maintain a history of calibration results for the FWD at the Calibration Center.

WinFWDCal

The calibration protocol as described herein has been automated in a software package named *WinFWDCal*. It is required that the computer program be used to carry out the procedure.

ANNUAL CALIBRATION PROCEDURE

In 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.

Equipment Preparation and Set Up Before Calibration

During set up, FWD-specific information will need to be transferred from the FWD Operating System (e.g., the FWD computer files) to the calibration computer. The annexes describe the procedure for obtaining this information for each type of FWD.

Falling Weight Deflectometer

The FWD shall 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 during general use. A checklist to help the FWD Operator prepare the FWD for calibration is provided in Annex A. It should be filled out in advance. A copy of the completed checklist shall be provided to the Calibration Operator.

Before beginning any calibration work, and throughout the entire calibration period, there shall be no data filters in operation in the FWD Operating System. The FWD Operator shall verify that all smoothing or filtering has been turned off.

Prior the calibration, the FWD shall be warmed up using the standard operating procedure for the particular brand of FWD.

FWD Drop Sequence:

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

Table 3. Suggested dynamic load levels for reference calibration*

Brand of FWD	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 US Customary values are not exactly the same. The FWD shall be calibrated in one unit system or the other. The values in the table are rounded with intervals that are approximately equally spaced.

It is the prerogative of the FWD Operator 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 the FWD normally uses in daily operation. However, in no instance shall the combination of static plate load plus maximum dynamic load exceed 106 kN (24,000 lbf). This limitation is required to protect the reference load cell and the concrete pavement used in the calibration procedure.

During set up the minimum number of drops at each load level will be determined by the *WinFWDCal* software based upon the deflection response of the concrete pavement. More than the minimum number of drops may be used, not to exceed ten drops per load level. The FWD

Operator shall program the drop sequence in the FWD computer, progressing from the lowest to the highest load level. The same number of drops shall be used at each load level. The same drop sequence shall be used for both load and deflection sensor calibration.

The software may advise that the deflections are either too large or too small to satisfy the precision requirements for reference calibration. If they are too large, the FWD may be moved further away from the sensor stand. If the deflections are too small, and if three load levels were used, four load levels should be tried. If the deflections are still too small, and the FWD cannot be moved closer to the sensor stand, then a sequence of higher load levels should be tried, if possible. If this does not solve the problem, then no further efforts shall be made to calibrate the deflection sensors.

FWD Calibration Equipment

Table 4 shows the equipment needed to perform the load cell and deflection sensor calibration. Detailed information for all components is in Appendix V—Specifications and Drawings.

Table 4. FWD calibration center equipment

Equipment	Notes
Reference load cell with signal cable	133 kN (30,000 lbf) maximum capacity, calibrated annually to 106 kN (24,000 lbf)
Reference accelerometer with signal cable	±5g maximum acceleration range, calibrated on the day of use.
Vishay 2310 signal conditioner with power cable	Used to amplify 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* software	Used to store the A/D output and perform the calculations needed for the calibration.
Accelerometer calibration platform	Used for daily calibration of the accelerometer. Also used to store accelerometer in a +1g 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 calibration stands.
Protective shipping case	For storage and shipping of Reference Load Cell, Vishay signal conditioner, Keithley DAQ board, and related cables.
Isolated concrete test pad	Designed to generate pavement deflections in the desired range. A test pad is recommended, but not required.

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

Reference Load Cell Calibration:

The reference load cell shall be calibrated at least once per year in accordance with the recommended procedure (Annex G).

Accelerometer Calibration:

The accelerometer shall be calibrated in the Earth's gravity field just prior to use for relative calibration to determine the daily response of the accelerometer. This calibration shall be repeated after four hours have elapsed.

The accelerometer, mounted in an aluminum box, shall be calibrated using the calibration platform. The platform shall be carefully adjusted using the bubble level to assure that the accelerometer is aligned with the Earth's gravity field. The accelerometer shall be calibrated in both +1 g and –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 damage the accelerometer.

The *WinFWDCal* software will guide the Calibration Operator through the accelerometer calibration procedure and calculate the calibration coefficients. The accelerometer box shall not be in the -1 g orientation for more than 20 seconds 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 shall be stopped. The box shall be placed upright in a +1 g gravity field for a period at least two times as long as it was inverted, up to a maximum of 24 hours, to return it to equilibrium. So, for instance, if it was upside down for one minute, it shall be allowed to equilibrate for at least two minutes before repeating the calibration of the accelerometer.

The accelerometer calibration is slightly temperature sensitive. Thus it is important that the accelerometer be calibrated shortly before its use. Temperature is monitored continuously by the *WinFWDCal* software. It will alert the Calibration Operator if the temperature changes by more than ±10°C (±18°F). If this occurs the accelerometer shall be recalibrated.

The FWD Calibration Procedure

It is recommended that deflection sensor calibration be done first, followed by load cell calibration. The *WinFWDCal* software shall be used for data acquisition and to make the associated quality assurance calculations.

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*.

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
Ref. Load Cell Calibration Constants	Automatic	Center Configuration File
Ref. Load Cell Calibration Date	Automatic	Center Configuration File
Reference Accelerometer Serial Number	Automatic	Center Configuration File
Ref. Accelerometer Calibration Constants (daily)	Computed	*WinFWDCal* Software
Ref. Accelerometer Calibration Date	Automatic	Calibration Computer
FWD Information		
FWD Owner	Manual	FWD Operator
FWD Operator Name	PDDX file*	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* Software
Ref. Load Cell Readings	Computed	*WinFWDCal* Software
FWD Load Cell Readings	PDDX file	FWD Computer
Ref. Accelerometer Readings	Computed	*WinFWDCal* Software
FWD Deflection Readings	PDDX file	FWD Computer
Interim Gain Factors from Ref. Calibration	Computed	*WinFWDCal* Software
FWD Relative Calibration Data	PDDX file	FWD Computer
Adjustment Factors from Relative Calibrations	Computed	*WinFWDCal* Software
Final Gain Factors	Computed	*WinFWDCal* Software

* The PDDX file is created by *WinFWDCal* software from FWD native output.

** For the first calibration according to this protocol, the Calibration Operator will supply the history of previous calibrations, if one is available.

Deflection Sensor Calibration

Deflection sensor reference calibration consists of two trials, where all of the sensors are calibrated simultaneously in a special stand. 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 shall not be calibrated unless they have separate, dedicated signal conditioning channels in the FWD microprocessor.

For reference and relative calibration the sensor stand shall 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 the Earth's gravity field. The sensor stand should be supported by the rest stop between trials.

Reference Calibration:

The reference calibration drop sequence established during set up shall be used.

The deflection sensors shall be placed in the sensor stand, centered on the reference accelerometer. The *WinFWDCal* software displays a diagram showing how to arrange the sensors in the stand (see Table 8 and Table 9 on page 91).

Perform the drop sequence for the first reference calibration trial. Review and accept or reject the data for each drop. The *WinFWDCal* software will graphically display the deflection-time data after each drop and report the peak deflection to be compared to the reported FWD peak.

At the conclusion of the drop sequence, transfer the FWD data electronically to the calibration computer and review the results. For each sensor *WinFWDCal* will compare 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 Cal Gain Factor.

The slope for an individual sensor is acceptable if its reported standard error is not more than 0.0020. The trial is acceptable if the standard errors for all sensors are not more than 0.0020.

If the first trial is acceptable, continue with the second trial. Invert the sensors in the stand before the second trial according to the diagram displayed by *WinFWDCal*. Repeat the same procedure that was used for the first trial.

Interim Gain Factor Acceptance Criteria:

After two trials have been accepted, *WinFWDCal* will calculate the average Reference Cal Gain Factor for each sensor, and display the results as the Interim Gain Factors. The difference in the gain factors for the two trials for each sensor and the root-mean-square (RMS) value for all sensors are reported. If the RMS value is not more than 0.003, then the reference calibration test is complete.

If the RMS value is greater than 0.003, this indicates that the gain factor for one or more sensors is not sufficiently repeatable. Two more reference calibration trials shall be performed.
The average of the four Reference Gain Factors for each sensor shall be reported as the Interim Gain Factors. If the RMS value for the four acceptable trials is not more than 0.003, then the reference calibration test is complete.

After four trials, if the RMS value still exceeds 0.003, then no further effort shall be made to calibrate the deflection sensors. The reason why the RMS value exceeds 0.003 should be investigated and corrected, if possible, before repeating the procedure.

Relative Calibration:

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

The *WinFWDCal* software will adjust the FWD data collected in the relative calibration, using the Interim Calibration Factors internally. *So the FWD Operator shall NOT enter the interim factors in the FWD Operating System before performing relative calibration*.

Perform the drop sequence for the first relative calibration trial. At the conclusion of the drop sequence, transfer the FWD data electronically to the calibration computer and review the results. For each sensor *WinFWDCal* will calculate the means ratio. The means ratio multiplied times the Interim Gain Factor gives the Relative Gain Factor.

WinFWDCal does an analysis of variance (ANOVA) for the data and reports the standard error. The standard error is acceptable if it is not more than 3 microns (0.12 mils).

A plot of the data for the 40 drops is displayed. The graph should be scanned to detect outliers (for instance, a loose senor in the stand). If the standard error is greater than 3 microns (0.12 mils) the first trial shall be rejected and repeated. (Do not reposition the sensors.) The reason why the standard error exceeds 3 microns should be investigated and corrected, if possible, before repeating the procedure. If acceptable results cannot be obtained after four trials, no further effort shall be made to calibrate the deflection sensors.

If the first trial is acceptable, continue with the second trial. Invert the sensors in the stand before the second trial according to the diagram displayed by *WinFWDCal*. Repeat the same procedure that was used for the first trial. Evaluate the data for second trial in the same way.

After two trials have been accepted, *WinFWDCal* will calculate the average Relative Gain Factor for each sensor, and display the results as the Final Gain Factors.

WinFWDCal calculates and displays a means ratio for each sensor which, when multiplied times the Interim Gain Factor, gives a Final Gain Factor for each sensor. The percent change from the Initial Gain Factor is also reported. Proceed to Evaluation and Acceptance of Final Results.

Load Cell Reference Calibration

Reference load cell calibration consists of at least two trials. The reference calibration drop sequence established during set up shall be used.

Perform the drop sequence for the first reference calibration trial. Review and accept or reject the data for each drop. The *WinFWDCal* software will graphically display the load-time data after each drop and report the peak load to be compared to the reported FWD peak.

At the conclusion of the drop sequence, transfer the FWD data electronically to the calibration computer and review the results. *WinFWDCal* will compare the FWD output (independent variable) versus the reference load cell peak (dependent variable) forced through zero. The slope of the regression line, when multiplied times the Initial Gain Factor, gives the Reference Cal Gain Factor.

The slope for the trial is acceptable if its reported standard error is not more than 0.0020.

If the first trial is acceptable, continue with the second trial. Repeat the same procedure that was used for the first trial.

Gain Factor Acceptance Criteria:

After two trials have been accepted, if the range of the two gain factors is not more than 0.003, then the results of the two trials shall be averaged and reported as the Final Gain Factor for the load cell. The reference calibration test is complete.

If the results are outside the allowable range, a third reference calibration trial shall be performed. If the standard deviation of the gain factors for three acceptable trials is not more than 0.003, then the results of the three trials shall be averaged and reported as the Final Gain Factor for the load cell. The reference calibration test is complete.

If the standard deviation exceeds 0.003, the load cell reference calibration procedure shall be repeated (one more trial), yielding a fourth gain factor. The reason why the standard deviation exceeds 0.003 should be investigated and corrected, if possible, before repeating the procedure.

If the standard deviation of all calibrations (four acceptable trials) is not more than 0.003, the average of all four results shall be used as the Final Gain Factor for the load cell, and the reference calibration test is complete. If this criterion cannot be met, no further effort shall be made to calibrate the load cell.

Evaluation and Acceptance of Final Results

Before accepting the load cell and deflection sensor Final Gain Factors, the factors shall be evaluated with respect to three criteria.

1. The Final Gain Factors from this calibration shall be compared to the corresponding gain factors from the previous calibration (i.e., the Initial Gain Factors). There shall be no more

than a one percent difference, either higher or lower for each individual deflection sensor and for the load cell. If this criterion is satisfied, then Final Gain Factor for the sensor shall be accepted. If this criterion is not satisfied for a sensor, then evaluate it according to the next criterion.

2. The Final Gain Factor for the sensor shall fall within a range of 0.980 to 1.020. If this criterion is satisfied, then the Final Gain Factor for the sensor shall be accepted. If this criterion is not satisfied for the sensor, then evaluate it according to the next criterion.

3. If a historical record of previous calibrations for the sensor is available for a period of four years or more, and there are at least three previous calibration results over this period of time, then the time rate of change of the Final Gain Factor for the sensor shall be no more than 0.1 percent per year. If this criterion is satisfied, then the Final Gain Factor for the sensor shall be accepted.

Certificate of Calibration:

If the final calibration results meet the acceptance criteria for all sensors, the Calibration Operator shall 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 System computer. An output file in PDDX format is provided by the *WinFWDCal* software to facilitate electronic data transfer.

Report and Retention of Data:

The FWD Operator shall be provided with an electronic copy and a paper copy of the calibration results. The FWD calibration report shall 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.

- Pre-calibration checklist

- Any other records produced as part of the calibration.

All paper records shall be annotated with the FWD unit identification (e.g., manufacturer's serial number or agency ID), and the calibration date.

The final results from the calibration shall be merged with the history file, a database of previous calibration results for the FWD. Both the FWD Operator and the Calibration Operator shall retain an electronic copy of the cumulative history file for the FWD. The *WinFWDCal* software will produce the cumulative history file.

Calibration records shall be retained by the Calibration Center for at least four years.

MONTHLY CALIBRATION PROCEDURE

Monthly Calibration can serve one of two purposes. With regular use it is a means to verify that the deflection sensors are functioning properly and consistently. 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 done.

Monthly Calibration uses a calibration stand provided by the FWD manufacturer. The deflection sensors are stacked vertically in the stand, one above another, so that all 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 done 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 500 microns (20 mils) 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, so as long as the effect is not too extreme, the adjustment ratios are still accurate.

Some FWDs may have fewer than seven or more than nine active deflection sensors. If they do, these procedures shall be modified to simultaneously calibrate the actual number of active sensors in use on the FWD.

Equipment Preparation

Falling Weight Deflectometer

The FWD shall 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 during general use. A checklist to help the FWD Operator prepare the FWD for calibration is provided in Annex A.

Before beginning any calibration work, and throughout the entire calibration period, there shall be no data filters in operation in the FWD Operating System. The FWD Operator shall verify that all smoothing or filtering has been turned off.

Prior to starting the calibration, the FWD shall be warmed up using the standard operating procedure for the particular brand of FWD.

Other Equipment

FWD calibration stand provided by the manufacturer.

Overview of the Procedure

Replicate deflection readings shall 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 shall be moved 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) shall be "conditioned" before beginning the calibration procedure to reduce the significance of set in the data analysis. The warm up drops shall be used for this purpose.

Monthly Calibration of the Deflection Sensors

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 shall 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. The sensor stand shall be held in a vertical position. Mark the location where it rests so that it can be relocated precisely on the same spot. This should be done 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 500 microns ±100 microns (20mils ±4 mils). If deflections in this range cannot be achieved, then 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 the relative calibration testing.

7. For each set, make two seating drops (no data recorded) followed by five replicate drops (for which data shall be recorded).

8. At the end of each set rotate the sensors in the stand as shown in Table 6 or 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 done as prescribed in order for the data analysis in *WinFWDCal* to work properly. If the direction of rotation is reversed, the calculations will be incorrect.

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

Stand Position		**Deflection Sensor Number in the Stand**								
(top)	**Set**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
A		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**						
(top)	**Set**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
A		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

9. With a nine-sensor FWD, a total of 45 drops shall be recorded (nine sets of five replicate drops for each set). With a seven-sensor FWD, 35 drops shall be recorded.

Monthly Calibration Data Analysis

Follow the *WinFWDCal* on screen instructions for set up of the procedure. Transfer the FWD data file electronically to the *WinFWDCal* software program for analysis. Options are provided in the software to indicate whether a normal data analysis is required or a special analysis for sensor replacement.

Adjustment of Gain Factors – Normal Analysis:

The *WinFWDCal* software 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 shall be made only when those changes are both significant and verified to be necessary. The following guidelines shall be used to evaluate the need for adjustment of the gain factors:

- If all of the adjustment ratios are between 0.997 and 1.003 inclusive, 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 shall 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 shall 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 shall be adjusted for *all* sensors. The Gain Factors for each sensor for the two trials shall be averaged and entered in the FWD Operating System. The calibration test is complete.

- If for one or more sensors the difference in the gains for the two trials is greater than 0.003, perform two more trials. If the second attempt also exceeds the allowable difference, the Annual Calibration procedure shall 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 done by the *WinFWDCal* software, and a Gain Factor is reported only for the replacement sensor.

Two relative calibration trials shall be performed. If the two gain factors agree within 0.003, then the Gain Factors for the two trials shall be averaged and entered in the FWD Operating System. The calibration test is complete.

If the difference is greater than 0.003, two more relative calibration trials shall 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 shall be entered in the FWD Operating System. The calibration test is complete.

If the standard deviation is more than 0.003, no further effort shall be made to calibrate the replacement sensor. The Annual Calibration procedure shall be performed as soon as possible.

Report

The relative calibration report shall consist of all printouts from the *WinFWDCal* software, annotated as necessary to explain any problems which might have been encountered.

ANNEX A. 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 B. SPECIAL PROCEDURES FOR CALIBRATING A DYNATEST FWD

- The FWD Operating System (i.e., the field program) should be programmed to provide the output from the FWD in either F10, F20 or F25 format. All file extensions shall be **Fnn**, where **nn** is the version number of the FWD field program. This format is needed so that *PDDXconvert* can read the FWD file for the *WinFWDCal* software.
- FWDs using Dynatest's *FWDWin* as the operating system shall save an F25 file in addition to the MDB database file, for use with *PDDXconvert*.
- The FWD should be warmed up 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.
- During the Set Up procedure in *WinFWDCal*, the **Warmup.Fnn** file will be read electronically to get information on sensor serial numbers, initial gains, etc.
- The FWD may be powered by a battery charger. Without a charger, the FWD electrical system may not have enough power for a full calibration. Charging the FWD shall be done in accordance with manufacturer’s recommendations. Some chargers can cause electrical noise on the time history signal during reference calibration..
- For trailer-mounted FWDs, the trailer must be attached to the tow vehicle during the calibration.
- For the Dynatest FWD, it is possible to be within the tolerance for the highest load, and yet to 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), 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 99 mm (3.875 inches) high, so the catch mechanism will be that much higher during load calibration. If the clearance is too small, reposition the target for the fourth drop height to provide the needed clearance.

Figure 31. Photo. Attachment of a Dynatest geophone in the stand.

- For the Dynatest HWD, take off the removable masses to get the peak load from the highest drop height into the range of 71kN (16,000 lbf) ±10 percent. This will avoid exceeding the capacity of the reference load cell and avoid damaging the test pad due to excessive deflections.
- Clean out all stones that are embedded in the rubber pad under the load plate. The FWD Operator shall complete this cleaning PRIOR to arrival at the calibration center.
- The calibration stand hardware can be assembled prior to the arrival of the FWD. The knurled knob shall be placed *above* the shelf in the calibration stand (see **Figure 31**). The knurled knob shall only be tightened by hand. Do NOT use a wrench to attach the hardware.
- Clean the bottoms 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 shall complete this cleaning PRIOR to arrival at the calibration center.
- After placing a geophone on the knurled knob in the stand, try to rock it lightly back and forth. If there is any motion, re-clean the bottom of the sensor. Each geophone must be securely fastened in the stand.
- Place a wooden block under the FWD's raise-lower bar during load cell calibration to reduce the noise and vibration.
- Be sure 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 shall do the bleeding PRIOR to arrival at the calibration center.
- Verify that the new calibration gains have been entered correctly into the FWD field program by printing a summary of the relative gains. Check for typos. The relative gain is the value that is determined from the calibration. DO NOT change the reference gains as those are determined by the manufacturer.

ANNEX C. SPECIAL PROCEDURES FOR CALIBRATING A JILS FWD

- 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.
- The JCAL 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.
- The FWD should be warmed up off the calibration test pad. Save the data in a file named WARMUP.DAT.
- During the Set Up procedure in *WinFWDCal*, there are three files from the FWD computer that need to be read electronically 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. The JILS.CFG file contains the load cell current gain.
- If the sensor gains or serial numbers are not able to be read electronically, type the values manually into the *WinFWDCal* set up screen.
- After reading the three configuration files, verify that each serial number is different. If they are not, rename the sensor numbers on the *WinFWDCal* set up screen with a number matching the sensor position on the FWD. As an example, if all of the sensor serial numbers are “CHOP”, rename them “CHOPn” where n is the number of the sensor starting at 1 for the center sensor at the load plate.
- For trailer-mounted FWDs, the trailer must be attached to the tow vehicle during the calibration.

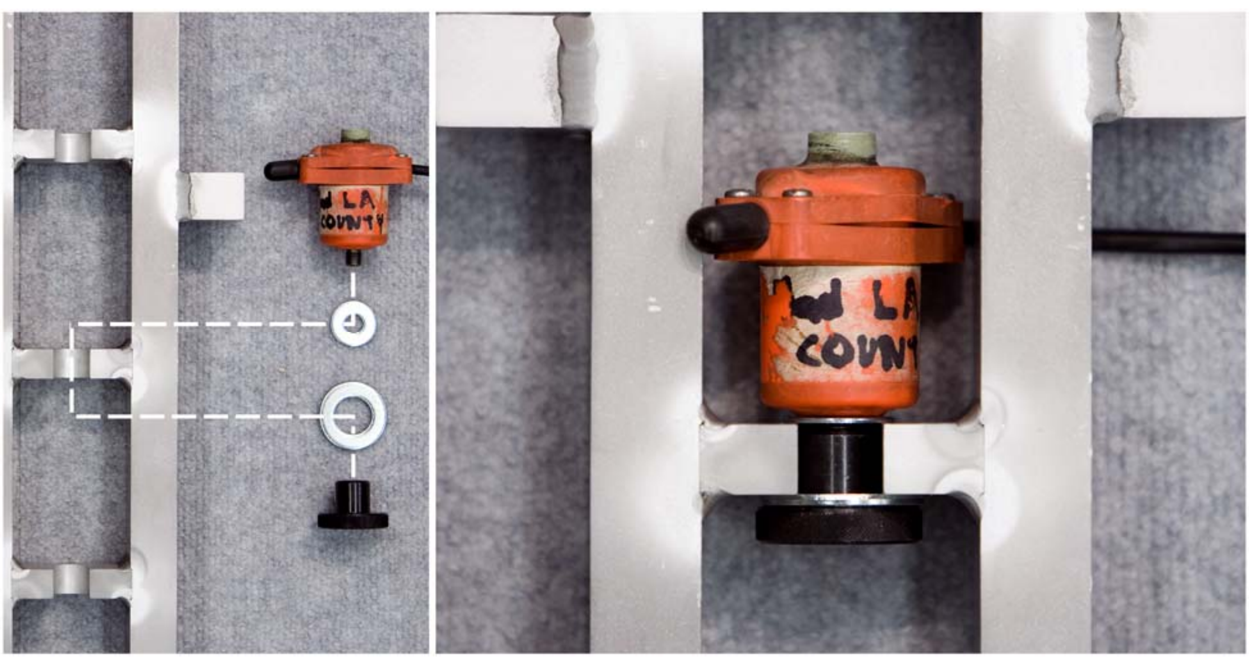

Figure 32. Photo. Attachment of a JILS geophone in the stand.

- Both the tow vehicle and the trailer must be sitting level when the FWD load plate is down on the floor. Shim under the wheels as needed to assure both vehicles are level. The tongue wheel can also be used to help level the trailer.
- Truck mounted FWDs should be sitting 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.
- *It is especially important that the load plate be 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 few millimeters (a fraction of an inch) at any point around the perimeter of the plate. Apply several seating drops before making this check.
- The geophone sensor bar attached to the back of the FWD shall be removed to allow the FWD to get close to the ball-joint anchor and the geophone stand.
- After removing the deflection sensors from the FWD, attach each geophone in the calibration stand with the knurled knob *below* the shelf as shown in Figure 32. The knurled knob shall only be tightened by hand. Do NOT use a wrench to attach the hardware.
- Be sure 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.
- The FWD may be powered by a battery charger. Without a charger, the FWD electrical system may not have enough power for a full calibration. Charging the FWD shall be done in accordance with manufacturer's recommendations. Some chargers can cause electrical noise on the time history signal during reference calibration..
- 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. Check for typos. 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.

ANNEX D. SPECIAL PROCEDURES FOR CALIBRATING A KUAB FWD

- 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 *PDDXconver*t can read the FWD file for the *WinFWDCal* software.
- 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.
- During the Set Up 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.
- If the sensor initial gains or serial numbers are not able to be read electronically, type the values manually into the *WinFWDCal* set up screen.
- The FWD may be powered by a battery charger. Without a charger, the FWD electrical system may not have enough power for a full calibration. Charging the FWD shall be done in accordance with manufacturer's recommendations. Some chargers can cause electrical noise on the time history signal during reference calibration..
- The FWD trailer must be attached to the tow vehicle during the calibration.
- Before the reference calibration procedure is performed, the FWD Operator shall first conduct a static calibration of the seismometers. The KUAB software will automatically file the static calibration factors.
- It will only be possible to calibrate the 300 mm (11.81 in) load cell on the KUAB. If the KUAB is outfitted with load cells having a diameter larger or smaller than 300 mm (11.81 in), these shall not be calibrated using the 300 mm diameter reference load cell, as the results would not be accurate.
- 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 shall not contact the calibration stand during calibration.
- A special two-column seismometer stand is used for deflection sensor calibration for KUAB FWDs with seismometers. The sensors mount on standoffs that are the same size as the ones on the FWD. After the set screw has been tightened the seismometer shall be firmly attached, and it shall not wobble or rock on the standoff. Do not over tighten the set screw or the hole may be stripped. Place the geophones in the calibration stand as diagrammed by *WinFWDCal*.
- The deflection sensor that is mounted through the load plate (i.e., the center sensor) is called sensor number zero (0) on the KUAB, but it is sensor number 1 as far as *WinFWDCal* is concerned.
- During calibration of seismometers, keep the stand aligned perpendicular to the load pulse from the FWD. The easiest way to do this is to stand facing the load plate of the FWD.

- KUABs outfitted with geophones use the same one-column calibration stand used for Dynatest geophones. After removing the deflection sensors from the FWD, attach each geophone in the calibration stand with the knurled knob *below* the shelf as shown in Figure 32. The knurled knob shall only be tightened by hand. Do NOT use a wrench to attach the hardware.
- A magnetic collar holds the KUAB geophone to the calibration stand as shown in Figure 33. A special magnetic cup holds the collar to the stand. Place the geophones in the calibration stand as diagrammed by *WinFWDCal*.

Figure 33. Photo. Attachment of a KUAB geophone in the stand.

- 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.
- 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 shall be considered to be "calibration verification" only.
- Verify that the new calibration gains have been entered correctly into the FWD field program by printing a copy of the FVO.INI file. Check for typos.

ANNEX E. SPECIAL PROCEDURES FOR CALIBRATING A CARL BRO FWD

- 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 the *WinFWDCal* software.
- 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 and at least one recorded drop. The FWD Operator shall prepare a list of the drops needed ahead of time, and be prepared to *reject* the first drop after the seating drops.
- 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.
- During the Set Up procedure in *WinFWDCal*, the HW_INI.TXT file will be read electronically to get information on sensor serial numbers, initial gains, etc.
- If the sensor initial gains or serial numbers are not able to be read electronically, type the values manually into the *WinFWDCal* set up screen.
- For trailer-mounted FWDs, the trailer must be attached to the tow vehicle during the calibration.
- 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.
- 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 shall not contact the calibration stand during calibration.
- After removing the deflection sensors from the FWD, attach each geophone in the calibration stand with the metric knurled knob *below* the shelf as shown in Figure 34. The knurled knob shall only be tightened by hand. Do NOT use a wrench to attach the hardware.
- 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.
- 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.

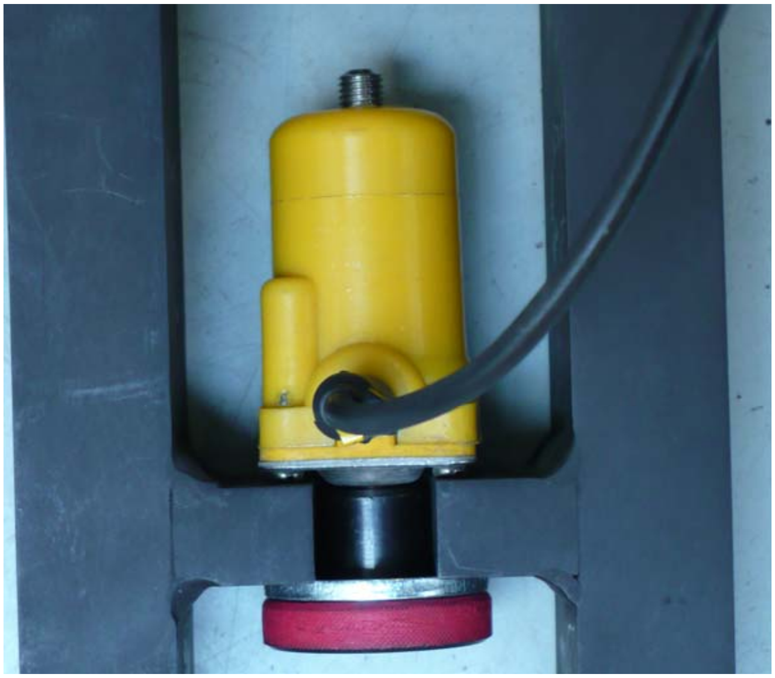

Figure 34. Photo. Attachment of a Carl Bro geophone in the stand.

ANNEX F. SPECIAL PROCEDURES FOR ON SITE CALIBRATIONS

The calibration protocol provides for performing Annual Calibrations at a location 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 calibration center. This is called *on site calibration*, meaning it is done at a site preferred by the FWD owner.

Figure 35. Photo. On site FWD calibration at Hawaii DOT Materials Lab.

The calibration procedure, outlined in Appendix I—FWD Calibration Protocol, should be used without exceptions. It must be carried out by a certified calibration center operator as required in AASHTO R 32-09.(3)

It is not required that a special test pad be constructed for on site calibrations. In this regard, AASHTO R 32 says:

> *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 noted on page 24 of this report, the recommended peak deflection is 500 µm (20 mils) and the minimum recommended deflection is 300µm (12 mils). Peak deflection is a useful way to identify suitable locations for performing calibrations. However, deflection is not the limiting criterion. The *WinFWDCal* software checks for two conditions:

- The maximum acceleration must not exceed five g's.
- The maximum number of replicate drops must not exceed ten 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 35 shows a calibration being done at Hawaii DOT 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 five g's. To overcome this problem, we moved the FWD trailer about 600 mm (24 in.) ahead of the stand, thereby reducing both the peak deflections and the maximum accelerations.

Keep in mind that the FWD must be sitting 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 use in FWD calibration, it may be helpful to apply the Facilities Review Form, Figure 42 in Appendix IV—Quality Assurance Reviews.

A simple procedure involving the 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 will work better than an asphalt pavement because it spreads the deflection basin over a wider area.

1. Position the deflection sensor 100 mm (4 in.) from a joint in the concrete. Position the FWD so the rear of the load plate is 750 mm (30 in.) ahead of the deflection sensor (i.e., 850 mm (34 in.) from the slab joint). If there is no pavement joint, then draw a line across the pavement that can be used to measure from.

2. While manually holding the sensor on the, floor (Figure 36), do one seating drop at 27 kN (~6000 lbf), then two drops at 70 kN (~16,000 lbf). Record the peaks for both 71 kN drops. Call this position #1.

   NB: If there is any concern that a 70 kN load will damage the test pad, use a lesser load level. Then scale the measured deflection linearly to 70 kN.

3. Repeat the above procedure with the deflection sensor positioned at 200 mm (8 in.), 300 mm (12 in.), 450 mm (18 in.) and 600 mm (24 in.) from the rear of the test pad. Keep the spacing between the sensor and the rear of the FWD load plate constant at 750 mm (30 in.). Name the positions sequentially (#1, #2, #3, etc.).

4. Plot the peak deflection at 70 kN (16,000 lbf) versus distance from the joint or the line. Find the distance where the deflection is roughly 500 µm (20 mils). Install the two stainless steel

inserts in the floor at that location as described in Concrete Anchor Installation on pages 208 and 209.

Figure 36. Photo. Locating a place to install the ball-joint floor anchor.

After the ball-joint anchor and the calibration stand have been installed (Figure 35), go through the Set Trigger and Determine Number of Drops routines in *WinFWDCal*. Adjust the position of the FWD, either closer to the calibration stand or further away, as needed to get a successful reference calibration.

It merits noting that 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.

ANNEX G. REFERENCE LOAD CELL CALIBRATION PROCEDURE

Introduction

The reference load cell is a precision instrument, capable of measuring loads within ±0.3 percent or better. Such a high degree of precision can be attained, however, only if this calibration procedure is followed exactly. It is essential that the reference load cell be 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 data acquisition board shall be considered a system of instruments which shall be calibrated together and used together. The load cell shall be calibrated to a maximum load of 100 kN (24,000 lbf).

This procedure is written with both metric and U.S. Customary units shown. The calibration operator shall 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 *WinFWDCal* computer program.

Frequency of Calibration

Calibration of the reference load cell shall be performed at least once per year. It shall 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

- Universal testing machine.

  A static testing machine, hydraulic or screw-powered, with a load capacity of 500 kN (100,000 lbf) or more shall be used. Although the reference load cell will only be calibrated to a capacity of 24,000 lbf (100 kN), 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 0-130 kN (0-30,000 lbf) range (slightly different ranges, such as 0-100 kN (0-24,000 lbf), 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 its calibration.

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

- Bearing blocks: 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 data acquisition board. The load cell has three measurement links contained in an aluminum housing.

- Measurements Group, Inc. Vishay model 2310 signal conditioner. This shall be the same signal conditioner that will be later used in the FWD calibration procedure.

- Keithley model KUSB-3108 data acquisition board. This shall be the same A/D board that will be later used in the FWD calibration procedure.

- Pushbutton trigger for activating the data acquisition system.

Calibration of Equipment

The universal testing machine shall be calibrated annually by a certified technician according to ASTM procedure E-74. The calibrated machine shall have a certified accuracy of 1.0 percent or better. The load indication system used for calibration shall be traceable to the National Institute for Science and Technology (NIST). The calibration certificate shall 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 shall be entered into the FWDCalCenterConfig.ini file used by *WinFWDCal* software prior to calibrating a reference load cell.

The Vishay 2310 signal conditioner amplifier shall be balanced according to the procedure described in the manufacturer's instruction manual. With the signal input terminals shorted together, at gain 100 the ac noise on the ±10 volt output terminals shall be 1 millivolt 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.

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

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

Equipment Inspection and Setup

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.

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.

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

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

- Excitation switch ON
- Excitation voltage set to 10 volts
- Filter set to 1000 Hz
- AC IN button fully extended (e.g., out)
- Set gain initially to 4.2 x100
  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 a/c line power.

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

Calibration Procedure

Perform three calibration trials according to the following procedure. The *WinFWDCal* software program 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 minutes. Turn on the computer and initialize the WinFWDCal program. If a hydraulic universal testing machine is used, turn the pump on and allow the machine to warm up for at least 30 minutes.

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 100 kN (24,000 lbf). Apply an indicated load of 100 kN (24,000 lbf) to the load cell three times. Apply the load at a rate of approximately 22-44 kN (5,000 to 10,000 lbf) 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 volts, the load cell may have been damaged by yielding, and it shall 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 the larger of 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 volts.

9. Replace and align the upper bearing block, rubber pad down. Apply a load of 100 kN (24,000 lb), 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 volts. Release the load. Record the gain setting.

   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 4.20x100 is acceptable. A gain of 4.25x100 or 4.21x100 is not.) In no case should the output at 100 kN (24,000 lb) exceed 99 percent of full scale. The largest gain that does not produce an output above 99 percent of full scale should be used.

   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 rezero the signal conditioner at this point.

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

11. Apply load at a rate of 5 kN (1,000 lbf) per minute. Use the pushbutton trigger to record the readings at 5 kN (1,000 lbf) intervals up to a maximum indicated load of 100 kN (24,000

lbf). While releasing the load, record a reading at 50 kN (12,000 lbf) and at zero pound loads.

12. 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 shall be within 10 mV of the earlier reading. If it is not, repeat the calibration procedure.

Data Analysis

The *WinFWDCal* software will perform the data analysis for each trial. It will use a step-up regression utility to calculate a fifth degree polynomial of the form:

$$Y = A_1V + A_2V^2 + A_3V^3 + A_4V^4 + A_5V^5$$

Figure 37. Equation. Load cell calibration algorithm.

where Y = the adjusted load calculated from the Universal testing machine indicated 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 shall be less than ±0.1 kN (±20 lbf).
- Each of the coefficients shall be statistically significant.

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

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

Enter the Coefficients in *WinFWDCal*

The load cell coefficients shall be entered in the FWDCalCenterConfig.ini file. Any of the coefficients that are not found to be significant shall 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 shall also be entered. This information is used to validate the load cell during FWD calibration.

APPENDIX II— SUGGESTIONS FOR SUCCESSFUL ANNUAL CALIBRATIONS

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

1. The deflection sensor calibration procedure will work better if the deflections are 400 microns (16 mils) 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 each registering the correct date and time. Reconcile them 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 minutes before calibration begins. This will reduce the variability of the data during calibration. The signal conditioner and accelerometer only need to be warmed up an additional five minutes 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 done.

5. Prior to starting the 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 and maybe more if the FWD is colder than room temperature.

6. At the beginning of each programmed series of drops, add two seating drops 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 sitting level* when the calibration is done. 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 alright to do load cell calibration on an area of concrete floor that is away from the test pad provided the FWD is level.

8. Position the reference load cell beneath the FWD load plate making sure 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 very 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 set up.

9. Be sure the FWD load plate is seated squarely on the reference load cell and on the concrete. To check this, after making a couple of seating drops 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 6 mm (¼-inch) or so. 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 (Figure **117**) should be tightly attached to the stand. Apply Locktite 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 be sure 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 similar to Table 8 in *WinFWDCal* will show how the sensors should be placed in the stand.

    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 done in sets of two, using the positioning shown in the table.

15. Place the 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, simply 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 similar to Table 9 in *WinFWDCal* will show how the sensors should be placed in the stand

16. The accelerometer calibration is slightly temperature sensitive. Temperature is monitored continuously by the *WinFWDCal* software; however the measurement point is at the KUSB data acquisition board (DAQ). It is important to keep the DAQ and the accelerometer box out

of direct sunlight to avoid measurement errors or false warnings.

Table 8. Geophone positions in single column stand (9 sensors)

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

Table 9. Seismometer positions in double column stand (7 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

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

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 problem and correcting it:

- Excessive noise at load levels of 40 kN (9,000 lbf) or more.

The noise, due either 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 the *WinFWDCal* software should be viewed to determine if the noise truly 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 data set.

  Standard deviations less than 0.11 kN (25 lbf) for the load cell, and 4 microns (0.16 mils) 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 hours at room temperature to eliminate most of the internal hysteresis. Full recovery can take three to six days, and the period is longer at cold temperatures. This is true whether the accelerometer is powered by the signal conditioner or not.

APPENDIX III—PAVEMENT DEFLECTION DATA EXCHANGE (PDDX) STANDARD, VERSION 2

INTRODUCTION

The purpose of the AASHTO Pavement Deflection Data Exchange (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 a period of years.

While the intent 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 so 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 standard is for pulse-loading devices (i.e., FWDs).

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

OVERVIEW OF PDDX VERSION 2

Version 2 of the PDDX Standard incorporates a small number of 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 files. Version 2 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 the way they appeared in Version 1.0. This may require updating PDDX file readers.

Three types of file formats are described in detail in the listings 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 for 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, and it 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 *needed to begin* doing an Annual Calibration. The data are transferred electronically from the FWD computer to 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 [section]. Each module contains a number of data items, each 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.**

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, 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 = ,

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 U.S. 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 the engineer 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 the 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-hour 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-hour 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 being used. 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. Typical English and metric units for applicable data are summarized in the following table. All units used in one PDDX file must be of the same system of units. Thus, a file must use only metric or only 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.*

Parameter	English System Units	Metric System Units
length	mil inch foot yard mile	micron millimeter centimeter meter kilometer
mass	pound	kilogram
time	second	second
force	pound-force kilopound-force (i.e., kip)	kiloNewton kilogram-force
pressure	pound-force per square inch	kiloPascal
temperature	Fahrenheit	Celsius
Frequency	Hertz	Hertz
angle	degree-minute-second	degree-minute-second

* 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 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, kilo-Pascal, 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.

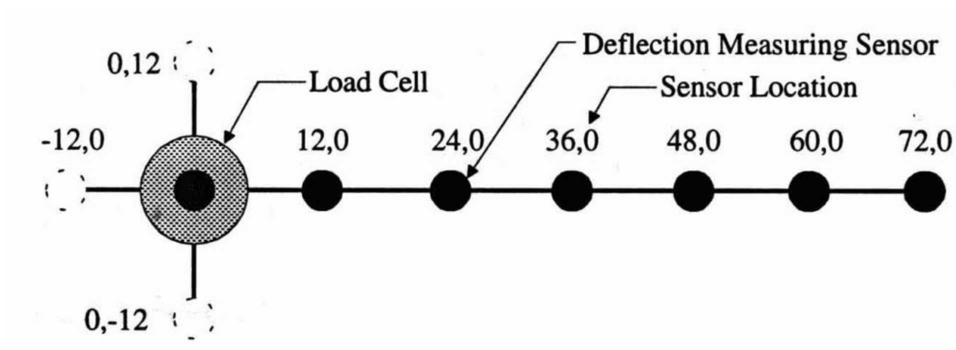

Figure 38. Chart. Typical load cell and deflection sensor configuration.

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. (See note below.)

Example: DeflectionSensorXAxisDistances = 0, 12, 24, 36, 48, 60, 72, -12, 0

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, the 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 mid- depth, pavement bottom.

Example: TemperatureSensorUse = air, surface, mid-depth

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 the 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

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 sensors' 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. In the Dynatest FWD, for instance, 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 the 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 distance measuring instrument (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 testing site are included, such as geographic location, client, and pavement feature and 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 Rd. 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 need not 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., AC, 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, where 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 data acquisition board.
Example: DropHistoryDataFrequency = 10000

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 number of the current test point where *locationcounter* is an integer starting at 1 and ascending for each test point in the current file.

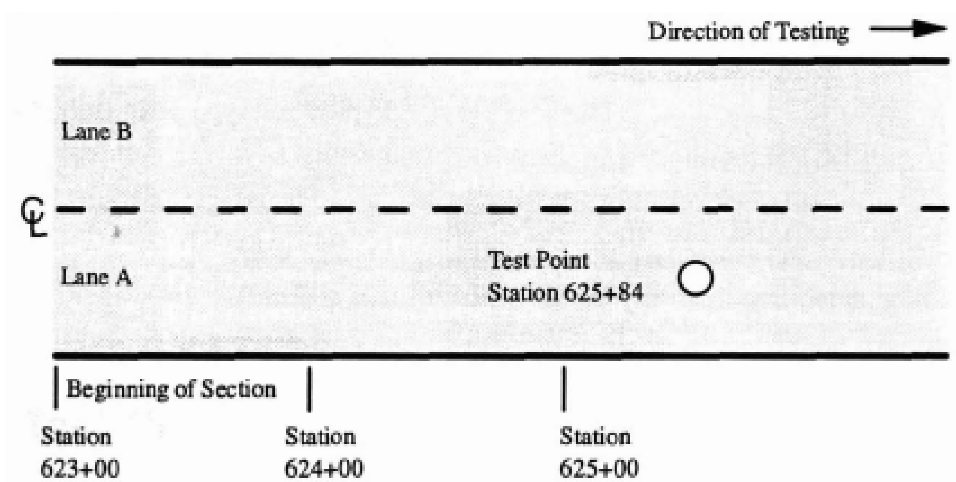

Figure 39. Chart. Example of a typical test location.

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
Note: Figure 39 shows a typical test location scenario.

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-hour 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.

FWD CALIBRATION RECORD FILE FORMAT

At the conclusion of each FWD calibration the *WinFWDCal* software creates a permanent electronic record of the calibration results in DDX file format. The file is named FWDCalibrationRecord dd-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

In addition, a FWD Calibration Center Information Section, as defined below, is appended.

The same file is created for both Annual Calibration 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 the 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 DOT

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 SensorReplacement).
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 X100
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

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 A instead of 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 = 1000

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 c_o.
Example: AccelRefCalibrationCoefficients = -4.52e-02, 1.241e+00, 1.048e-03, -1.369e-04
Notes: The form of the equation is acceleration (g) = $c_o + \Sigma(c_i$ volts).

Accelerometer Daily Calibration Date
Syntax: AccelDailyCalibrationDate = *date*
Description: Date of the last daily flip calibration in dd-mmm-yyyy format.
Example: AccelDailyCalibrationDate = 8/3/2005

Accelerometer Daily Calibration Time
Syntax: AccelDailyCalibrationTime = *time*
Description: The time of the last daily flip calibration of the accelerometer in hour:minute 24-hour 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 X1

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: Together, the Daily calibration readings are used to confirm 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

FWD CALIBRATION DATA EXCHANGE FILE FORMATS

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 to reduce transcription errors and speed up the process of FWD calibration.

At the beginning of a calibration the FWD computer needs to provide some information about the load cell and 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 Calibration or a Monthly Calibration has been completed the FWD operating program needs to be able to locate and read the results from a file named FWDCalibrationOutput dd-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 here. 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 IV—QUALITY ASSURANCE REVIEWS

The purpose of a quality assurance (QA) review is to achieve consistency of calibrations from center-to-center. 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 done annually to ensure 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 quality assurance 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.

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 two additional days should be scheduled for that.

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.

Prior to the review, the Calibration Operator is provided with a pre-QA review questionnaire (Figure 40) to assure a smooth and efficient review. An operator review form (Figure 41) and a facilities review form (Figure 42) will be 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. It also is used to provide 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 vitally important that the FWD that is used be in good working order*. It is not required that the FWD pass 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

When the review begins, the Calibration Operator, FWD Operator, and the QA reviewer meet to discuss the anticipated flow of the review process. This is 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 semi-automated process takes 15-45 minutes 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 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 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, that the serial numbered equipment are correct, that the reference devices are up to date on their calibrations, and that 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.

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.
Non-Compliant	Operator does not demonstrate an adequate understanding of the calibration protocol or its implementation.

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 reviewer through the important observation points. This includes the set-up procedure in the *WinFWDCal* software, deflection sensor calibration, load cell calibration, and documentation and certification of the FWD calibration.

Upon completion of the FWD calibration, a meeting with the Calibration Operator and QA reviewer is held 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 will inform 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 43.

A written report documenting the QA visit should be done as soon as possible after the visit, preferably within two weeks. The Certificate of Compliance is valid for fifteen months, but the next QA visit must be scheduled within twelve months. This allows some flexibility in scheduling, but ensures communication within one year.

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 number 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 40. Chart. 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: ______________________________

Keyed to FWD Calibration Protocol – April 2007 Page 1

Figure 41. Chart. 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:

Keyed to FWD Calibration Protocol – April 2007 Page 2

Figure 41. Chart continued. 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:

Keyed to FWD Calibration Protocol – April 2007 Page 3

Figure 41. Chart continued. 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:

Keyed to FWD Calibration Protocol – April 2007 Page 4

Figure 41. Chart continued. 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:

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:

Keyed to FWD Calibration Protocol – April 2007 Page 5

Figure 41. Chart concluded. 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 ±5g Accelerometer:		
Reference Load Cell:		

Required Changes & Improvement Recommendations

____
____
____
____

Reviewed By: ______________________
Date(s): ______________________
Signature: ______________________
Title: ______________________
Agency: ______________________
Phone: ______________________
Email: ______________________

Keyed to FWD Calibration Protocol – April 2007 Page 1

Figure 42. Chart. 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:

Keyed to FWD Calibration Protocol – April 2007 Page 2

Figure 42. Chart. continued. 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:

Keyed to FWD Calibration Protocol – April 2007 Page 3

Figure 42. Chart concluded. Center facilities QA review form.

Certificate of Compliance

Jim Wooten

Indiana Department of Transportation

Has satisfactorily completed the FHWA-LTPP FWD Calibration Center Quality Assurance Review and is found to be compliant with the guidelines and procedures set forth by the FHWA FWD Calibration Protocol, June 2008.

This certification is valid for 15 months from the date below.

Recertification should be scheduled 3 months before expiration.

David Orr, PE
Senior Engineer
Cornell Local Roads Program

June 19, 2008
Date

Figure 43. Chart. Center Operator Certificate of Compliance

APPENDIX V—SPECIFICATIONS AND DRAWINGS

SPECIFICATIONS

1. General specifications

1.1. Description

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 assembly drawings for each assembly.

Table 13. Parts required for one hardware set.

Assembly	Drawing #
Accelerometer Box Assembly	CLRP-AB01
Ball Joint Anchor Assembly	CLRP-BJ01
Geophone Stand Assembly*	CLRP-GCS01
Seismometer Stand Assembly*	CLRP-SCS01
Geophone Adapters Assembly	CLRP-GA01
Reference Load Cell Assembly	CLRP-LC01

* In some cases only one stand is ordered for a hardware set.

1.2. Materials

The required materials are described in the referenced drawings (Table 13).

1.3. Manufacturing Requirements/Conflicts

The contractor shall 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 sub-assembly. If there is a conflict between the drawings and the specifications, the specifications shall govern.

1.4. Surface Smoothness

An industrial quality surface finish is desired.

All machined surfaces shall have a smoothness of 63 micro-inches or less.

1.5.The mill surface finish on aluminum extrusions shall be inspected for nicks, cuts and dings, and a reasonable effort shall 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 shall be thoroughly cleaned and anodized according to MIL-A-8625F Type 2, Class 2 (Black). All parts shall have a cosmetically homogeneous appearance after being anodized.

If for any reason parts must be stripped to remove the anodizing, a phosphoric chromic solution shall be used, followed by surface polishing to remove pitting and achieve a 63 micro-inch smoothness.

1.7.Locktite

Where Locktite is required, medium strength #242 Locktite shall be used.

1.8.Delivery/Acceptance

The contractor shall provide a guaranteed delivery time. All parts shall be assembled and delivered to the address provided by the purchasing agency.

The purchasing agency shall have seven (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 shall replace them at no additional charge.

1.9. Method of Payment

Payment shall be authorized upon acceptance of the complete order.

1.10. Accelerometer Box Assembly Specifications (Dwg. CLRP-AB01)

1.11. Description

The Accelerometer Box Assembly is designed to house a Silicon Designs Model 2220 accelerometer, provide some EMI shielding, and additional physical protection. The box assembly mounts on the calibration platter, the geophone calibration stand (described elsewhere), and the seismometer calibration stand (described elsewhere) by means of two #10-24 knurled head thumbscrews through the lip on the box.

1.12. Materials

All of the materials for the Accelerometer Box Assembly are described in the referenced drawing and the bill of materials.

1.13. Manufacturing Requirements

The accelerometer box top and bottom, and the box assembly and calibration platter, shall be assembled together to ensure proper alignment prior to delivery to the customer. The accelerometer box top and bottom shall also be fitted into the geophone calibration stand and the seismometer calibration stand (both described elsewhere), and the fit should be a firm coupling to both stands without any gaps or interference between mating surfaces.

Each aluminum part shall be cleaned and then anodized in accordance with Section 1.5.

Upon delivery, the customer shall finish assembly of the box by mounting the accelerometer and the Amphenol receptacle, mating the box top and bottom, and mounting the bubble level and attaching the leveling screws to the calibration platter.

2. Ball Joint Anchor Assembly Specifications (Dwg. CLRP-BJ01)

2.1.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.

2.2.Materials

All of the materials for the Ball Joint Anchor Assembly are described in the referenced drawing and the bill of materials.

2.3.Manufacturing Requirements

Upon delivery, the customer shall finish assembly of the anchor by attaching the base bar and the clamp base to the ball joint. The clamp shall be attached to the clamp base and the rest stop shall be mounted to the anchor assembly

3. Geophone Calibration Stand Assembly Specifications (Dwg. CLRP-GCS01)

3.1.Description

The Geophone Calibration Stand Assembly is designed to hold up to ten geophones from the Dynatest, Carl Bro, KUAB, or JILS FWD. The accelerometer box (Section 2) mounts to the middle shelf in the stand. The stand is attached to the ball joint anchor (Section 3) during the calibration procedure.

3.2. Materials

All of the materials for the Geophone Calibration Stand are described in the referenced drawing and the bill of materials.

3.3. Manufacturing Requirements

Prior to welding the stand, the parts shall be cleaned and dry fitted together. A qualified TIG welder shall do all of the welding.

After welding, the stand shall be cleaned and then anodized in accordance with Section 1.5.

After delivery, the customer shall finish assembly by adding handles and bubble levels as needed and Locktiting the connector pin in place.

4. Seismometer Calibration Stand Assembly (Dwg. CLRP-SCS01)

4.1. Description

The Seismometer Calibration Stand Assembly is designed to hold up to 10 KUAB seismometers in a two-column configuration. Additionally, the accelerometer box (Section 2) mounts to the middle shelf in the stand. The stand is attached to the ball joint anchor (Section 3) during the calibration procedure.

4.2. Materials

All materials for the Seismometer Calibration Stand Assembly are described in the referenced drawing and the bill of materials.

4.3. Manufacturing Requirements

Prior to welding the stand, the parts shall be cleaned and dry fitted together. A qualified TIG welder shall do all of the welding.

After welding, the stand shall be cleaned and anodized in accordance with Section 1.5.

After delivery, the customer shall finish assembly by adding handles and bubble levels as needed and Locktiting the connector pin in place.

5. Geophone Adapter Specifications

5.1. Description

The Geophone Adapters are used to couple 3 different types of geophones to the Geophone Calibration Stand (Section 4) and allow for ease of movement of the geophones within the stand.

5.2.Materials

All materials for the Geophone Adapters are described in the referenced drawing and the bill of materials

5.3.Manufacturing Requirements

The Geophone Adapters shall be dry-fit into the Geophone Calibration Stand sensor shelves to ensure a loose sliding fit in the slotted hole on each shelf.

6. Reference Load Cell Assembly (Dwg. CLRP-LC01)

6.1. 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 either a 12 inch or 300 mm load plate.

6.2. Materials

All materials for the Reference Load Cell Assembly are described in the referenced drawings and bill of materials.

6.3. Manufacturing Requirements

Prior to welding the base to the body, the parts shall be cleaned and dry fitted together. A certified TIG welder shall do all of the welding.

After welding, the load cell parts shall be cleaned and anodized in accordance with Section 1.5, with the exception of the Measuring Links (Dwg. CLRP-LC04) which shall NOT be anodized.

After delivery, the customer shall have the Measuring Links gaged by a qualified strain gage installer. Then, the load cell shall be fully assembled, conditioned and calibrated according to Annex G.

COMPLETE DRAWING LIST

The following is 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	Page Number	Part Name	Revision*
CLRP-AB01	141	Accelerometer Box Assembly	C
CLRP-AB02	142	Accelerometer Box Bottom	E
CLRP-AB03	143	Accelerometer Box Top	G
CLRP-AB04	144	Calibration Platter	E
CLRP-AB05	145	Accelerometer Wiring	C
CLRP-BJ01	148	Ball Joint Anchor Assembly	B
CLRP-BJ02	149	Clamp	C
CLRP-BJ03	150	Clamp Base	D
CLRP-BJ04	151	Base Bar	D
CLRP-BJ05	152	Rest Stop	E
CLRP-GCS01	155	Geophone Stand Assembly	H
CLRP-GCS02	156	Geophone Stand Side Rail	E
CLRP-GCS03	157	Geophone Stand Top Shelf	C
CLRP-GCS04	158	Geophone Stand Bottom Shelf	C
CLRP-GCS05	159	Geophone Stand Sensor Shelf	F
CLRP-GCS06	160	Geophone Stand Accelerometer Shelf	E
CLRP-GCS07	161	Geophone Stand Handle Holder	F
CLRP-GCS08	162	Geophone Stand Connector Pin	B
CLRP-SCS01	165	Seismometer Stand Assembly	F
CLRP-SCS02	166	Seismometer Stand Side Rail	B
CLRP-SCS03	167	Seismometer Stand Top Shelf	B
CLRP-SCS04	168	Seismometer Stand Sensor Shelf	D
CLRP-SCS05	169	Seismometer Stand Standoff	E
CLRP-SCS06	170	Seismometer Stand Bottom Shelf	B
CLRP-SCS07	171	Seismometer Stand Handle Holder	F
CLRP-SCS08	172	Seismometer Stand Connector Pin	B
CLRP-SCS09	173	Seismometer Stand Shelf Subassembly	C
CLRP-SCS10	174	Seismometer Stand Accelerometer Shelf	D
CLRP-SCS11	175	Seismometer Stand Accelerometer Shelf Subassembly	B
CLRP-GA01	178	Geophone Adapter Assemblies	B
CLRP-GA02	179	Carl Bro Adapter	E

Drawing Number	Page Number	Part Name	Revision*
CLRP-GA03	180	JILS Adapter	F
CLRP-GA04	181	KUAB Adapter	A
CLRP-LC01	184	Load Cell Assembly	E
CLRP-LC02	185	Load Cell Body	B
CLRP-LC03	186	Base Plate	B
CLRP-LC04	187	Measuring Link	C
CLRP-LC05	188	Cover Plate	E
CLRP-LC06	189	Foot	C
CLRP-LC07	190	Guide Fingers	C
CLRP-LC08	191	Interior Connector Wiring	B
CLRP-LC09	192	Strain Gage Layout	B
CLRP-LC10	193	Bridge Wiring	A
CLRP-DAQ01	196	Vishay to DAQ Cable	D
CLRP-DAQ01A	197	Vishay 2310B BNC to DAQ Cable	A
CLRP-DAQ01B	198	Vishay 2310B BNC to DAQ Cable –Stock Parts	A
CLRP-DAQ02	199	Vishay to Load Cell DAQ Cable	C
CLRP-DAQ03	200	Accelerometer Signal Cable	C
CLRP-DAQ04	201	Pushbutton to KUSB DAQ Cable	C

* Current as of 02/10/2009.

ACCELEROMETER BOX

Figure 44. Photo. Accelerometer box.

BM-AB Accelerometer Box Bill of Materials

Table 15. Fabricated parts required for accelerometer box assembly.

Dwg. 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 accelerometer box assembly.

Vendor Part Number	Item	Vendor	Quantity
96877A209	Flat Head Phillips Machine Screw, 18-8 SS, 4-40 Thd,, 3/8" Length, Mil Spec 51959-15	McMaster-Carr	4
91400A110	Pan Head Phillips Machine Screw, 18-8 SS, 4-40 Thd, 1/2" Length, Mil Spec 51957-17	McMaster-Carr	2
91737A072	Fillister Head Phillips Machine Screw, 18-8 SS, 4-40 Thd, 1/4" Length	McMaster-Carr	7
91746A876	Knurled Head Thumb Screw, Slotted, 18-8 SS, 10-24 Thread, 1/2" Length, 1/4" Head Diameter, 1/2" Length	McMaster-Carr	2
91755A205	Retaining Washer, Nylon 6/6, #4 Screw Size, 7/64" Inside Diameter, 17/64" Outside Diameter, 0.027"-0.037" Thick	McMaster-Carr	2
2198A85	Bull's-eye Level, Glass, Surface-Mount, Center Circle & Cross Lines, 1-1/4" Base Diameter, 7/16" Height	McMaster-Carr	1
23015T64	Leveling Mount, Polyethylene Base, 3/8"-16 Thread, 50 lbf Maximum Load, 1" Length	McMaster-Carr	3
98520A145	Locking Wing Nut, Zinc Alloy, Nylon-Insert, 3/8"-16 Screw Size, 1-1/2" Wing Spread	McMaster-Carr	3
2220-005	Accelerometer, ± 5g with calibration certificate	Silicon Designs	1
654-PT02A106P	Amphenol Receptacle, PT02A-10-6P	Mouser Electronics	1

Table 17. Vendor contact information for 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 accelerometer box.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$912.00	
Accelerometer (±5g)	1	Silicon Designs	$580.00	
Misc. Hardware	1		$38.00	

*Indicates the cost in Feb. 2009.

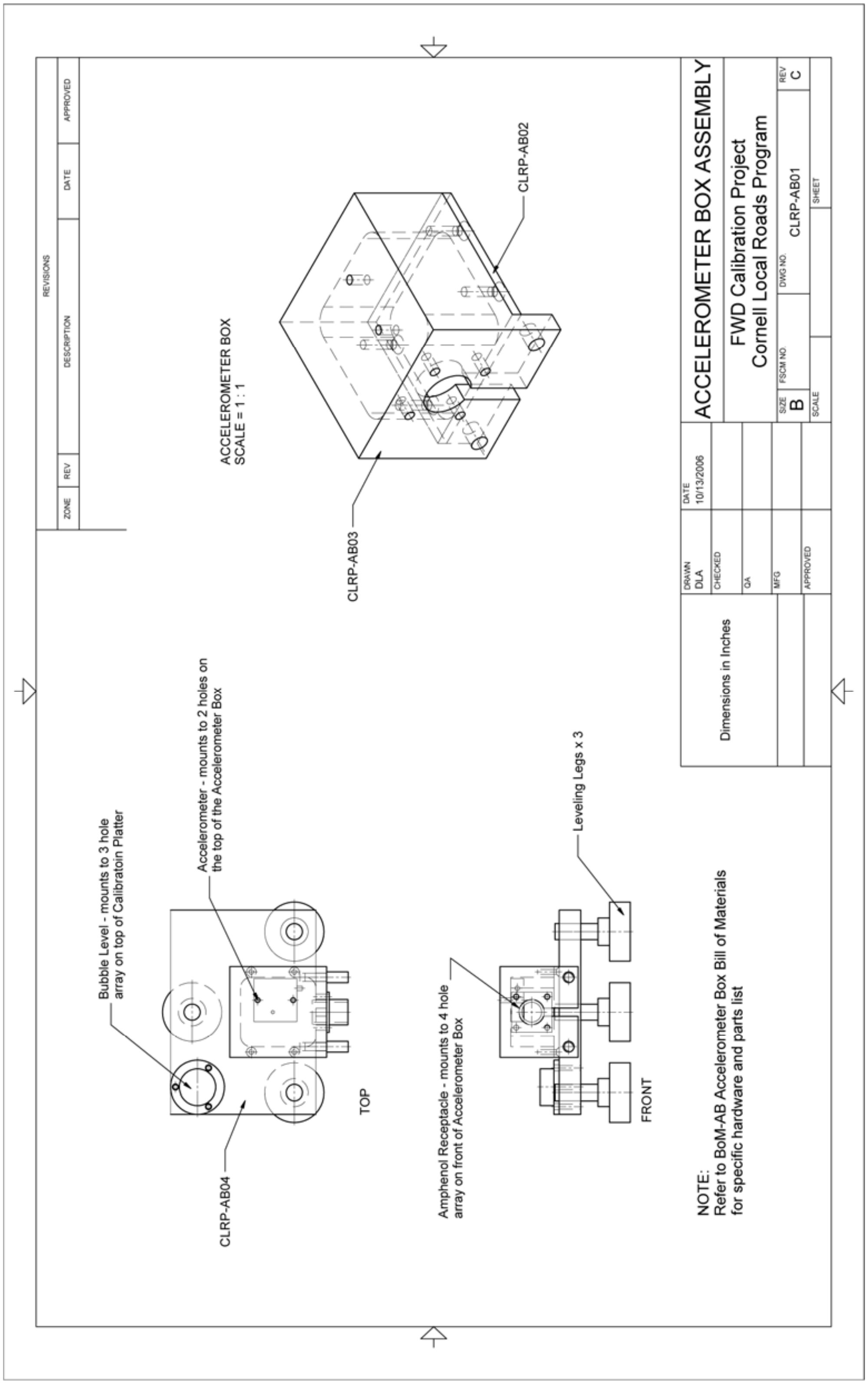

Figure 45. Drawing. CLRP-AB01 Accelerometer Box Assembly.

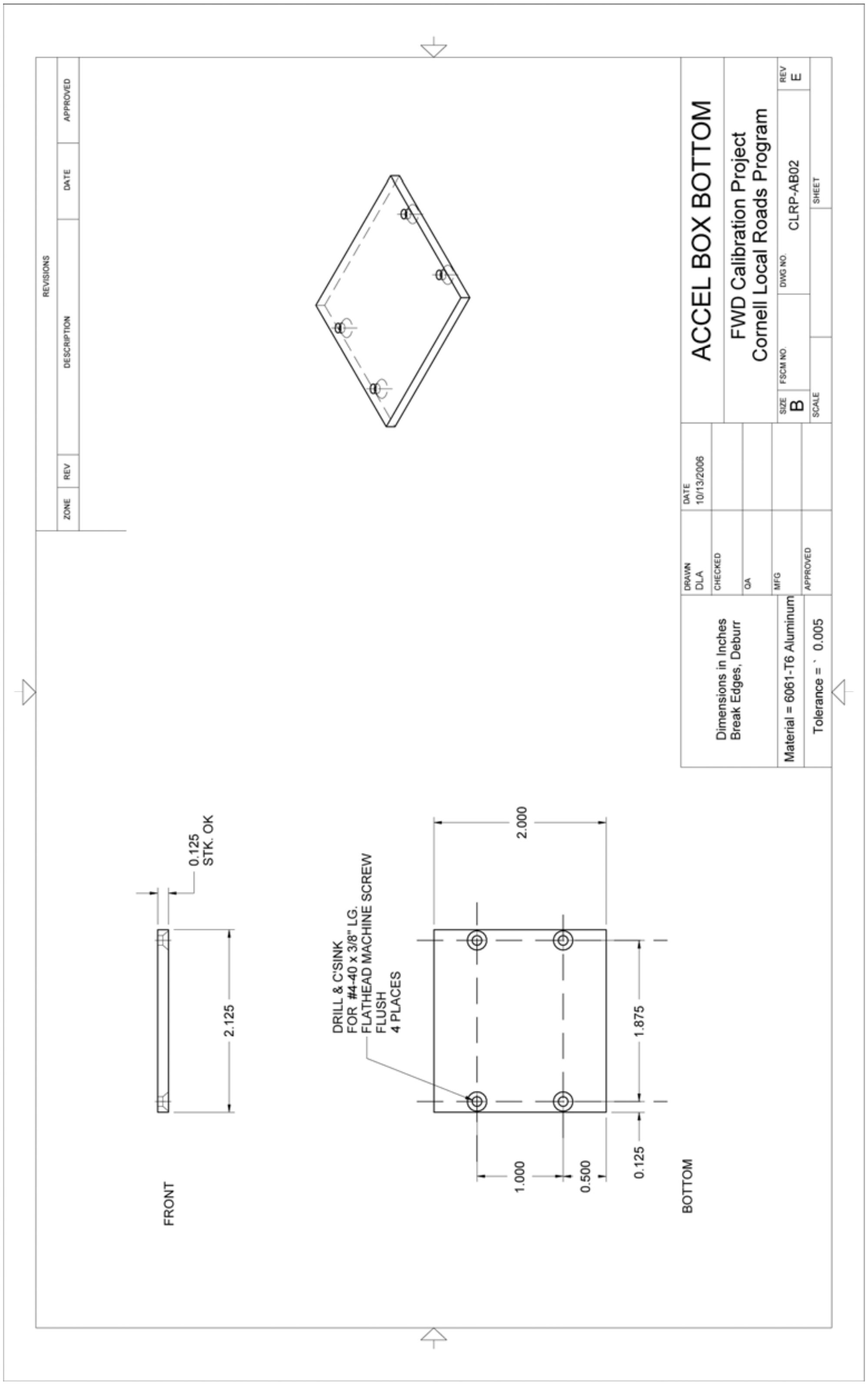

Figure 46. Drawing. CLRP-AB02 Accelerometer Box Bottom.

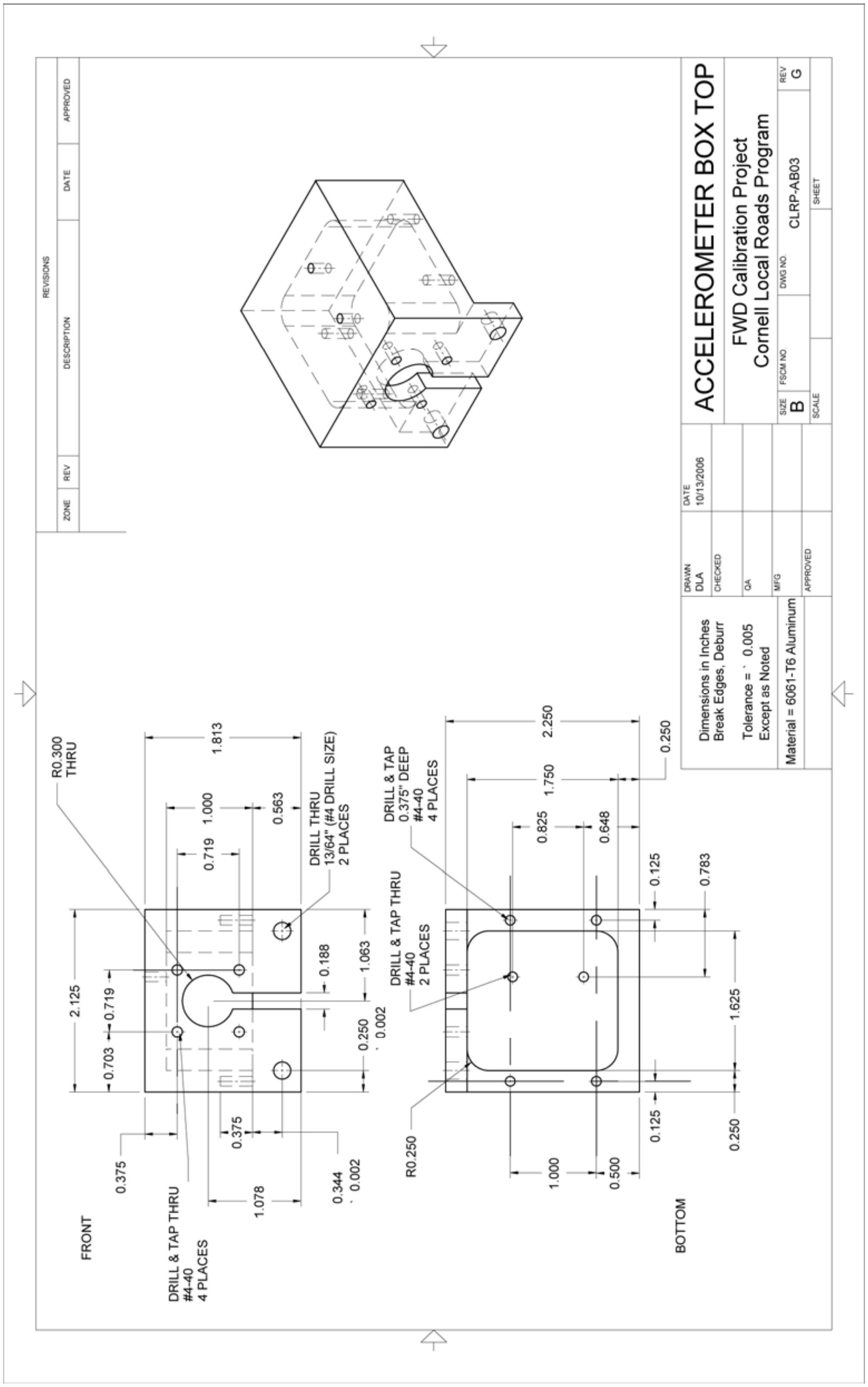

Figure 47. Drawing. CLRP-AB03 Accelerometer Box Top.

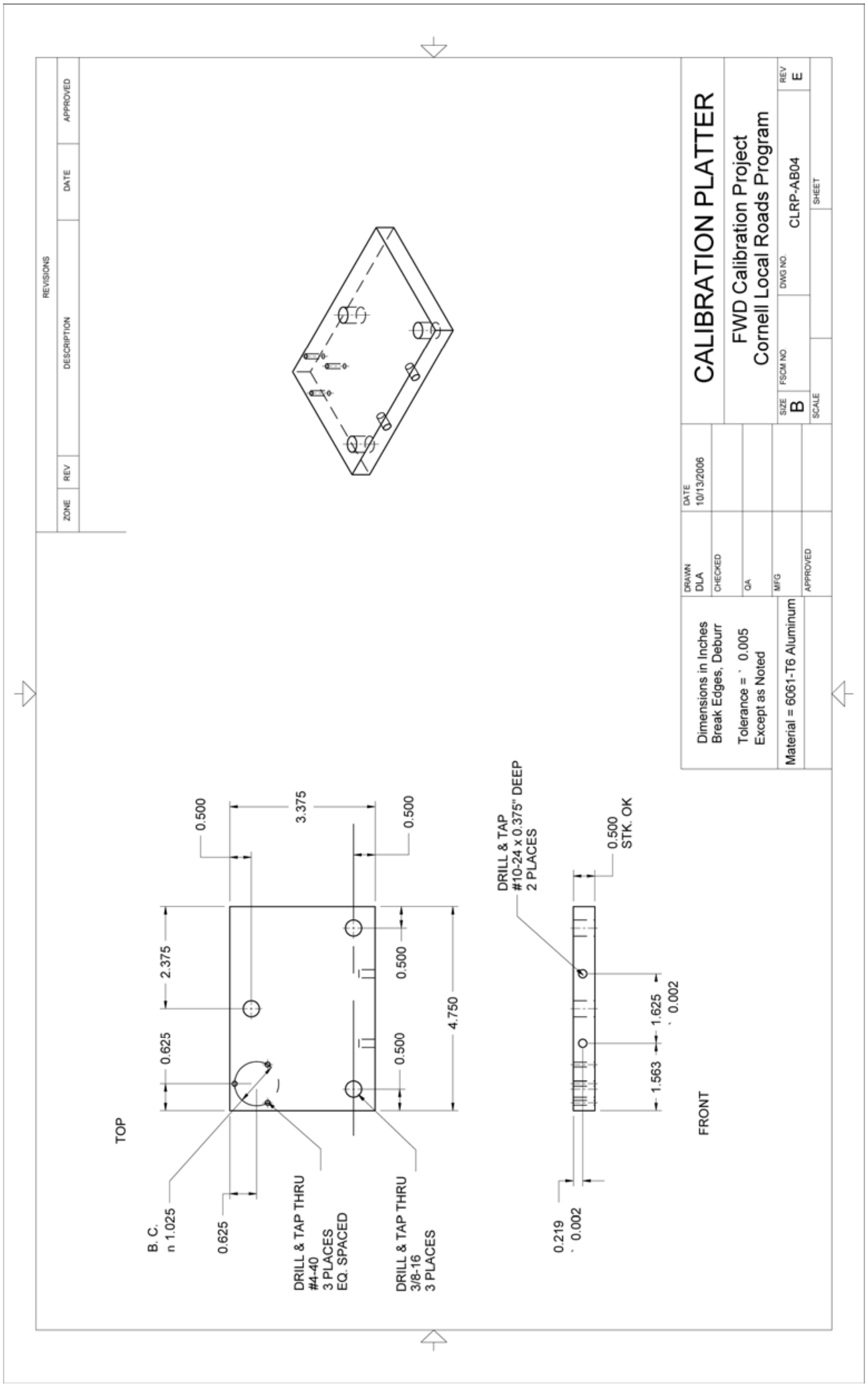

Figure 48. Drawing. CLRP-AB04 Calibration Platter.

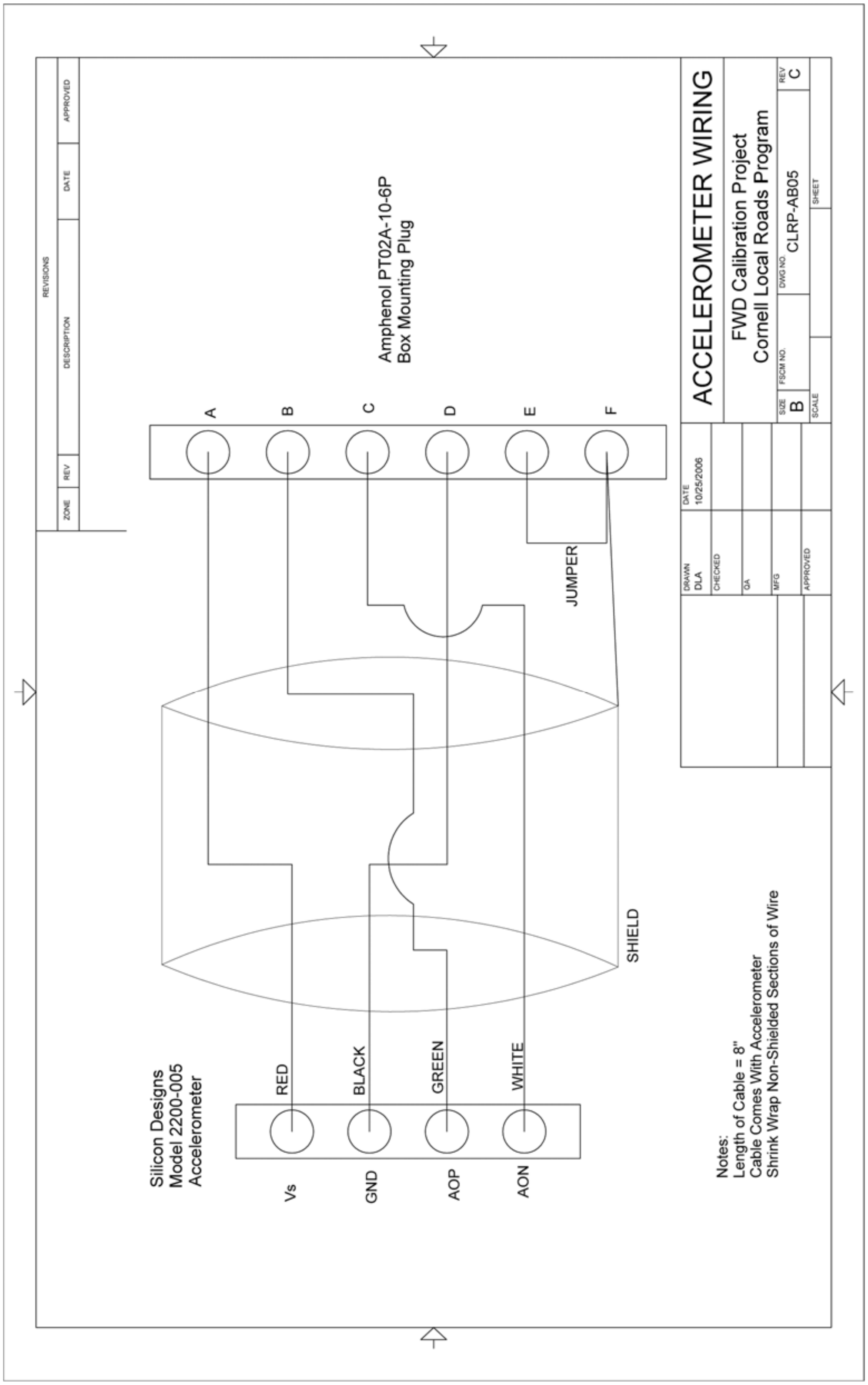

Figure 49. Drawing. CLRP-AB05 Accelerometer Wiring.

BALL JOINT ANCHOR

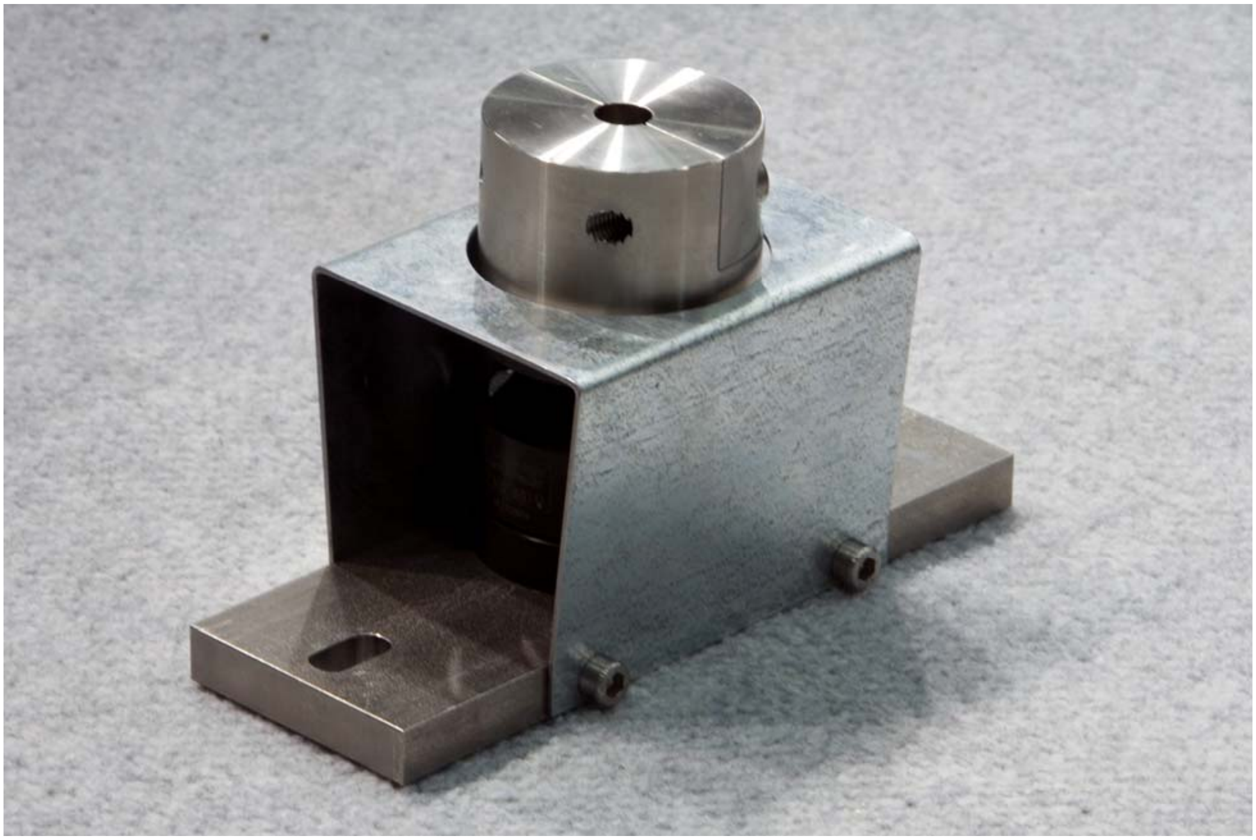

Figure 50. Photo. Ball joint anchor.

BM-BJ Ball Joint Anchor Bill of Materials

Table 19. Fabricated parts required for the ball joint anchor assembly.

Dwg. 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 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, 16mm Length, 1.25mm Pitch	McMaster-Carr	6
91292A148	Socket Head Cap Screw, 18-8 Stainless, M8 Thread, 25mm Length, 1.25mm Pitch	McMaster-Carr	2
91292A135	Socket Head Cap Screw, 18-8 Stainless Steel, M6 Thread, 16mm Length, 1mm Pitch	McMaster-Carr	4

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 ball joint anchor.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$919.00	
Techno/Sommer KG60 Ball Joint	1	Techno/Sommer	$143.00	
Misc. Hardware	1		$31.00	

*Indicates the cost in Feb. 2009..

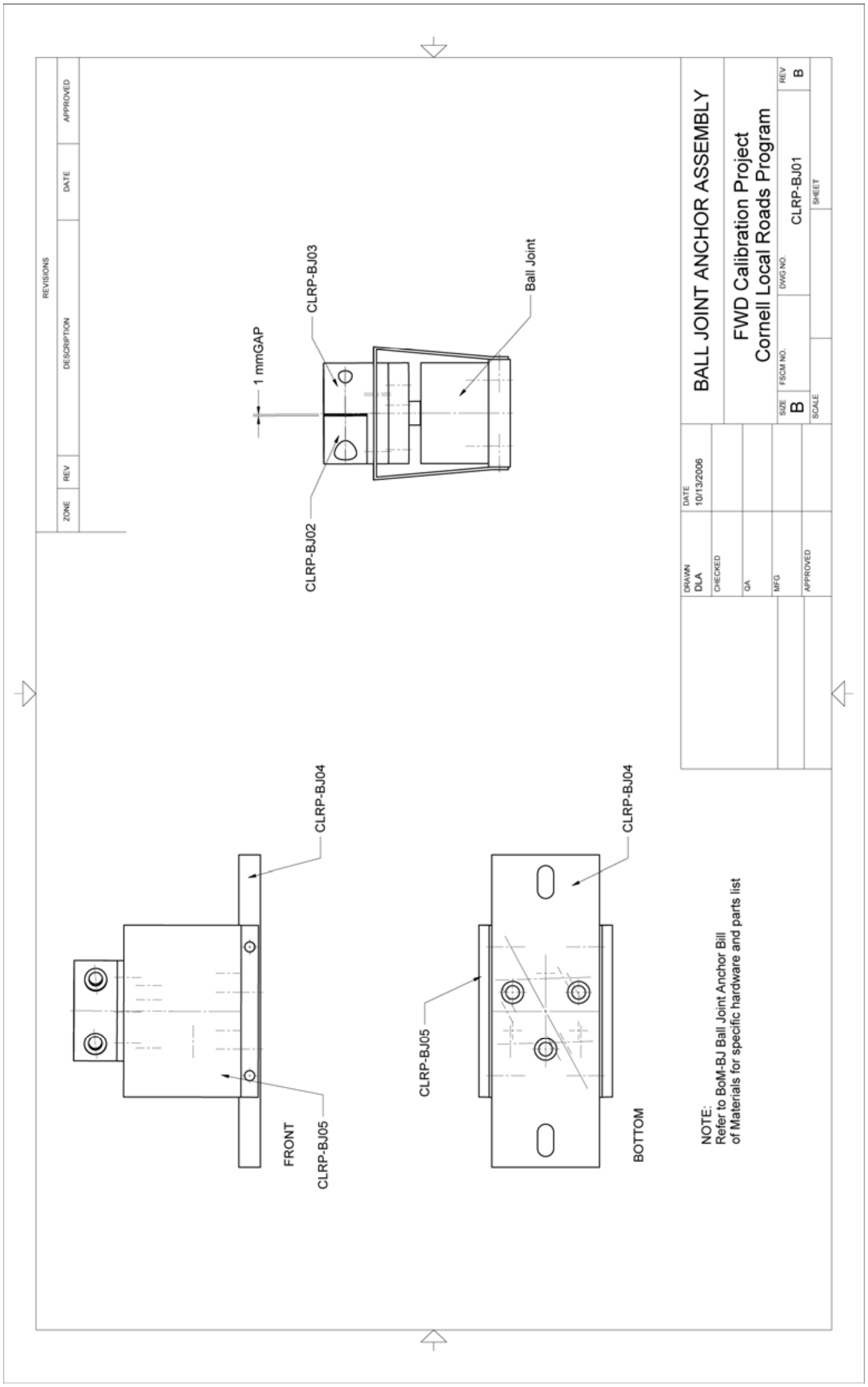

Figure 51. Drawing. CLRP-BJ01 Ball Joint Anchor Assembly.

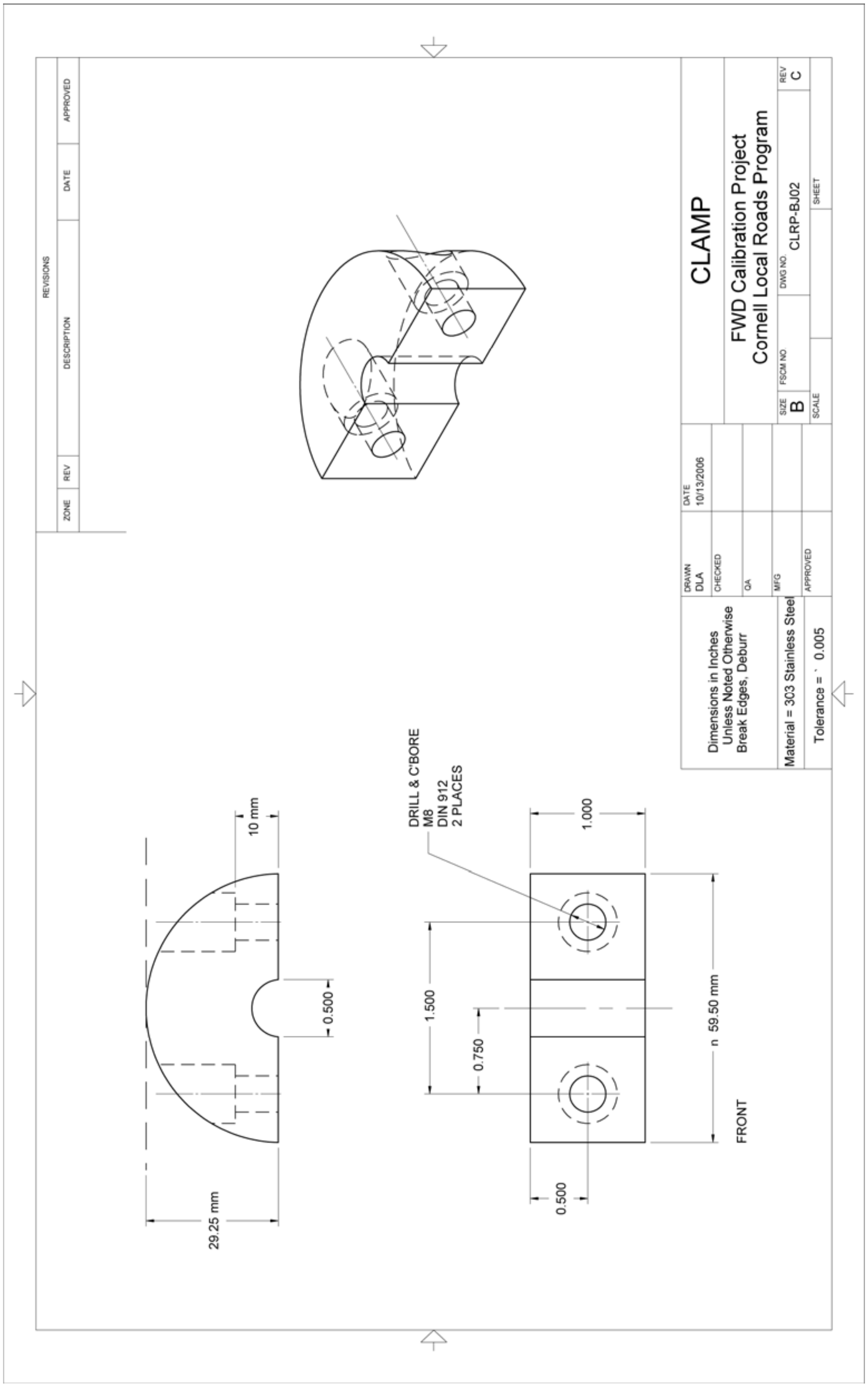

Figure 52. Drawing. CLRP-BJ02 Clamp.

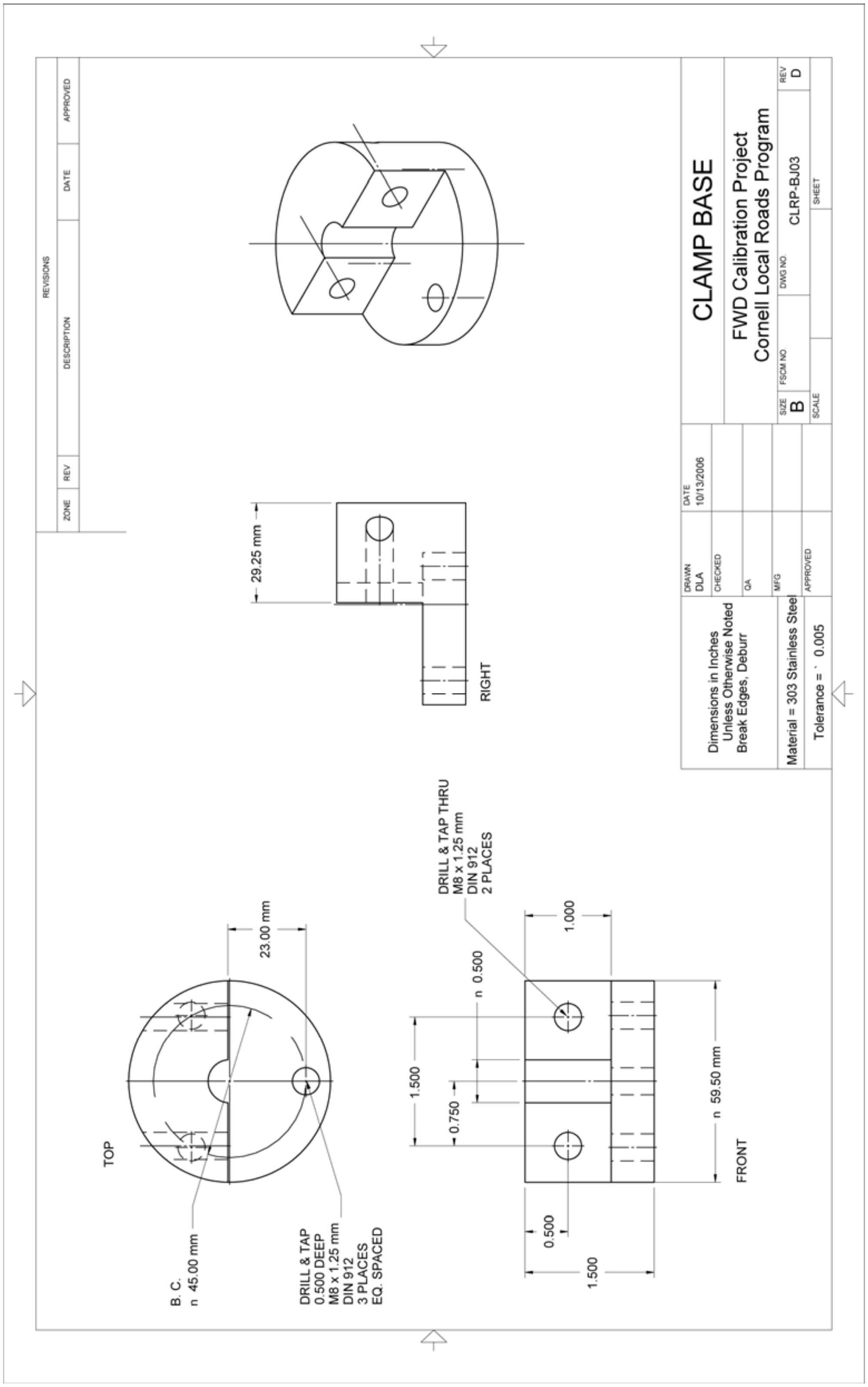

Figure 53. Drawing. CLRP-BJ03 Clamp Base.

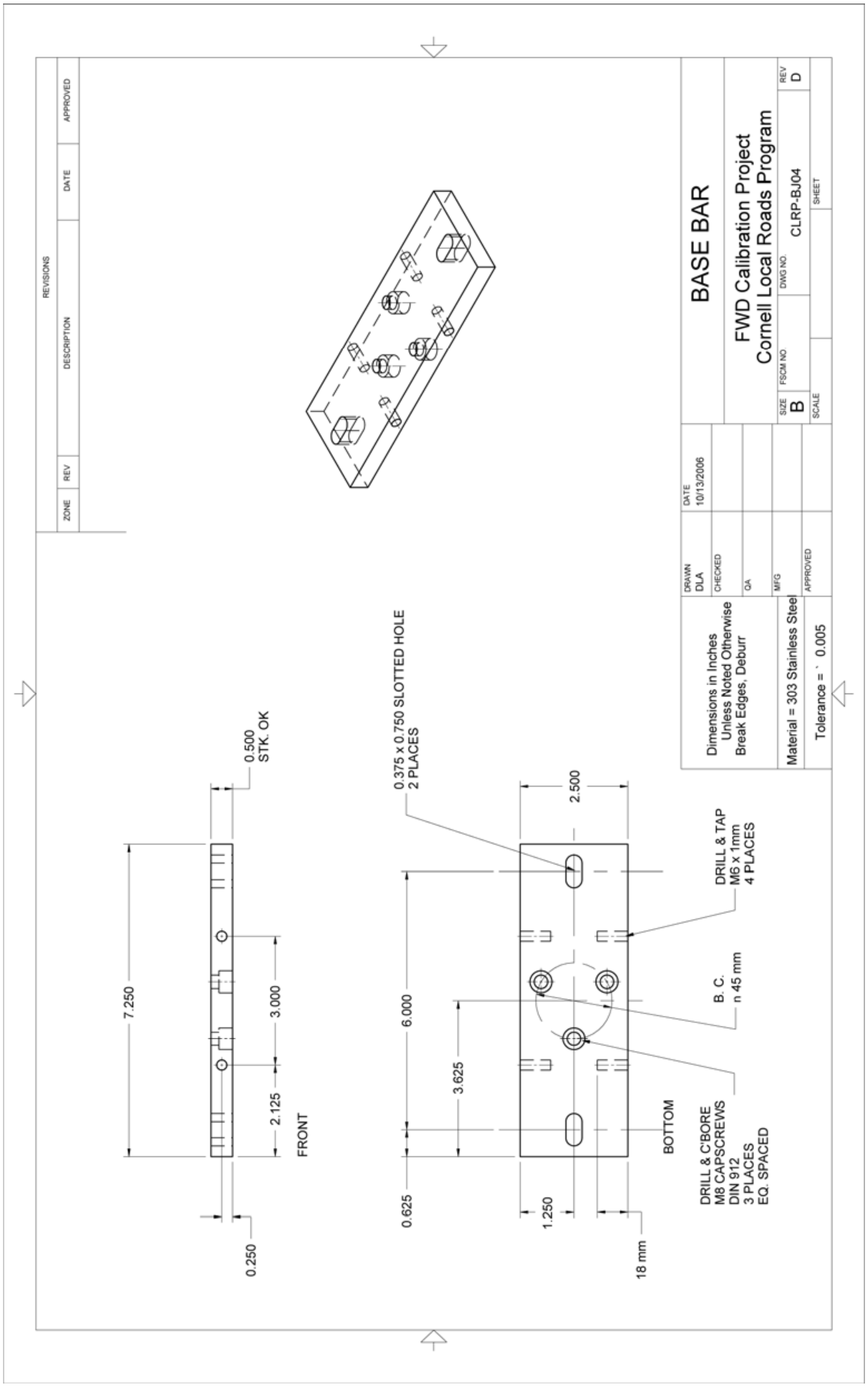

Figure 54. Drawing. CLRP-BJ04 Base Bar.

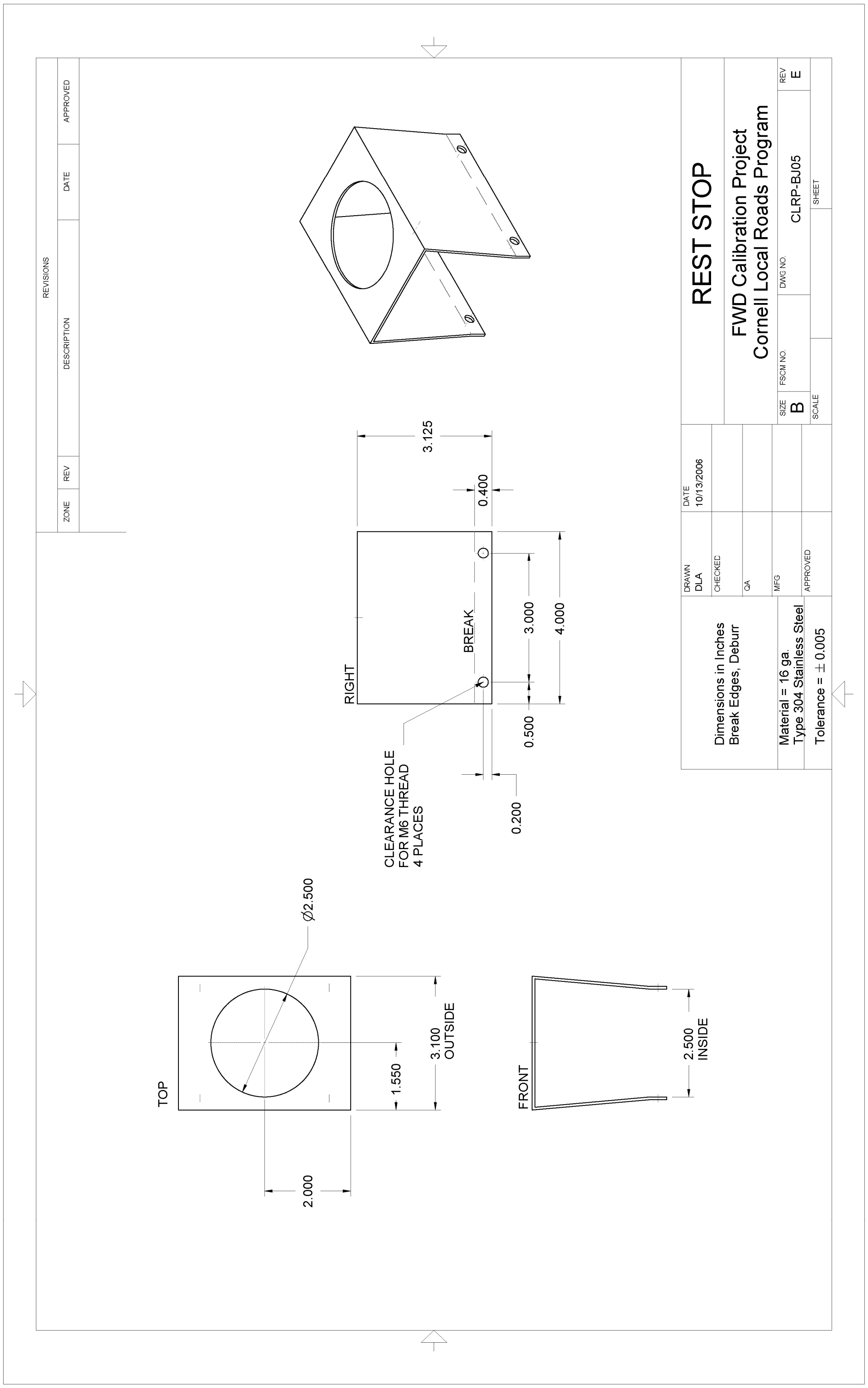

Figure 55. Drawing. CLRP BJ05 Rest Stop.

GEOPHONE CALIBRATION STAND

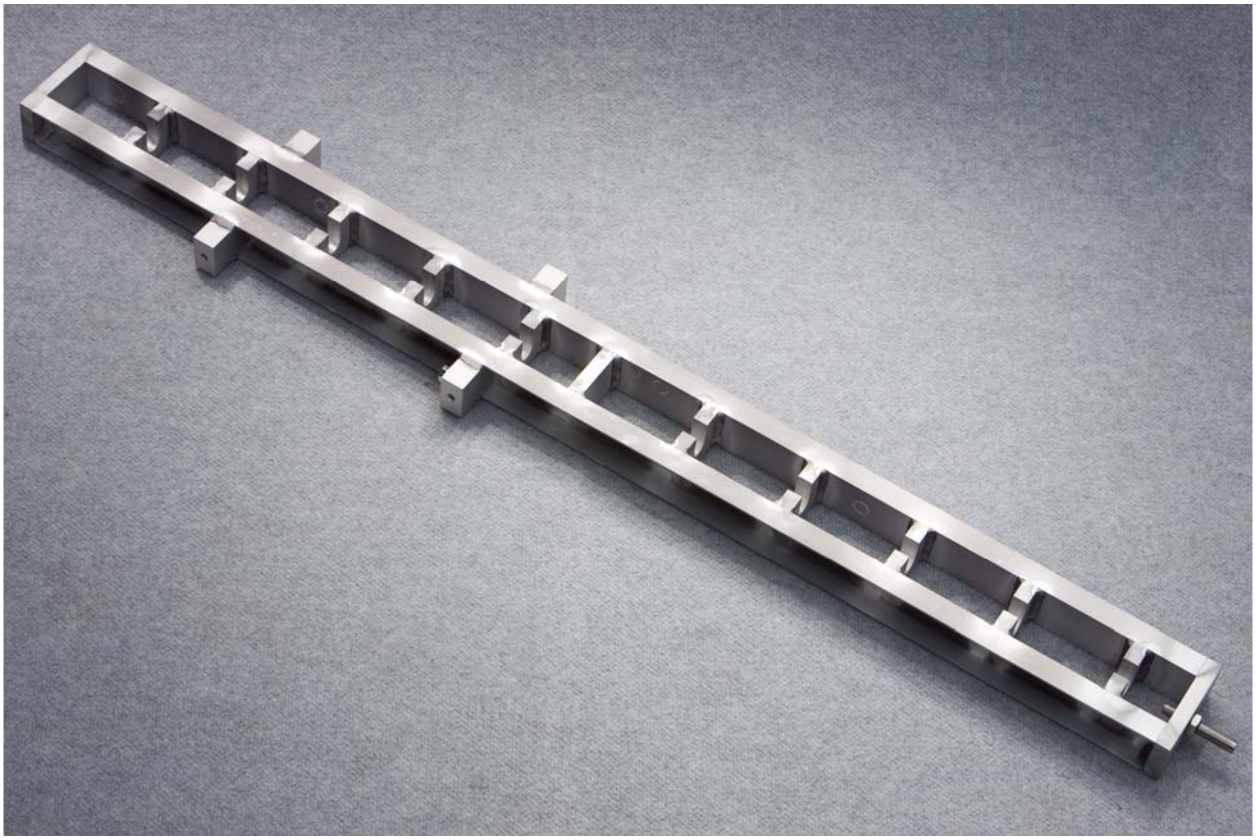

Figure 56. Photo. Geophone calibration stand.

BM-GCS Geophone Calibration Stand Bill of Materials

Table 23. Fabricated parts required for geophone calibration stand assembly.

Dwg. 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 Accel. Shelf	1
CLRP-GCS07	Geophone Stand Handle Holder*	4
CLRP-GCS08	Geophone Stand Connector Pin*	1

* Identical to DWG# CLRP-SCS07

**Identical to DWG# CLRP-SCS08

Table 24. Hardware items required for geophone calibration stand assembly.

Vendor Part Number	Item	Vendor	Quantity
62385K65	Tapered Handle, Smooth Phenolic, 3/8"-16 X 1/2" Threaded Stud, 1" Diameter	McMaster-Carr	2
2198A85	Glass Surface-Mount Bull's-eye Level Center Circle & Cross Lines, 1-1/4" Base Diameter, 7/16" Height	McMaster-Carr	1
91737A072	18-8 Stainless Steel Fillister Head Phillips Machine Screw 4-40 Thread, 1/4" Length	McMaster-Carr	3

Table 25. Vendor contact information for 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 geophone calibration stand.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$1407.00	
Misc. hardware	1		$30.00	

*Indicates the cost in Feb. 2009.

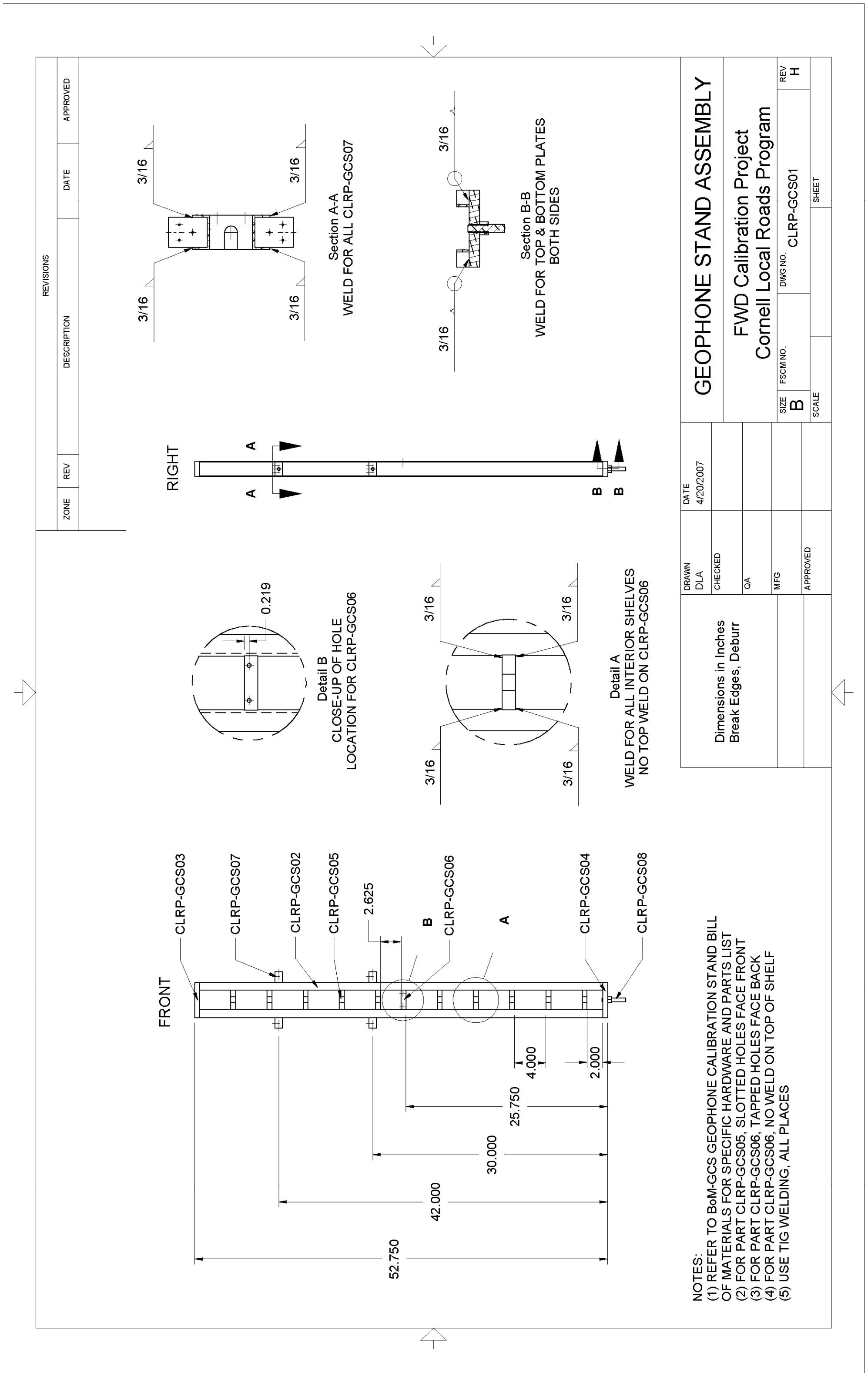

Figure 57. Drawing. CLRP-GCS01 Geophone Stand Assembly.

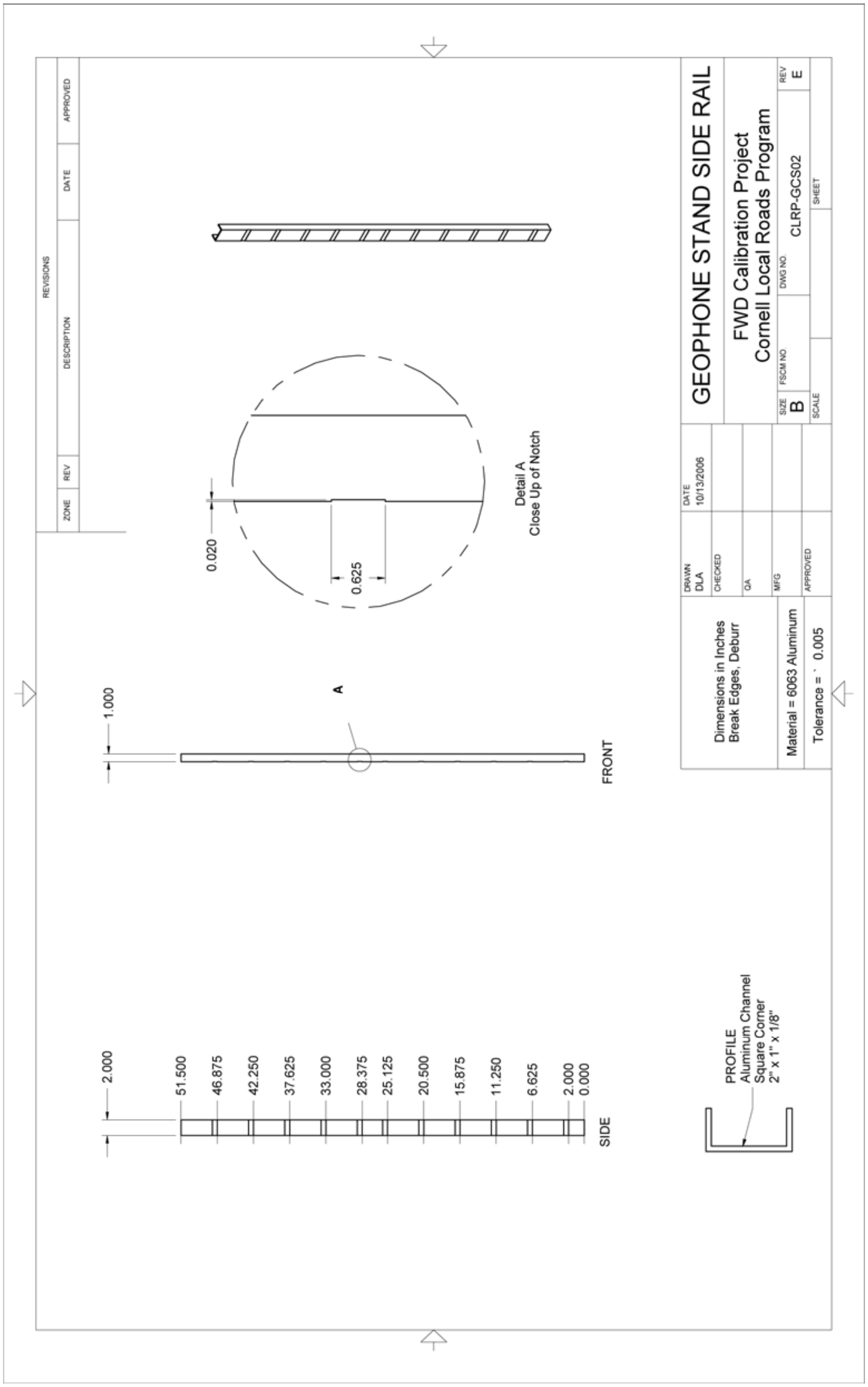

Figure 58. Drawing. CLRP-GCS02 Geophone Stand Side Rail.

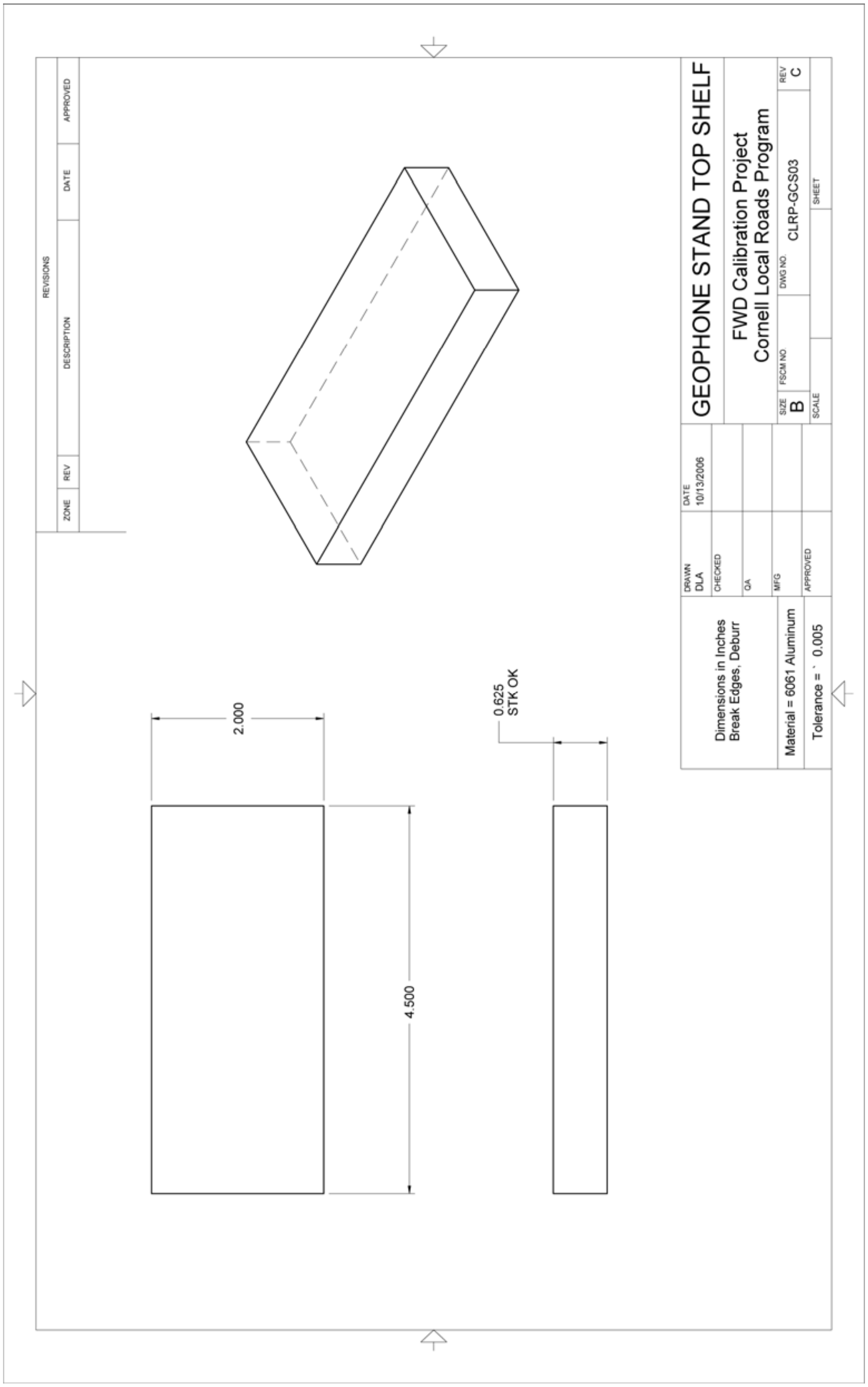

Figure 59. Drawing. CLRP-GCS03 Geophone Top Shelf.

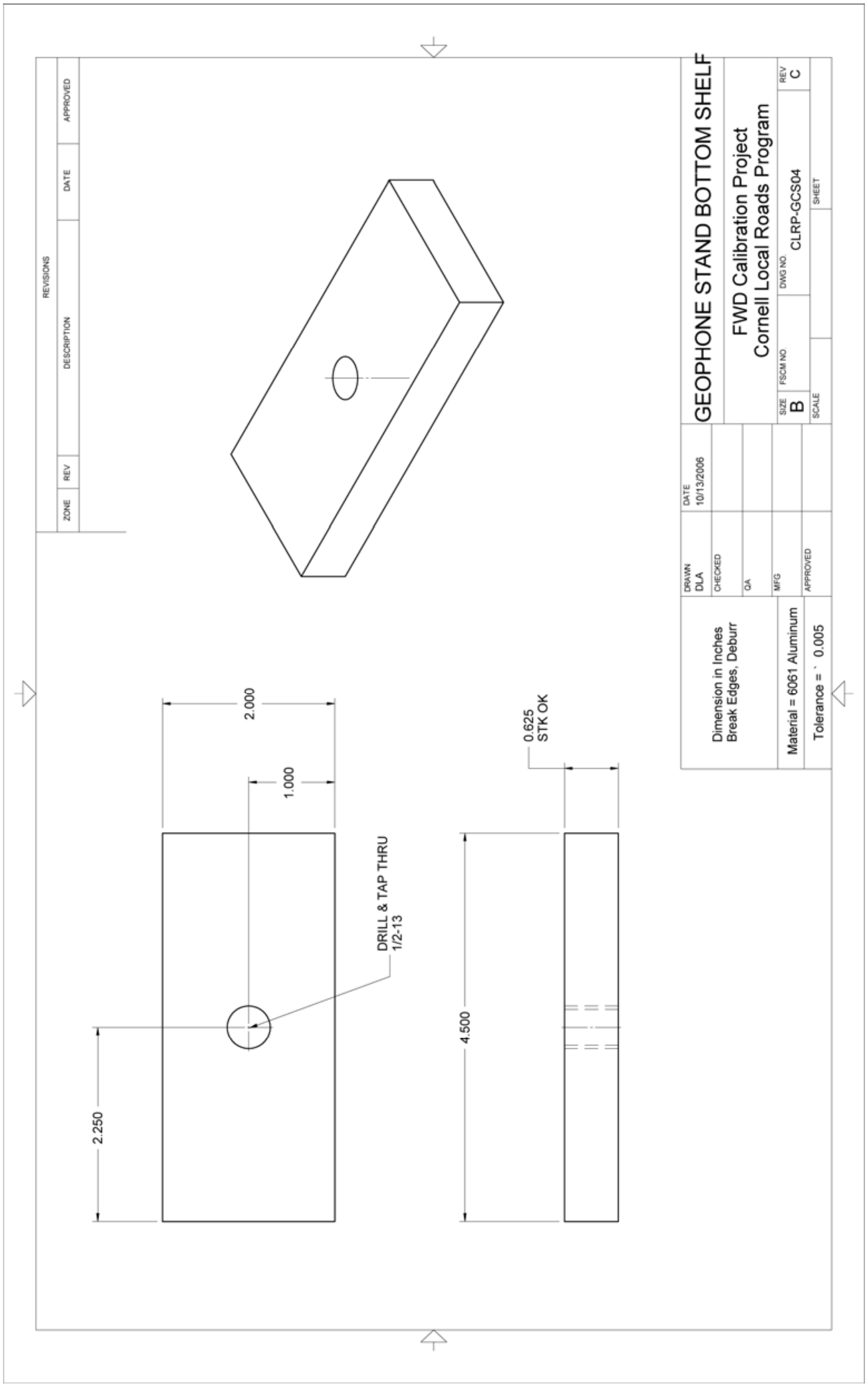

Figure 60. Drawing. CLRP-GCS04 Geophone Stand Bottom Shelf.

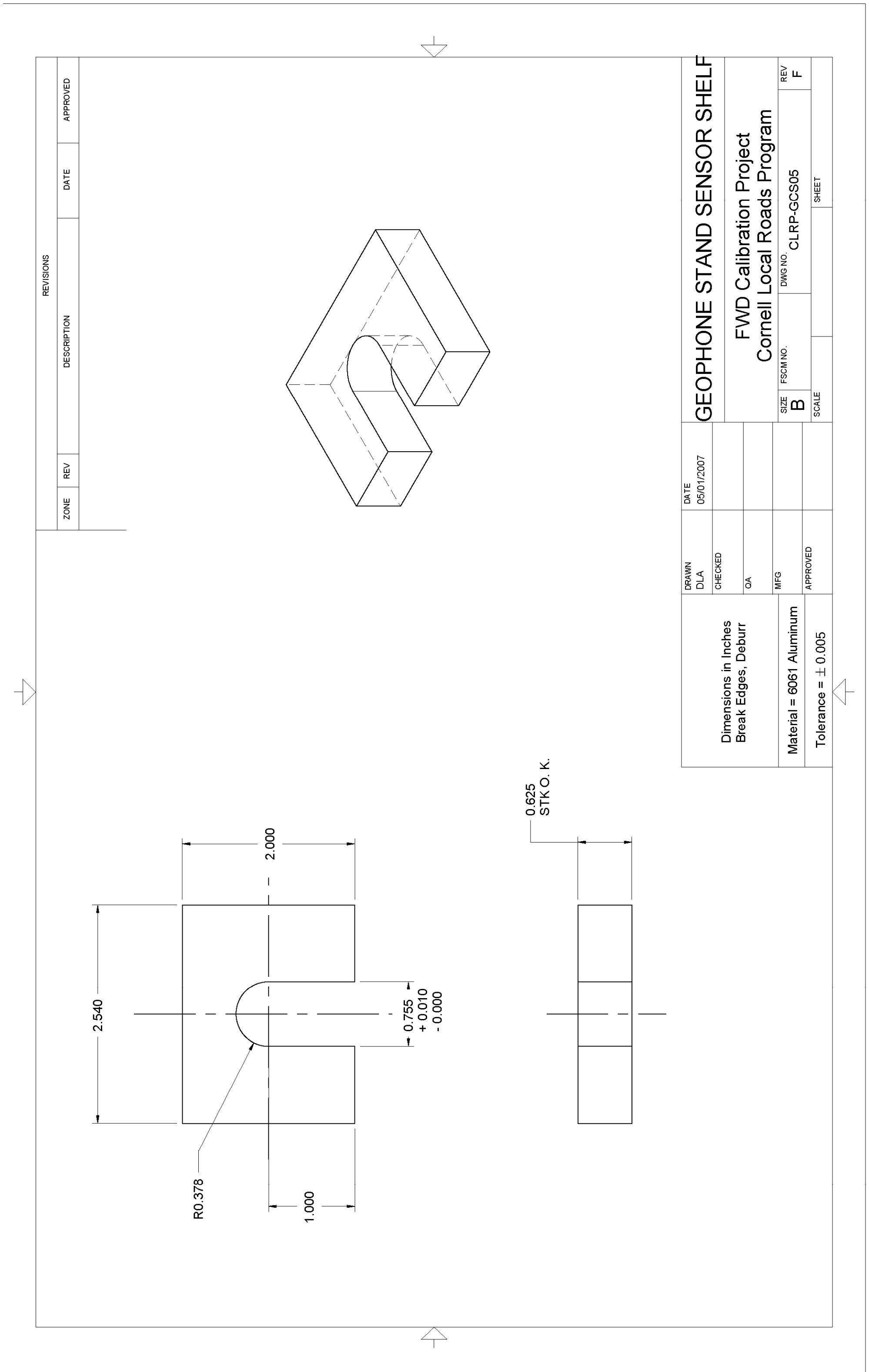

Figure 61. Drawing. CLRP-GCS05 Geophone Stand Sensor Shelf.

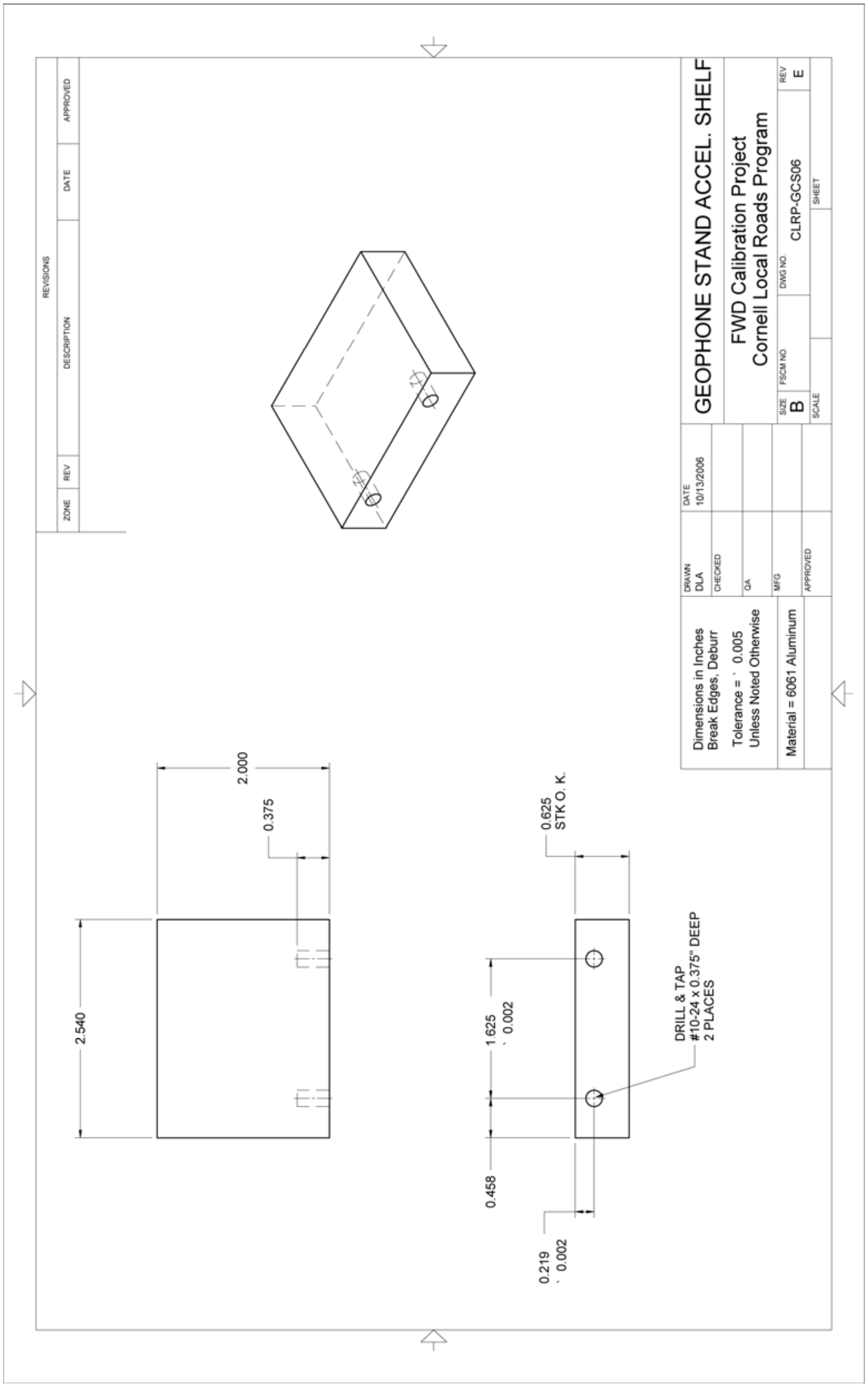

Figure 62. Drawing. CLRP-GCS06 Geophone Stand Accelerometer Shelf.

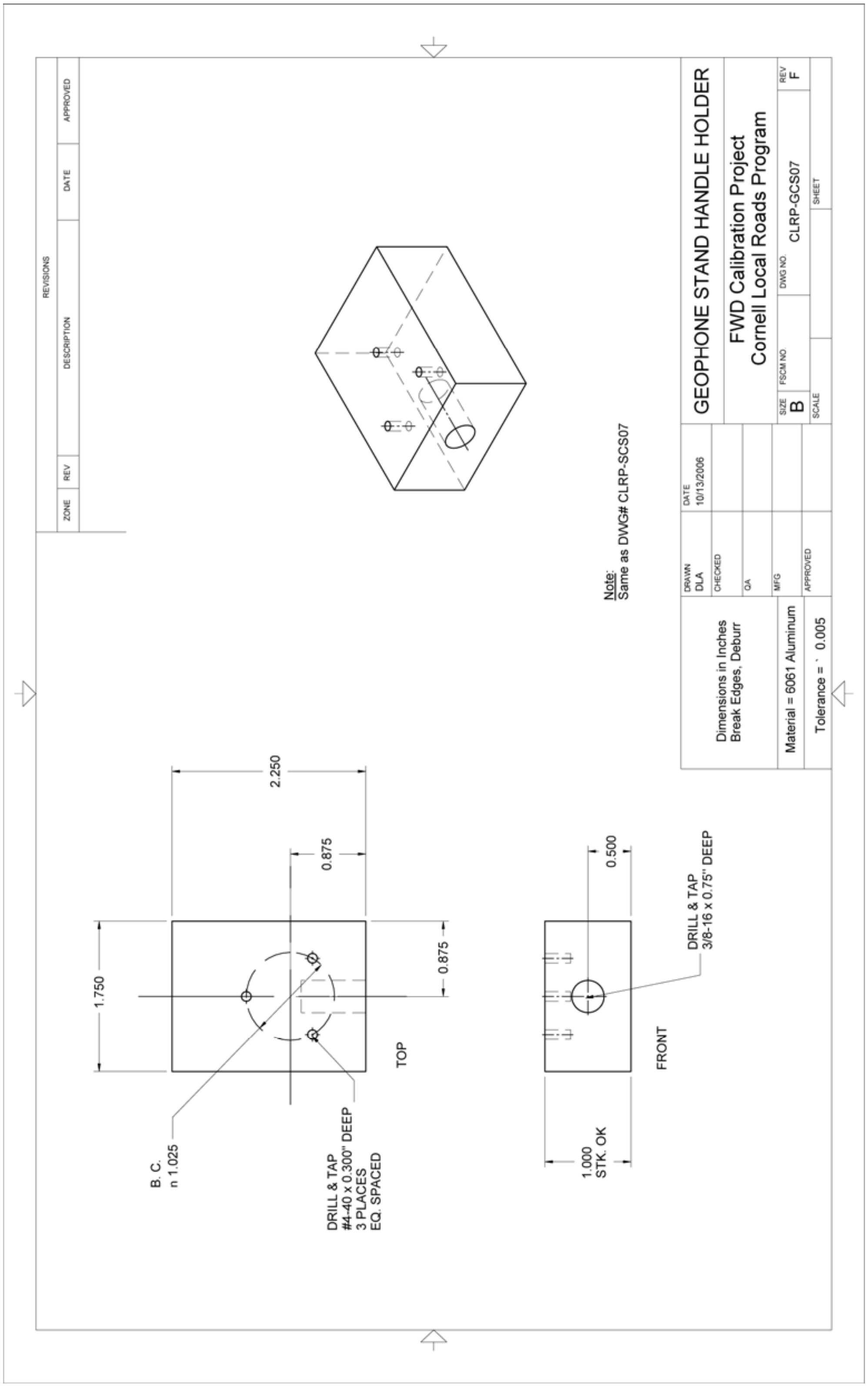

Figure 63. Drawing. CLRP-GCS07 Geophone Stand Handle Holder.

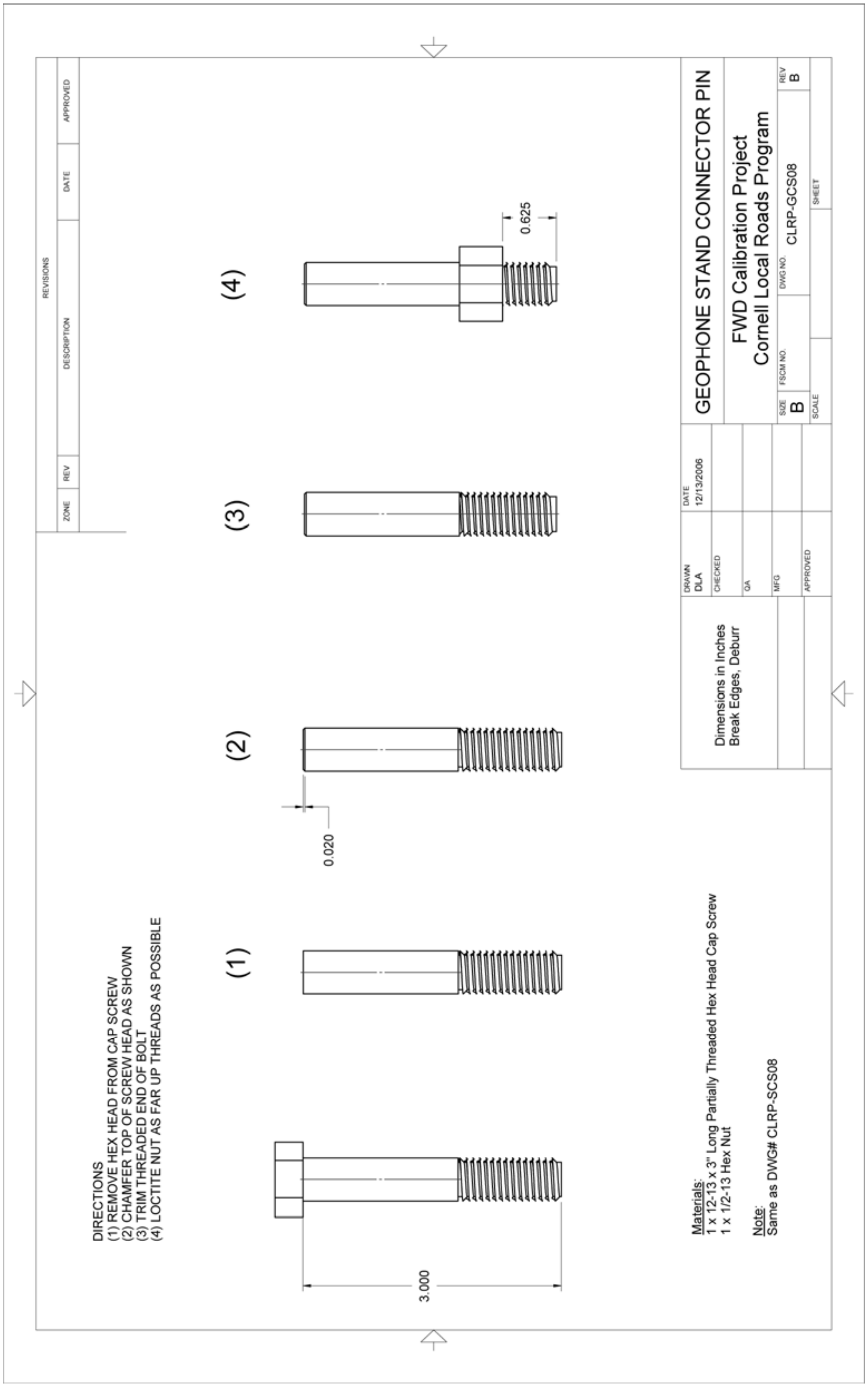

Figure 64. Drawing. CLRP-GCS08 Geophone Stand Connector Pin.

SEISMOMETER CALIBRATION STAND

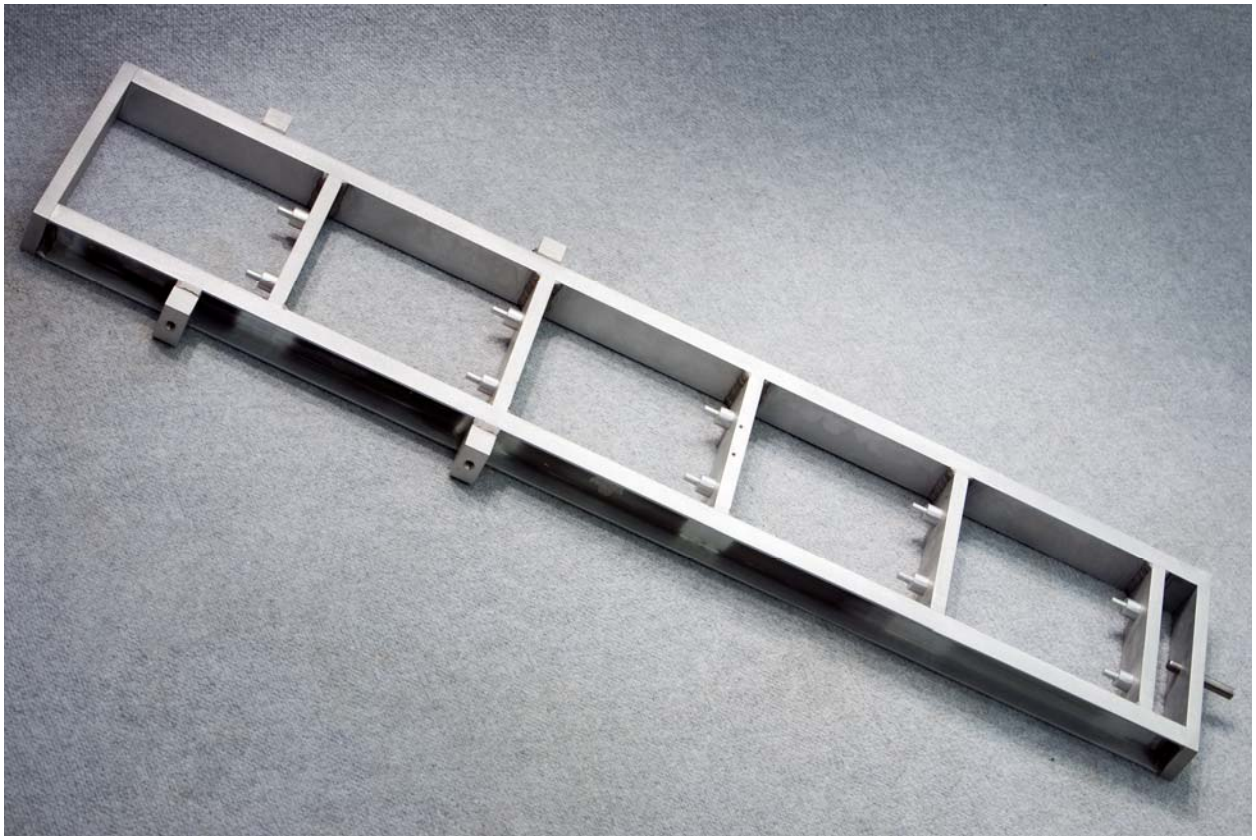

Figure 65. Photo. Seismometer calibration stand.

BM-SCS Seismometer Calibration Stand Bill of Materials

Table 27. Fabricated parts required for seismometer calibration stand assembly.

Dwg. 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*	4
CLRP-SCS08	Seismometer Stand Connector Pin**	1
CLRP-SCS09	Seis. Stand Shelf Subassembly	4
CLRP-SCS10	Seismometer Stand Accel. Shelf	1
CLRP-SCS11	Seismometer Stand Accelerometer Shelf Subassembly	1

Table 28. Hardware items required for seismometer calibration stand assembly.

Vendor Part Number	Item	Vendor	Quantity
62385K65	Tapered Handle, Smooth Phenolic, 3/8"-16 X 1/2" Threaded Stud, 1" Diameter	McMaster-Carr	2
2198A85	Glass Surface-Mount Bull's-eye Level Center Circle & Cross Lines, 1-1/4" Base Diameter, 7/16" Height	McMaster-Carr	1
91737A072	18-8 Stainless Steel Fillister Head Phillips Machine Screw 4-40 Thread, 1/4" Length	McMaster-Carr	3

Table 29. Vendor contact information for 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 seismometer calibration stand assembly.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$1425.00	
Misc. hardware	1		$30.00	

*Indicates the cost in Feb. 2009.

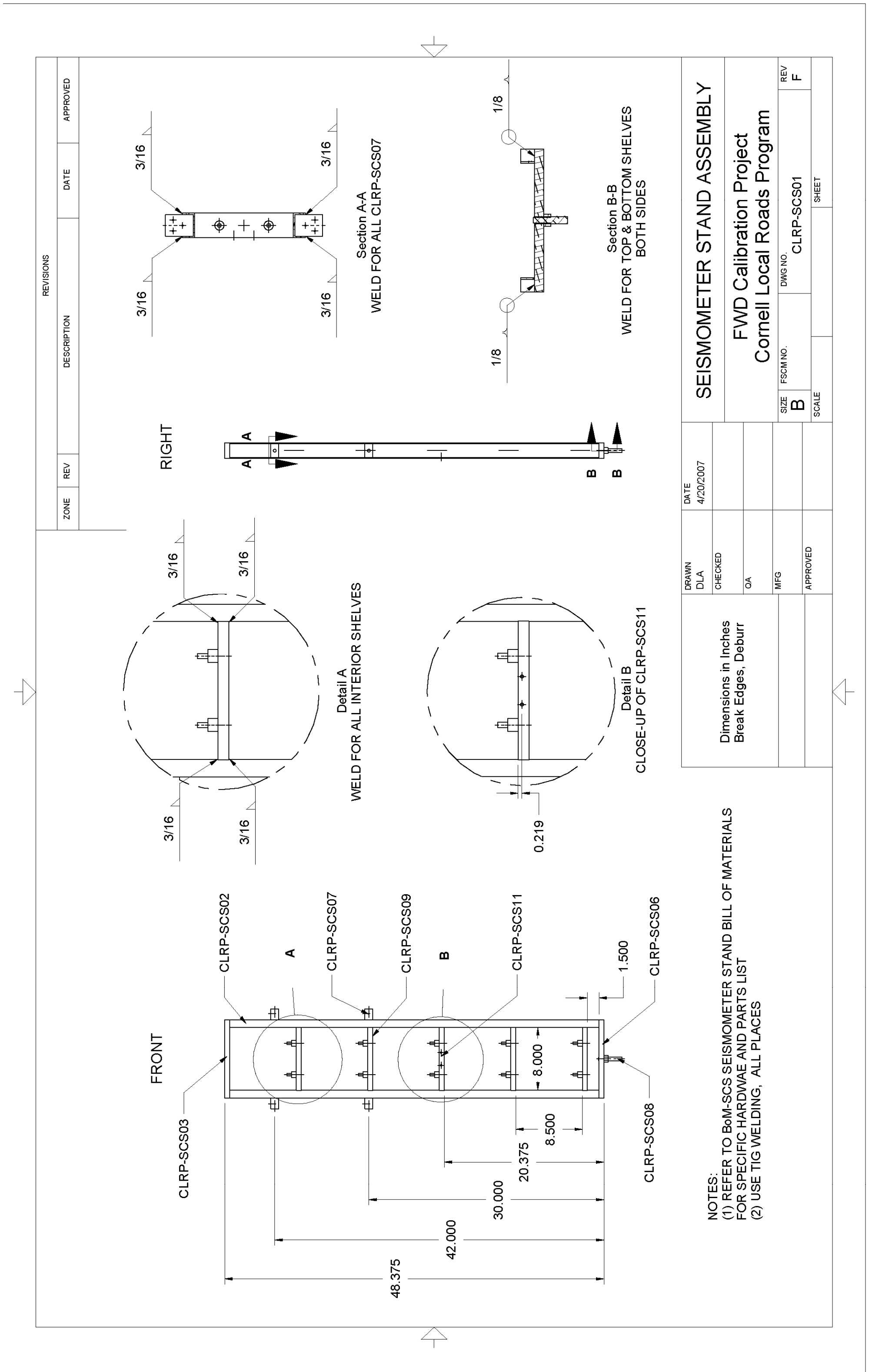

Figure 66. Drawing. CLRP-SCS01 Seismometer Stand Assembly.

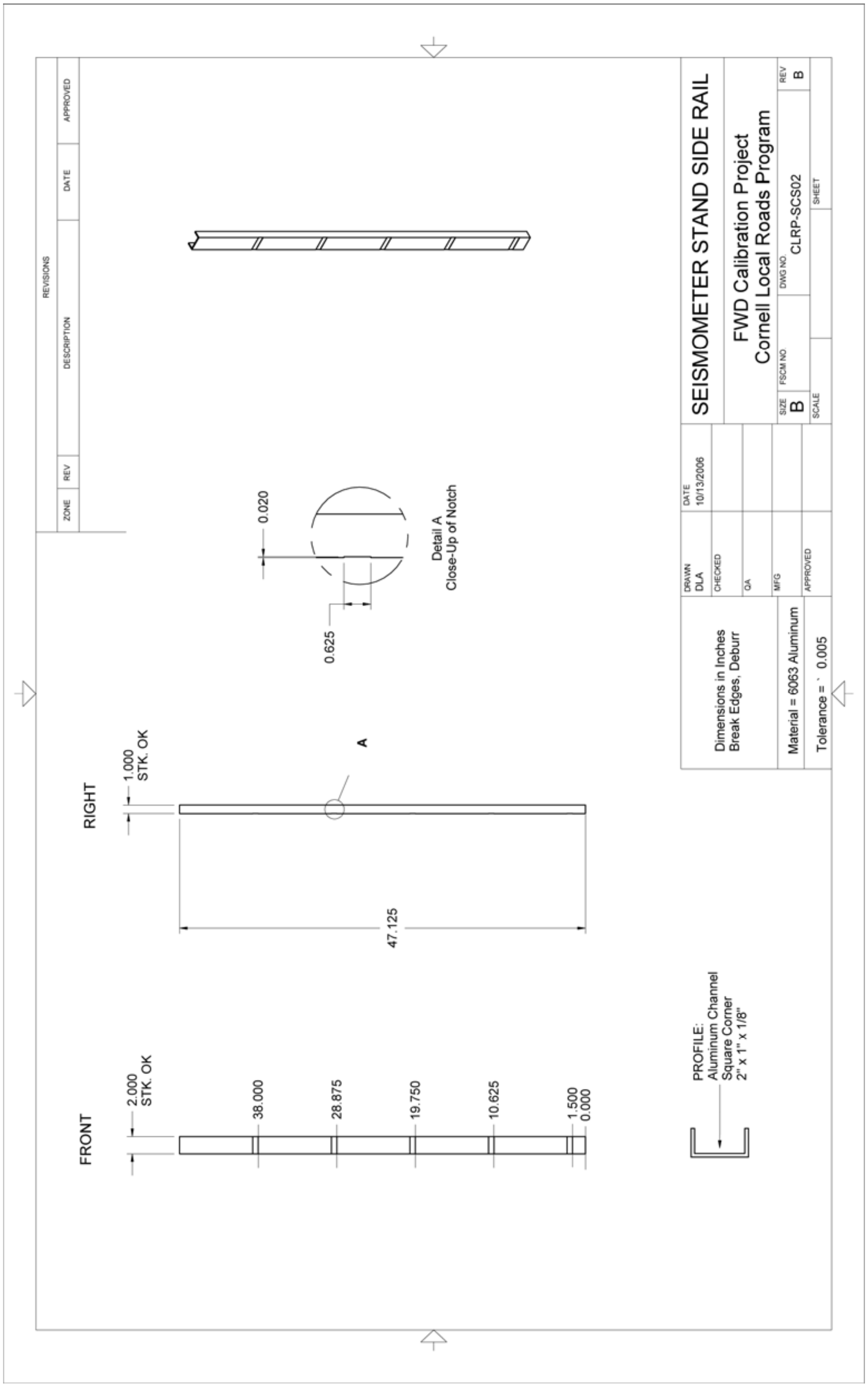

Figure 67. Drawing. CLRP-SCS02 Seismometer Stand Side Rail.

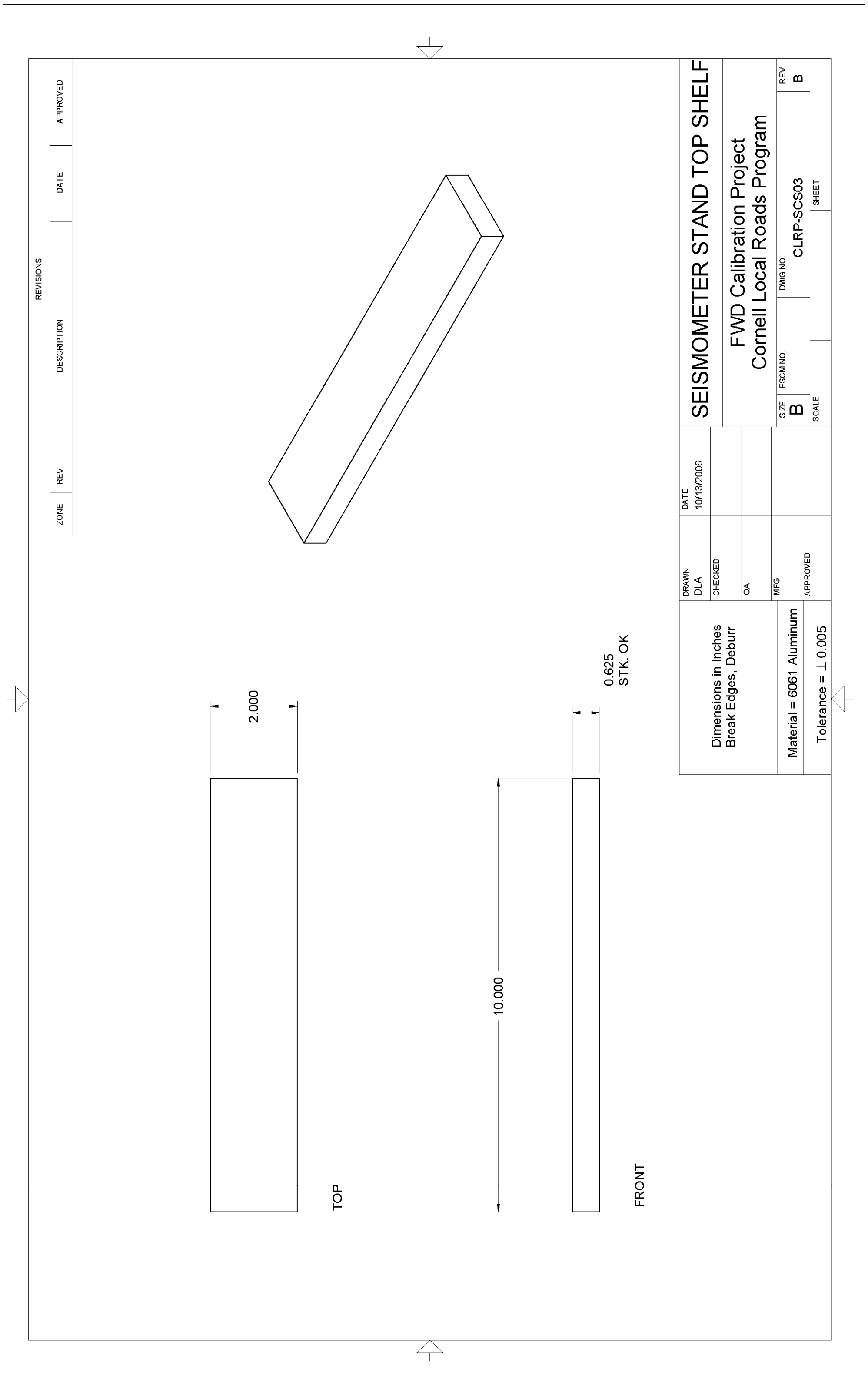

Figure 68. Drawing. CLRP-SCS03 Seismometer Stand Top Shelf.

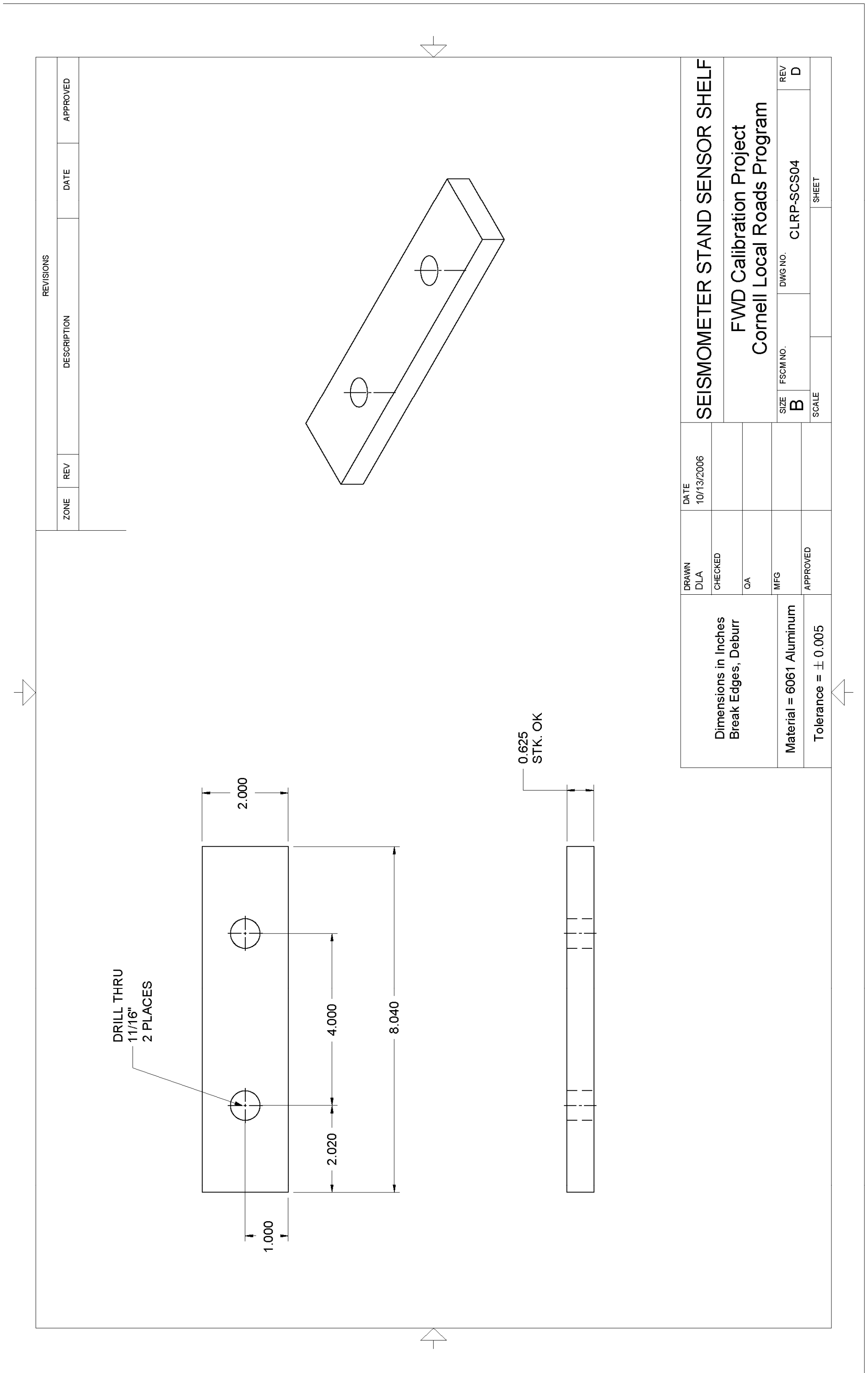

Figure 69. Drawing. CLRP-SCS04 Seismometer Stand Sensor Shelf.

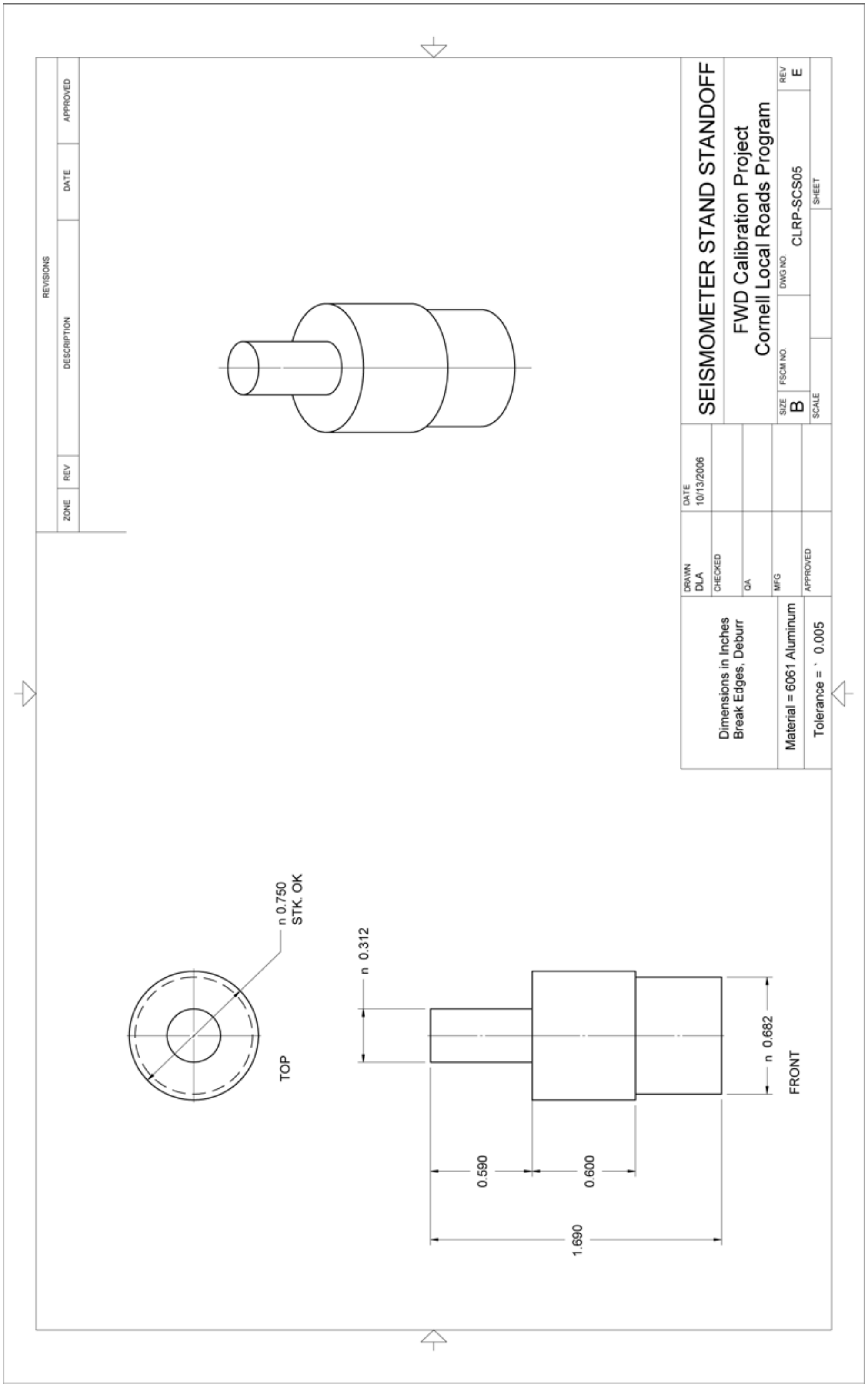

Figure 70. Drawing. CLRP-SCS05 Seismometer Stand Standoff.

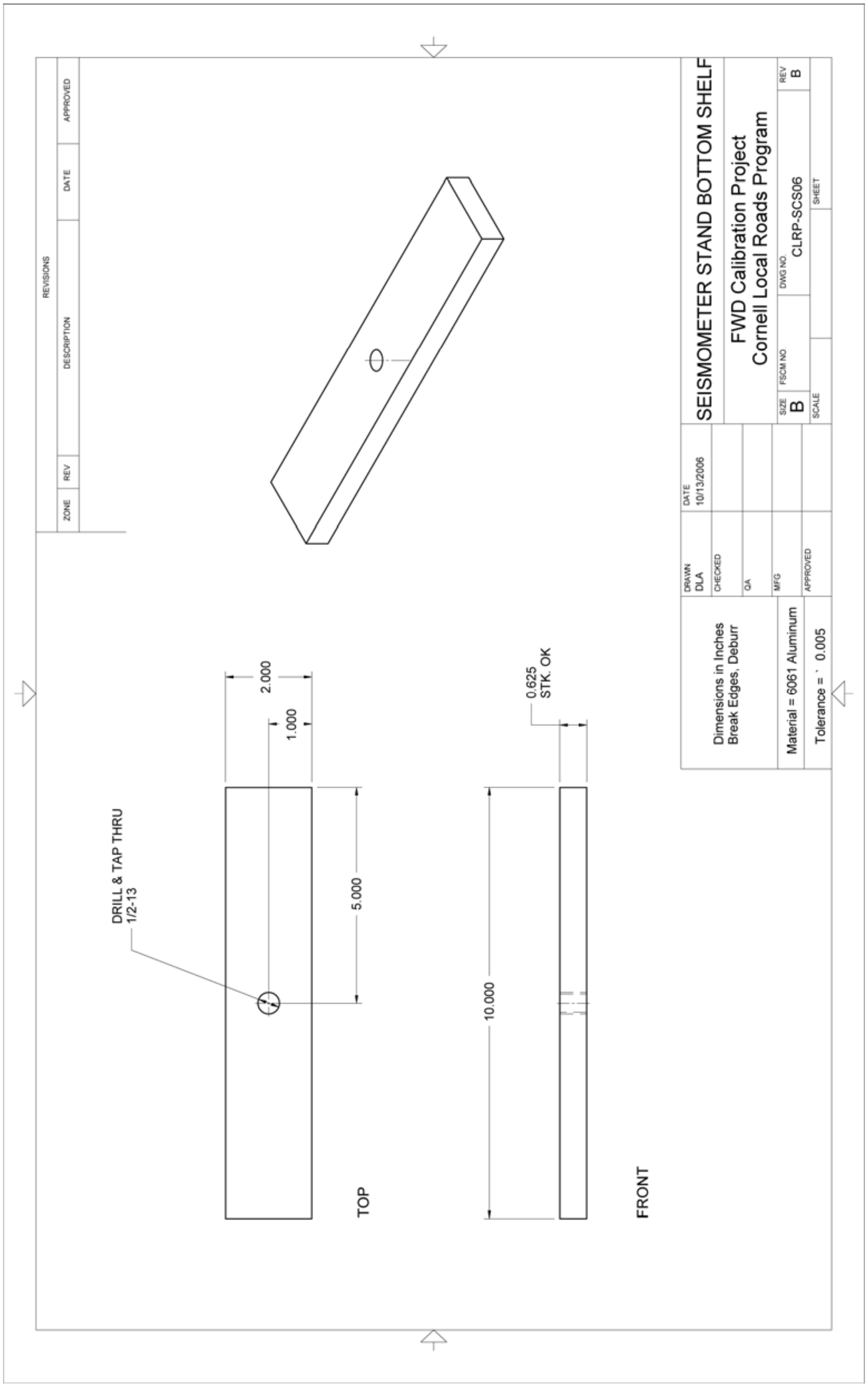

Figure 71. Drawing. CLRP-SCS06 Seismometer Stand Bottom Shelf.

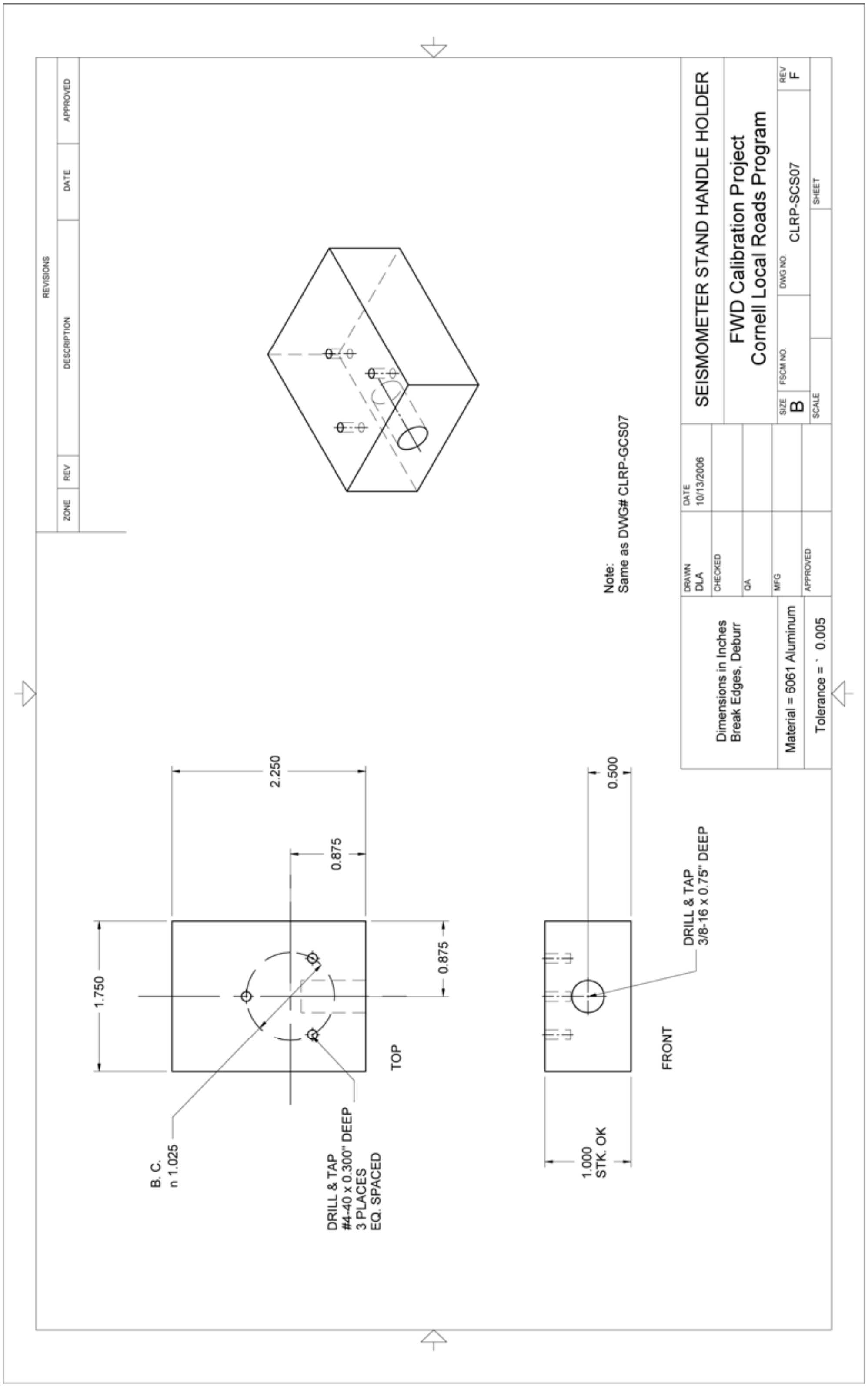

Figure 72. Drawing. CLRP-SCS07 Seismometer Stand Handle Holder.

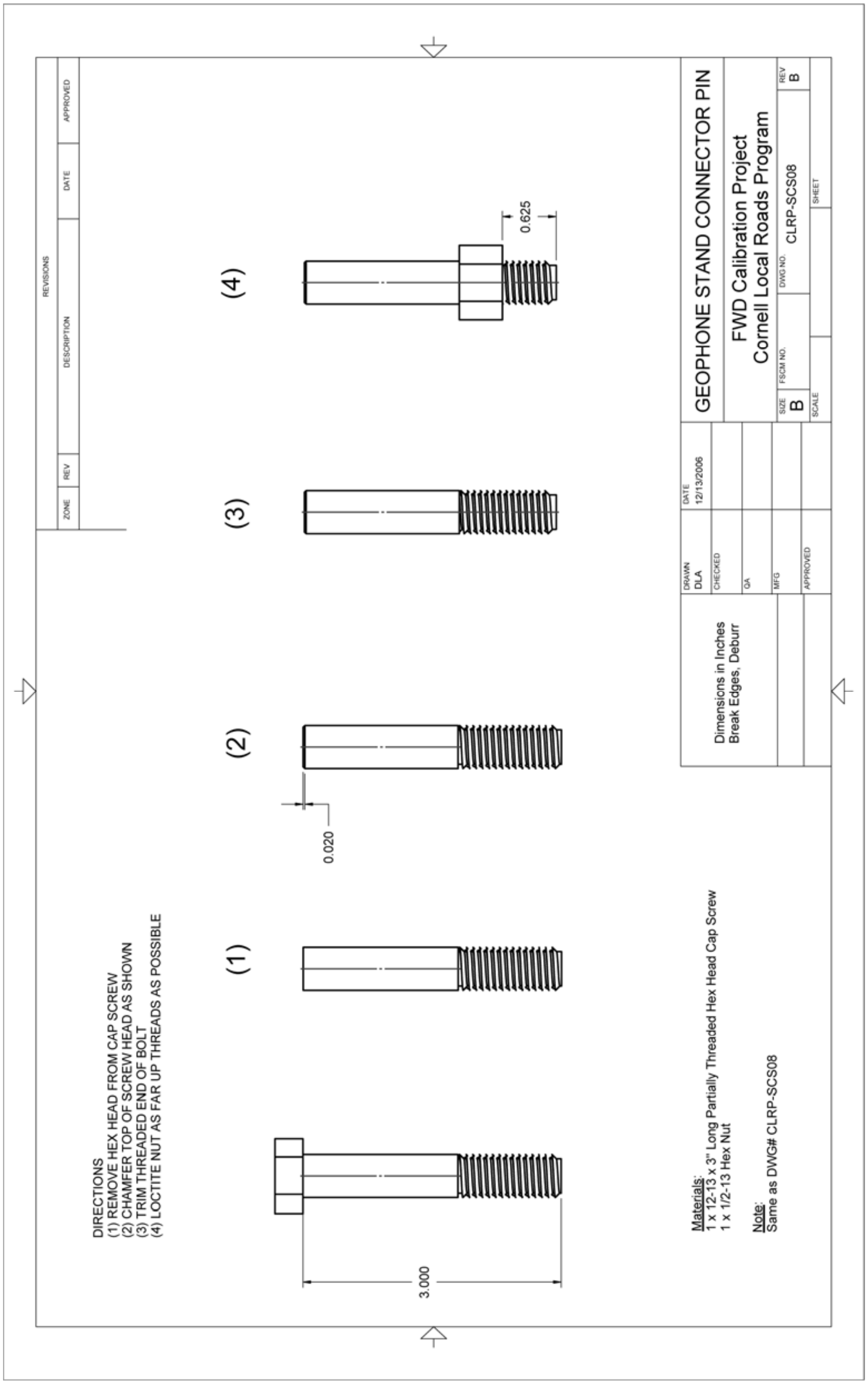

Figure 73. Drawing. CLRP-SCS08 Seismometer Stand Connector Pin.

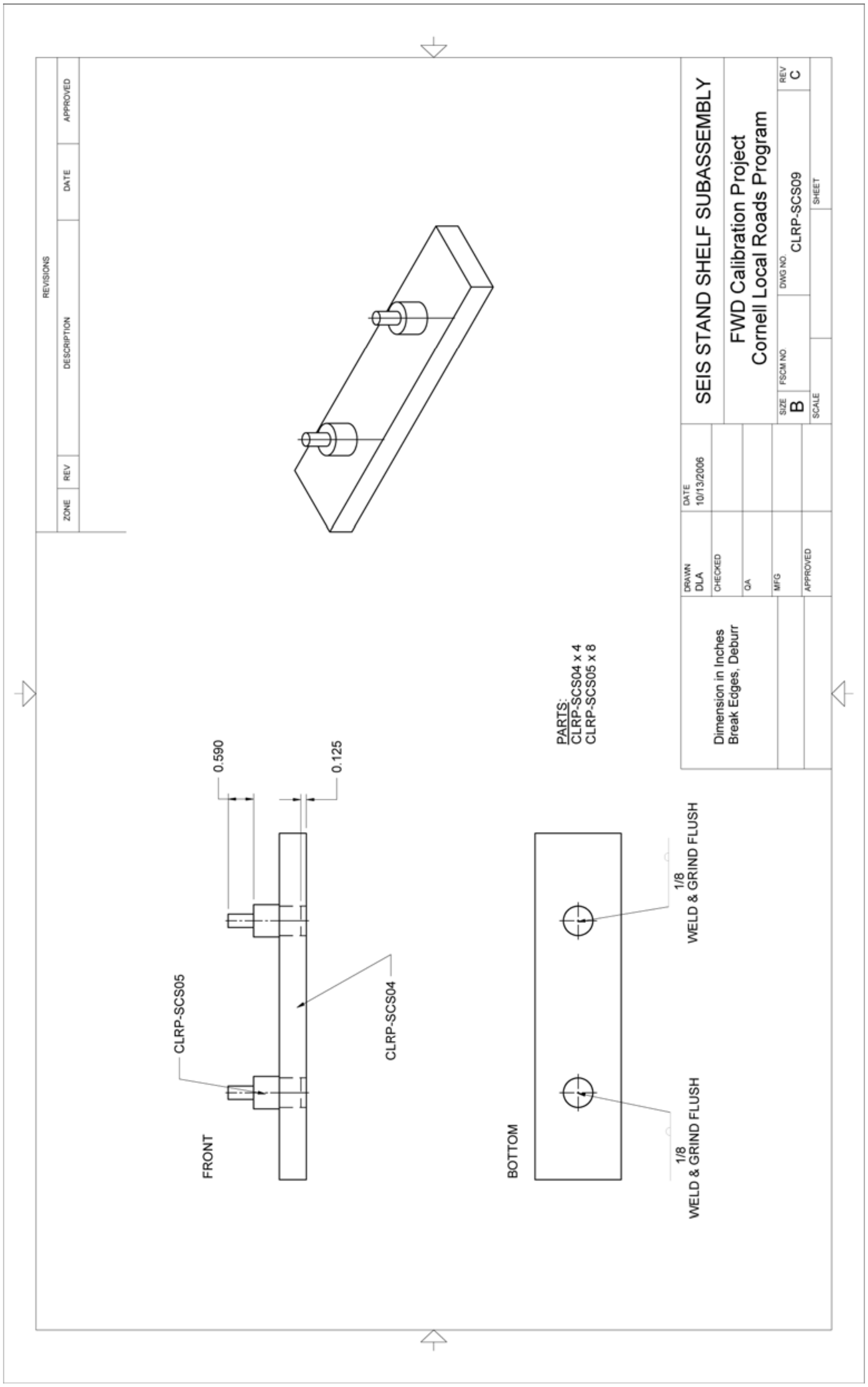

Figure 74. Drawing. CLRP-SCS09 Seismometer Stand Shelf Subassembly.

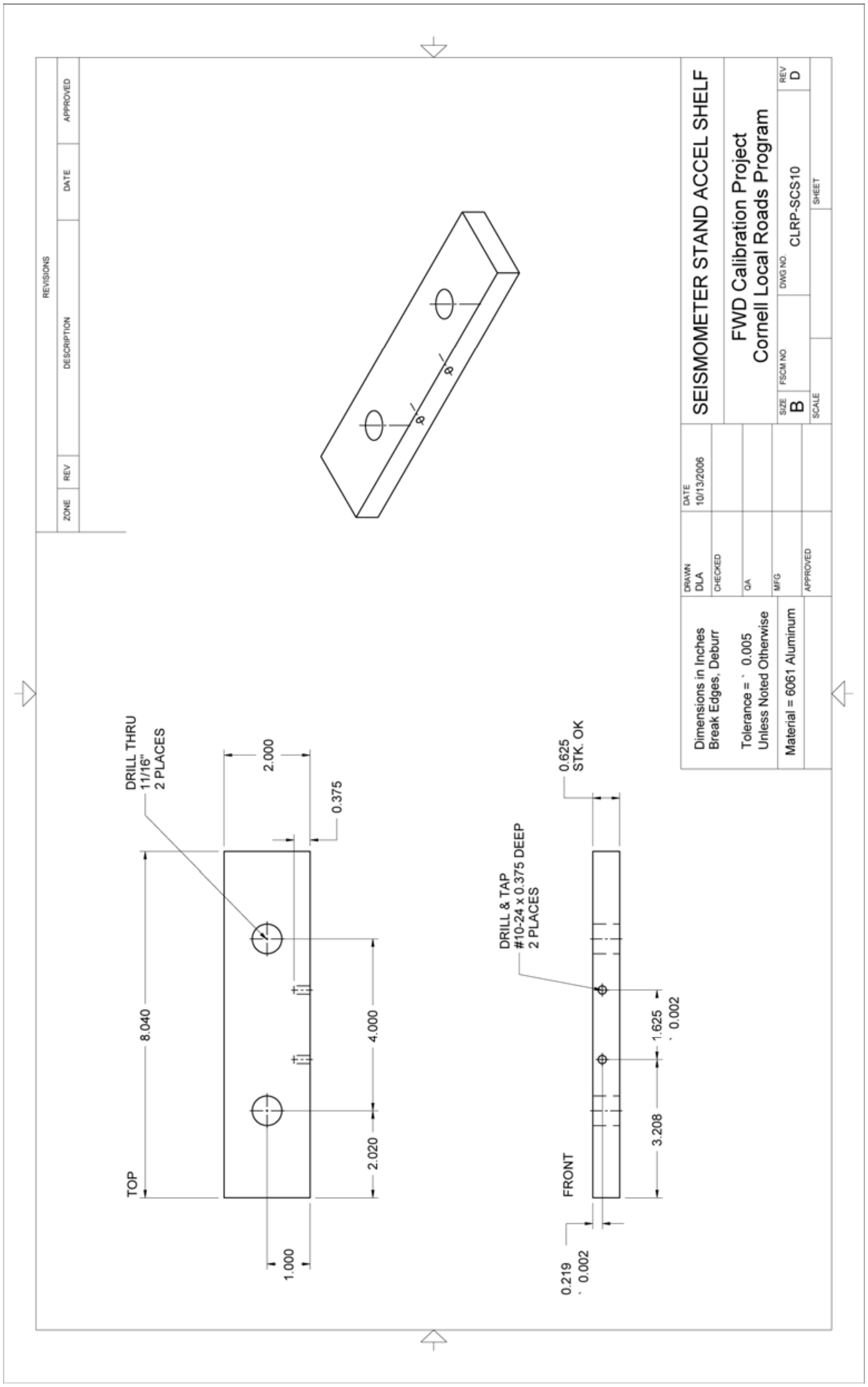

Figure 75. Drawing. CLRP-SCS10 Seismometer Stand Accelerometer Shelf.

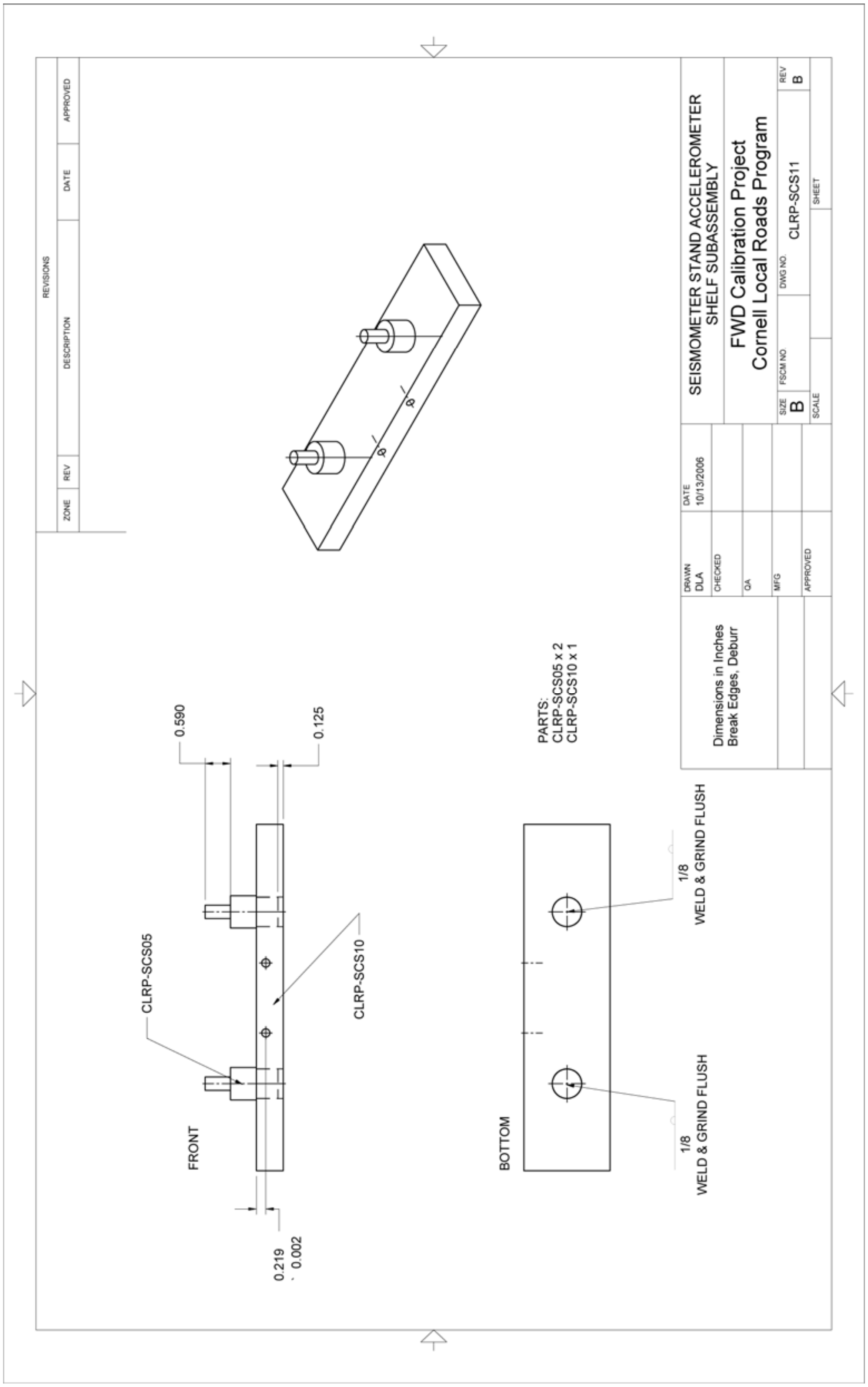

Figure 76. Drawing. CLRP-SCS11 Seismometer Stand Accel. Shelf Subassembly.

GEOPHONE ADAPTERS

BM-GA Geophone Adapters Bill of Materials

Table 31. Fabricated parts for use as geophone adapters.

Dwg. Number	Description	Quantity
CLRP-GA02	Carl Bro Adapter	10
CLRP-GA03	JILS Adapter	10
CLRP-GA04	KUAB Adapter	10

Table 32. Hardware items req. for use of geophone adapters.

Vendor Part Number	Item	Vendor	Quantity
90126A036	SAE Flat Washer, Zinc-Plated Steel, 3/4" Size, 13/16" Inside Diameter, 1-1/2" Outside Diameter, 0.108" Min. Thick	McMaster-Carr	10
94744A273	Flat Washer, Zinc-Plated Steel, 3/8" Screw Size, 0.406" Inside Diameter, 1.25" Outside Diameter, 0.090"- 0.112" Thick	McMaster-Carr	10
92865A212	Hex Head Cap Screw, Grade 5 Zinc-Plated Steel, 3/8"-24 Thread, 5/8" 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" Diameter, 9/32" Thick, 20 Pull lbs	McMaster-Carr	10
6121K93	Steel Round Knurled-Rim Knob Solid Hub, 1-1/2" Diameter	McMaster-Carr	10
92949A246	18-8 SS Button Head Socket Cap Screw 10-24 Thread, 7/8" Length	McMaster-Carr	10
90730A011	18-8 SS Undersized Machine Screw Hex Nut 10-24 Screw Size, 5/16" Width, 7/64" Height	McMaster-Carr	10

Table 33. Vendor contact information for geophone adapters.

Vendor	Web site	Notes
McMaster-Carr	www.mcmaster.com	See web site for area specific contact information located in the 'About Us' section
Morton Machine Works	www.mortonmachine.com	125 Gearhart St, PO Box 97, Millersburg, PA 17061, (800) 441-2751

Table 34. Hardware costs for geophone adapters.

Part	Quantity	Supplier	Cost*	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.

*Indicates the cost in Feb. 2009.

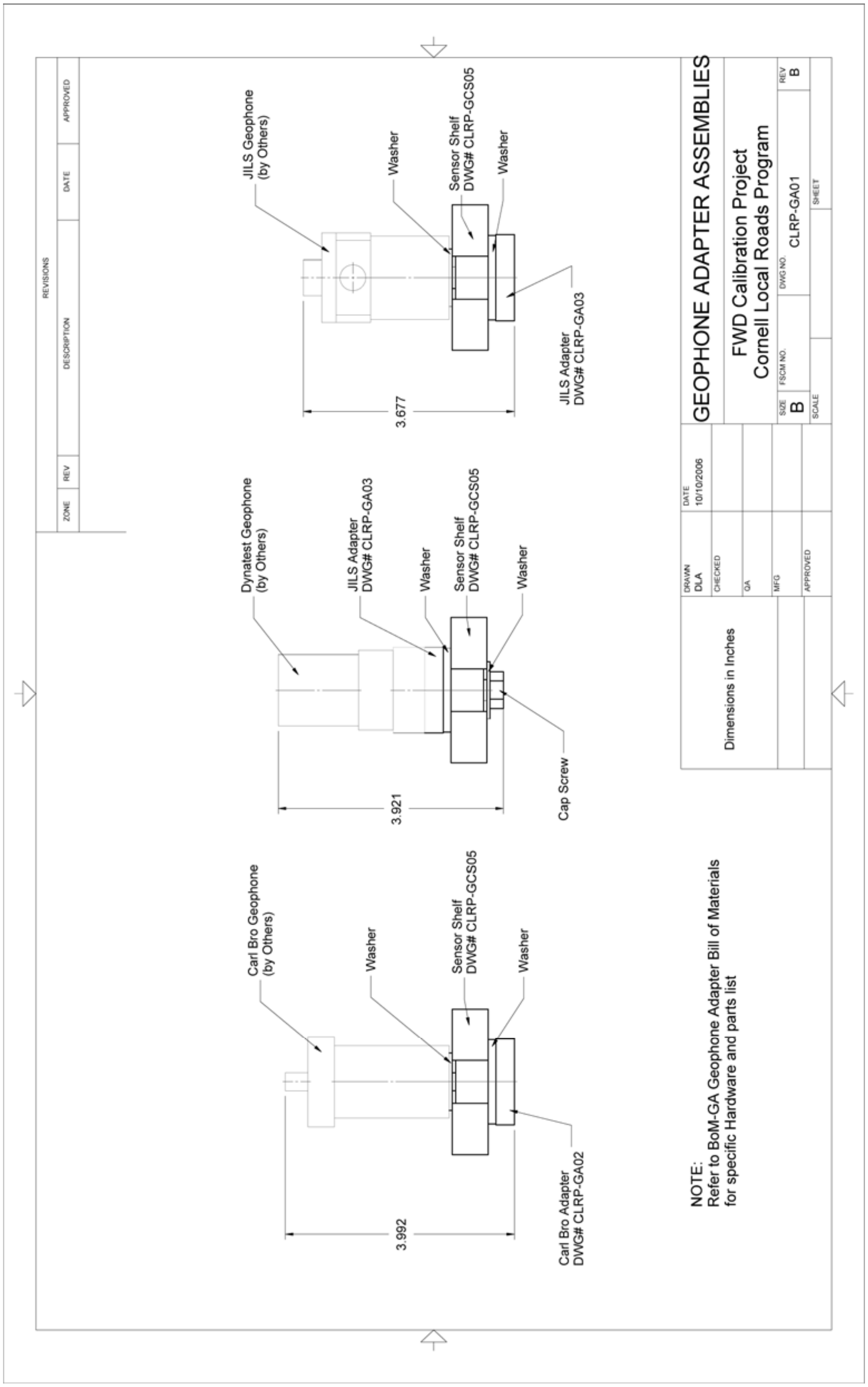

Figure 77. Drawing. CLRP-GA01 Geophone Adapter Assemblies.

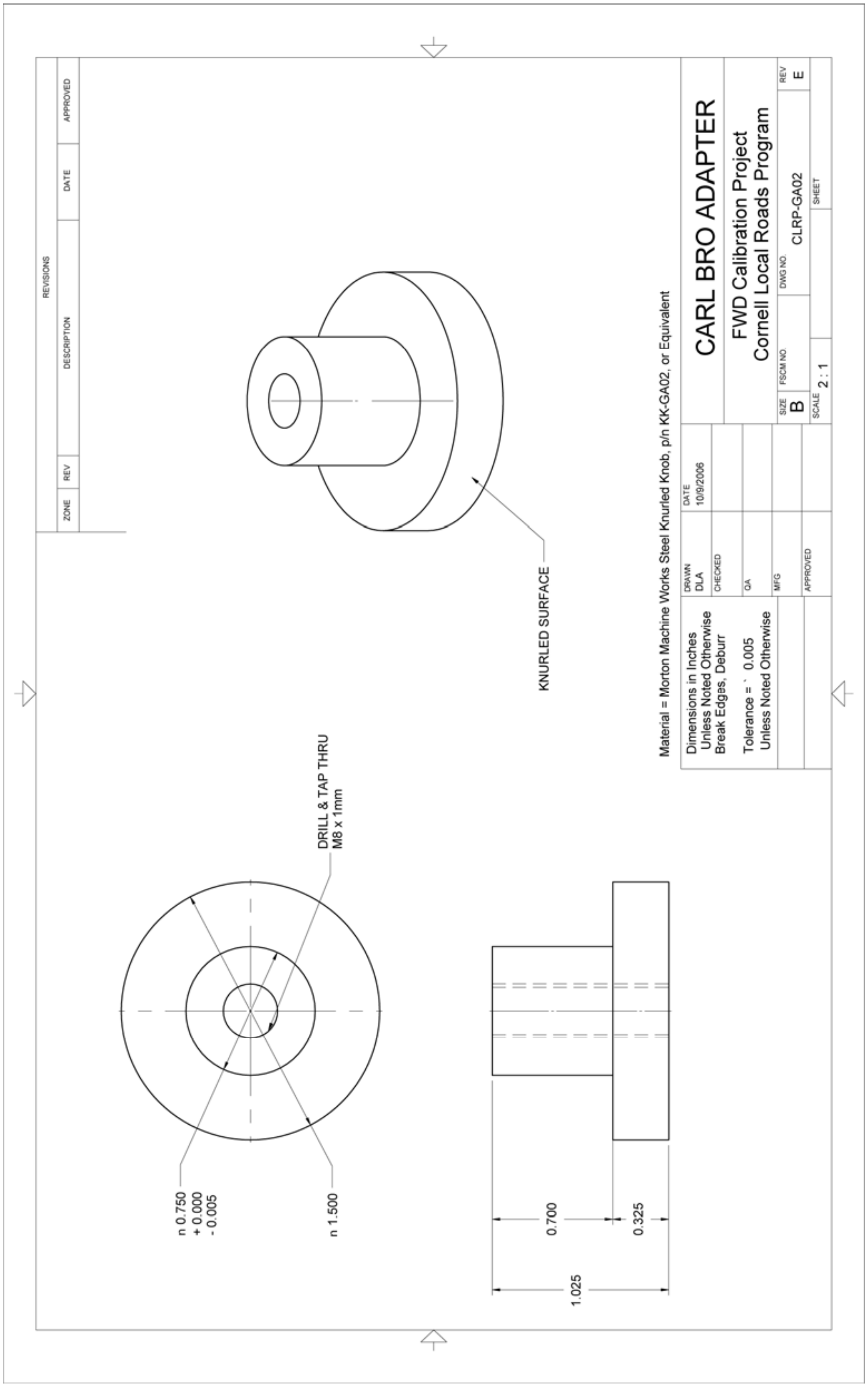

Figure 78. Drawing. CLRP-GA02 Carl Bro Adapter.

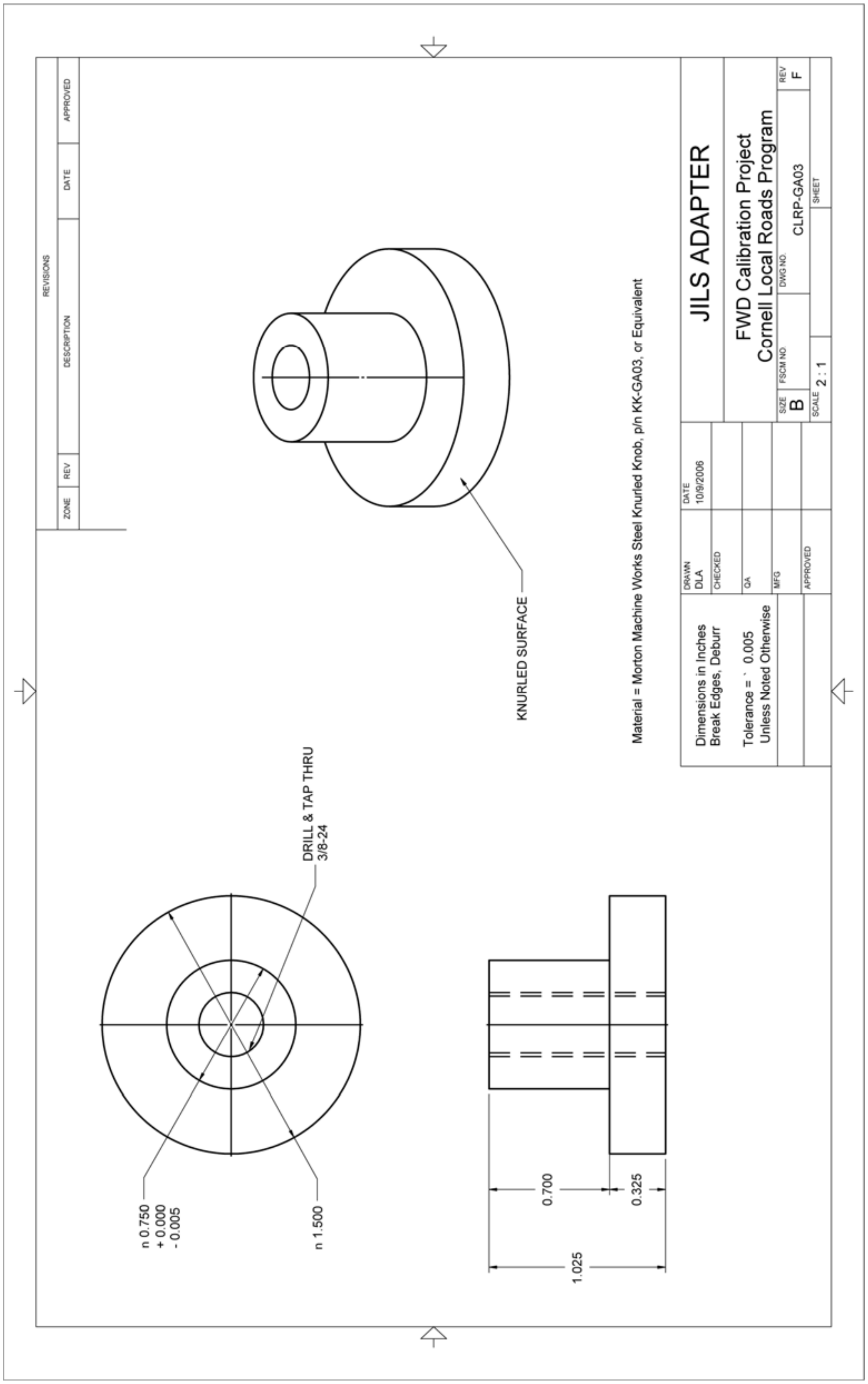

Figure 79. Drawing. CLRP-GA03 JILS Adapter.

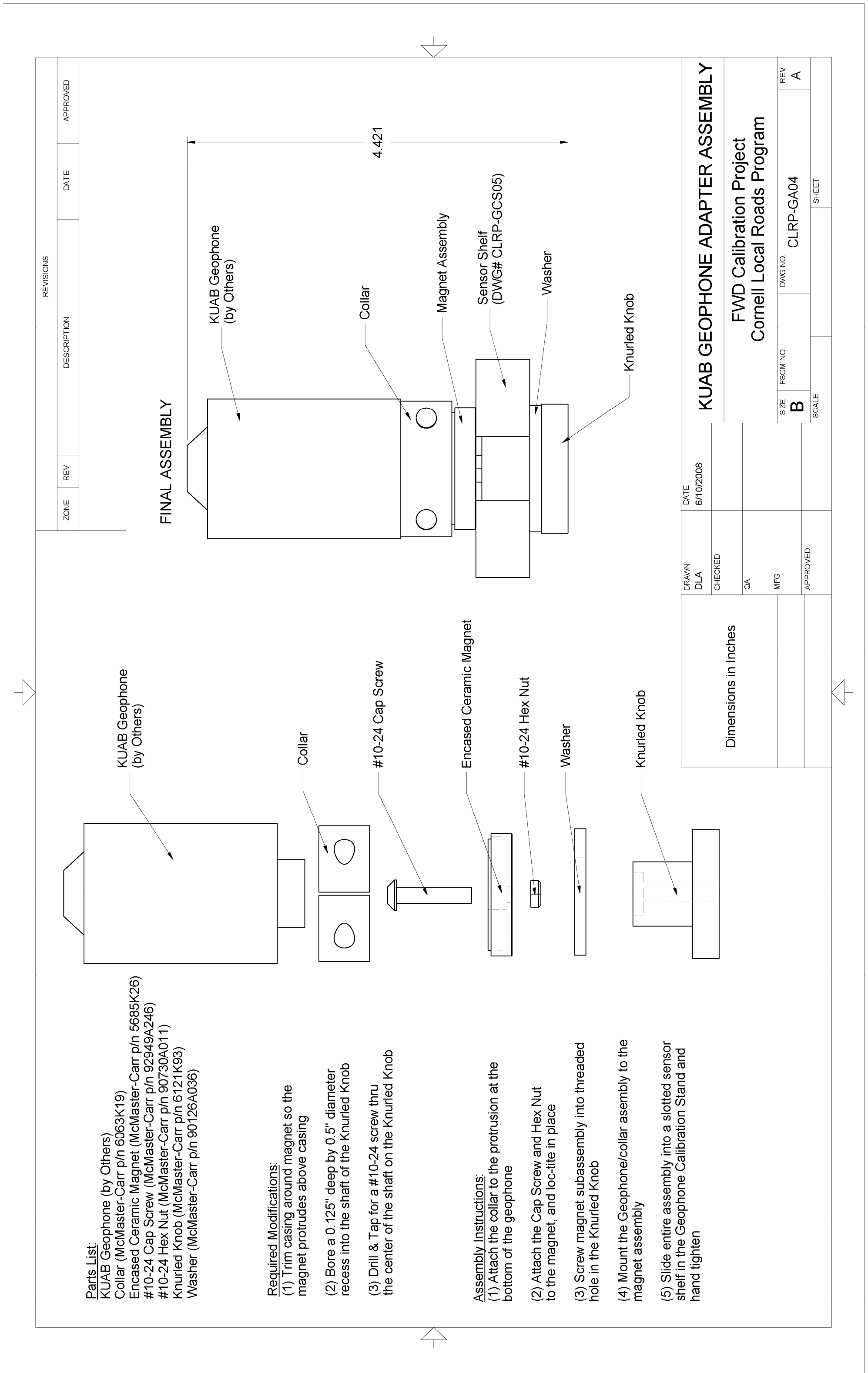

Figure 80. Drawing. CLRP-GA04 KUAB Adapter.

REFERENCE LOAD CELL

BM-LC Reference Load Cell Bill of Materials

Table 35. Fabricated parts for the reference load cell.

Dwg. 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 Gage Layout	3
CLRP-LC10	Bridge Wiring Detail	1

Table 36. Equipment and hardware items required for the load cell.

Vendor Part Number	Item	Vendor	Quantity
92196A325	Socket Head Cap Screw, 18-8 SS. ¼”-28 Thread, 1” Length	McMaster-Carr	12
91771A563	Flat Head Phillips Machine Screw, 18-8 SS, ¼”-28 Thread, 1-1/4” Length	McMaster-Carr	6
91737A072	Fillister Head Phillips Machine Screw, 18-8 SS, #4-40 Thd, ¼” Length	McMaster-Carr	4
654-MS3102A14S-5P	Amphenol Box Mount Receptacle, MS3102A-14S-5P	Mouser Electronics	1
N2A-13-S054Y-350	Transducer-Class Strain Gages, General Purpose 90° Rosette, 0.125” Gage Length, 350 Ohm Resistance	Vishay Micro-Measurements	12
SC2513-18-FF	White plastic, foam filled shipping case	Danielle’s Case Co.	1

Table 37. Vendor contact information.

Vendor	Web site	Notes
McMaster-Carr	www.mcmaster.com	See web site for specific contact information located in the "About Us" section
Mouser Electronics	www.mouser.com	See web site for specific contact information located in the "Contact Us" section
Vishay Micro-Measurements	www.vishay.com	See web site for specific contact information located in the "Sales Representatives" section
Danielle's Case Co.	http://danielles.com/	See web site for specific contact information located in the "Contact Us" section

Note: A complete reference load cell assembly, cable, and case can be purchased from Dynatest Production & Support Center, Starke, FL (mailto:psc@dynatest.com). Cost in Feb. 2009 is $10,500.

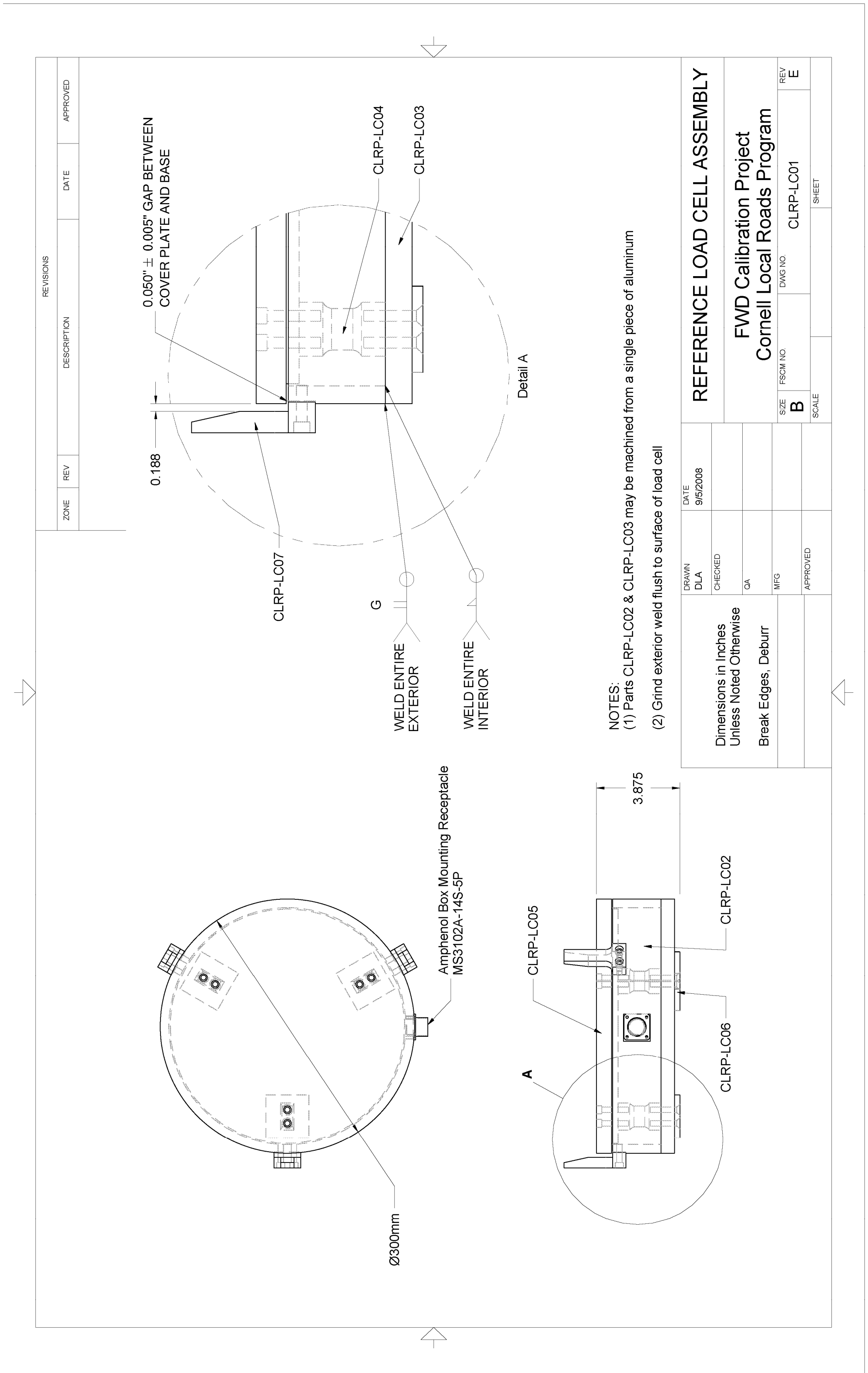

Figure 81. Drawing. CLRP-LC01 Load Cell Assembly.

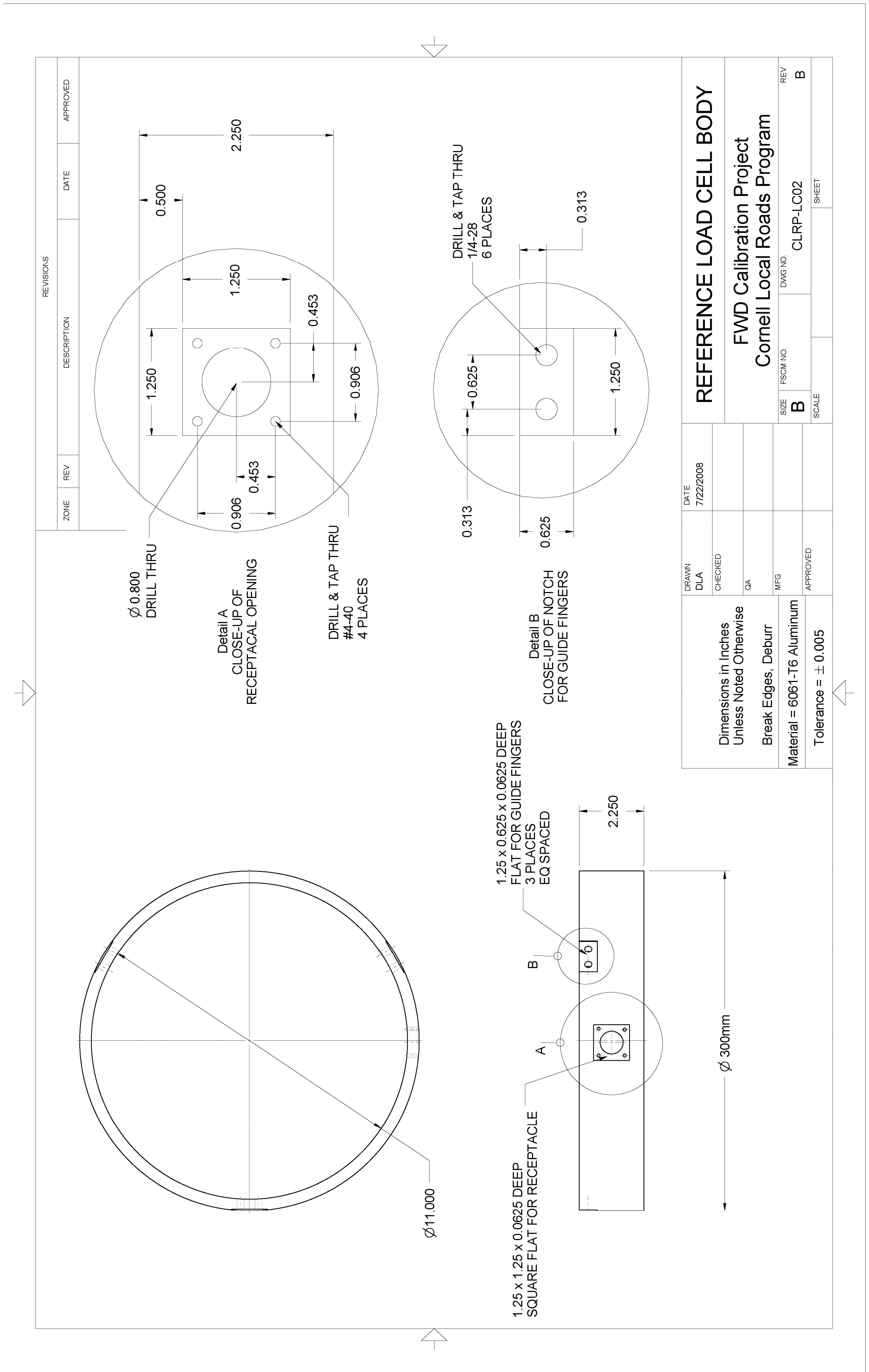

Figure 82. Drawing. CLRP-LC02 Load Cell Body.

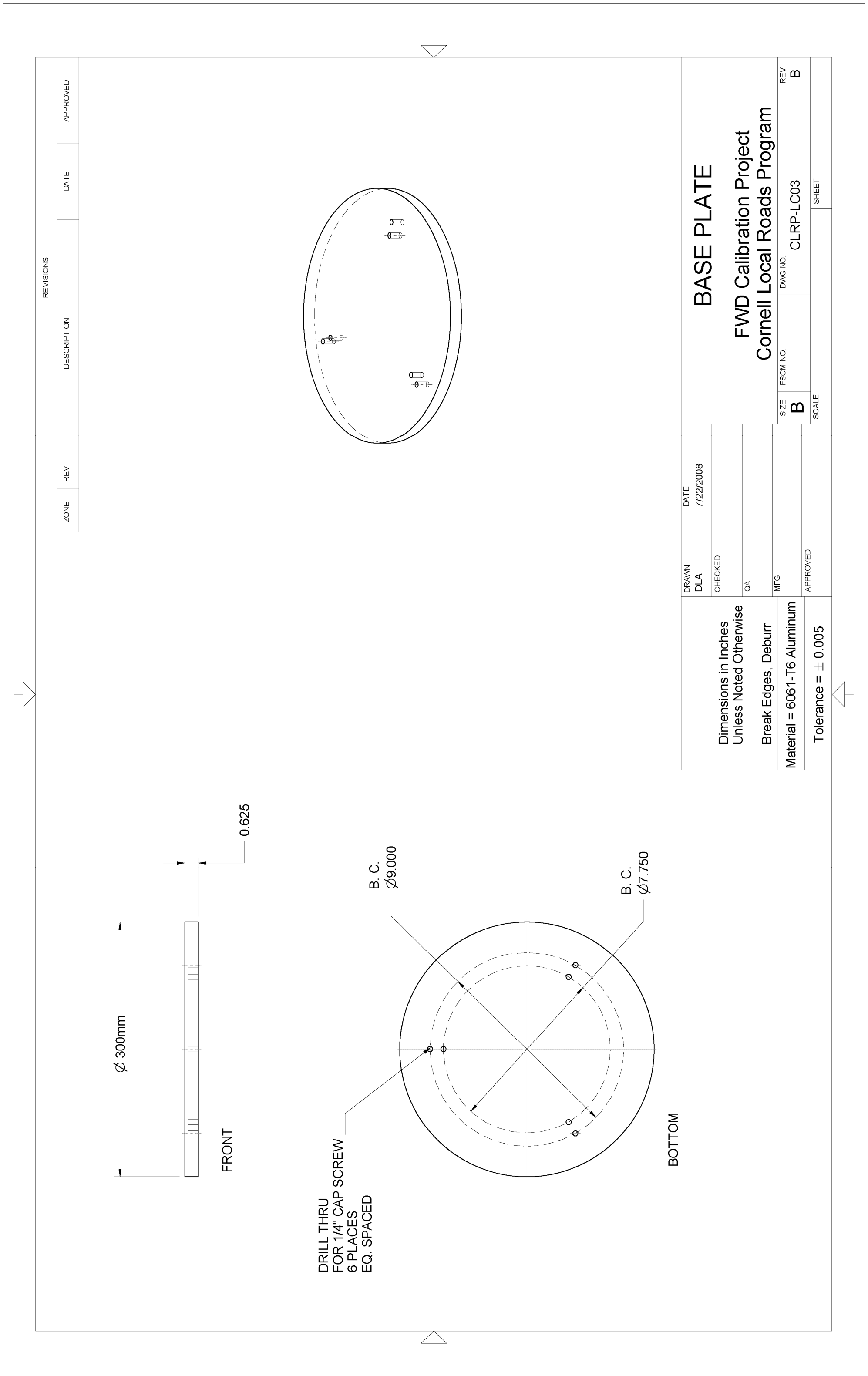

Figure 83. Drawing. CLRP-LC03 Base Plate.

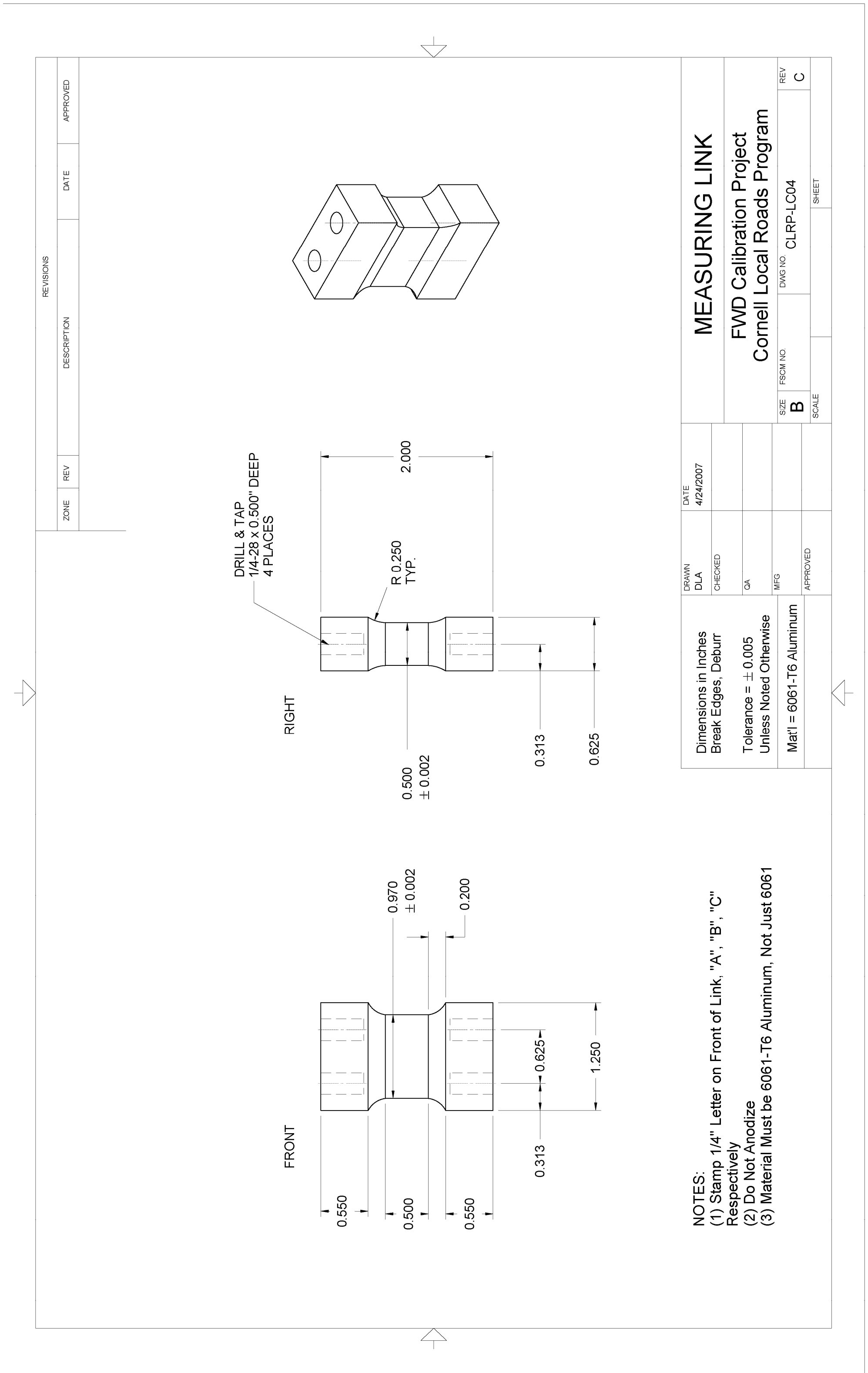

Figure 84. Drawing. CLRP-LC04 Measuring Link.

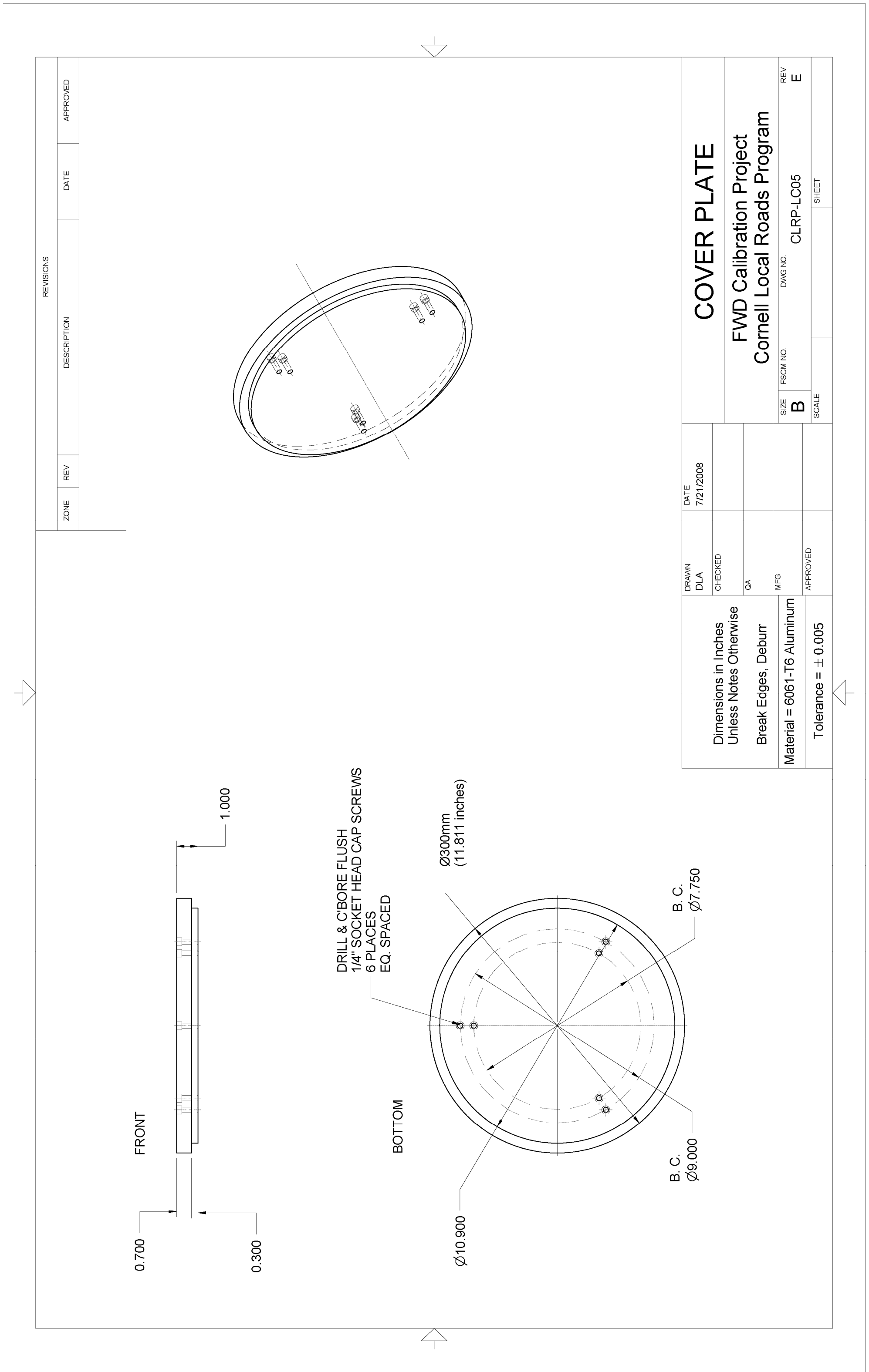

Figure 85. Drawing. CLRP-LC05 Cover Plate.

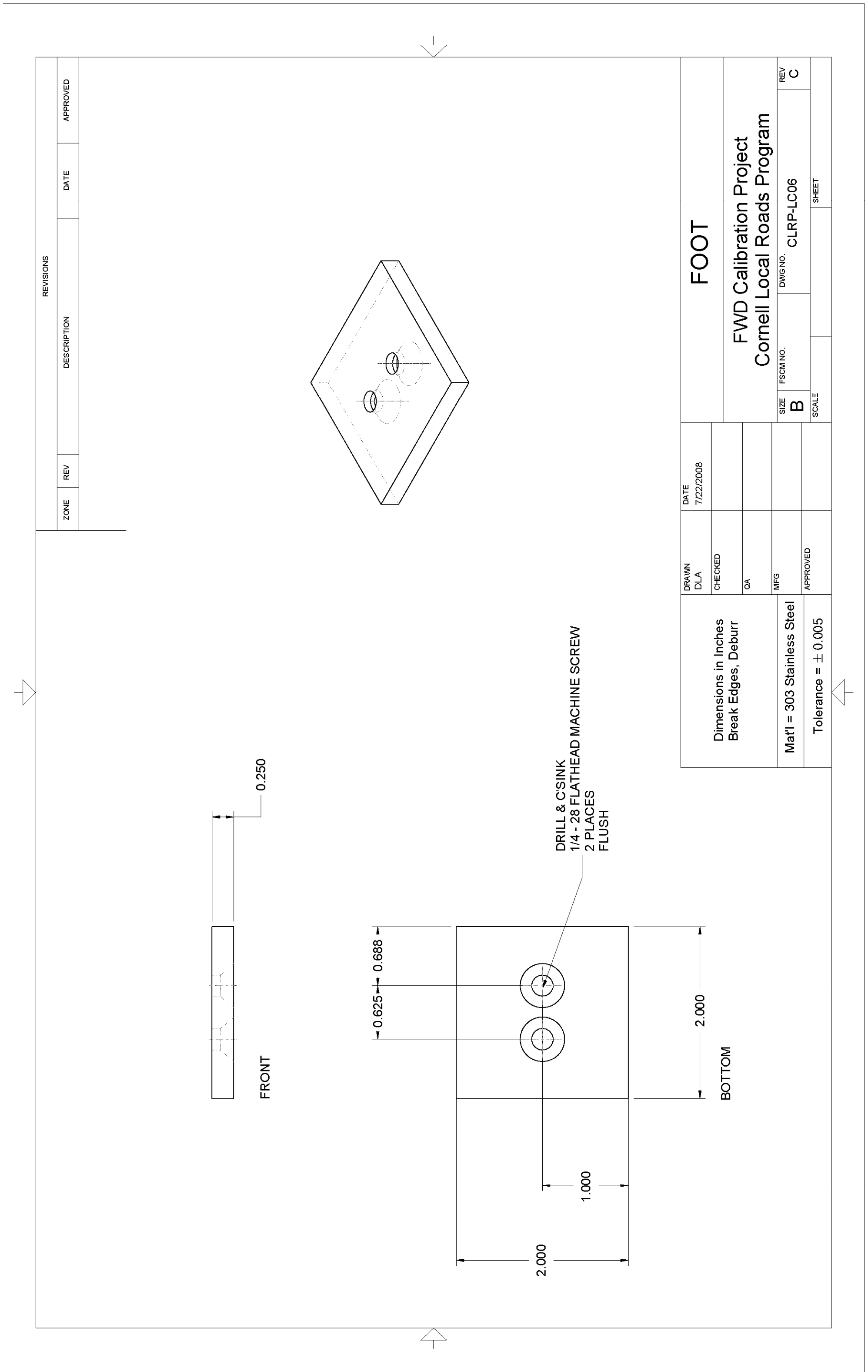

Figure 86. Drawing. CLRP-LC06 Foot.

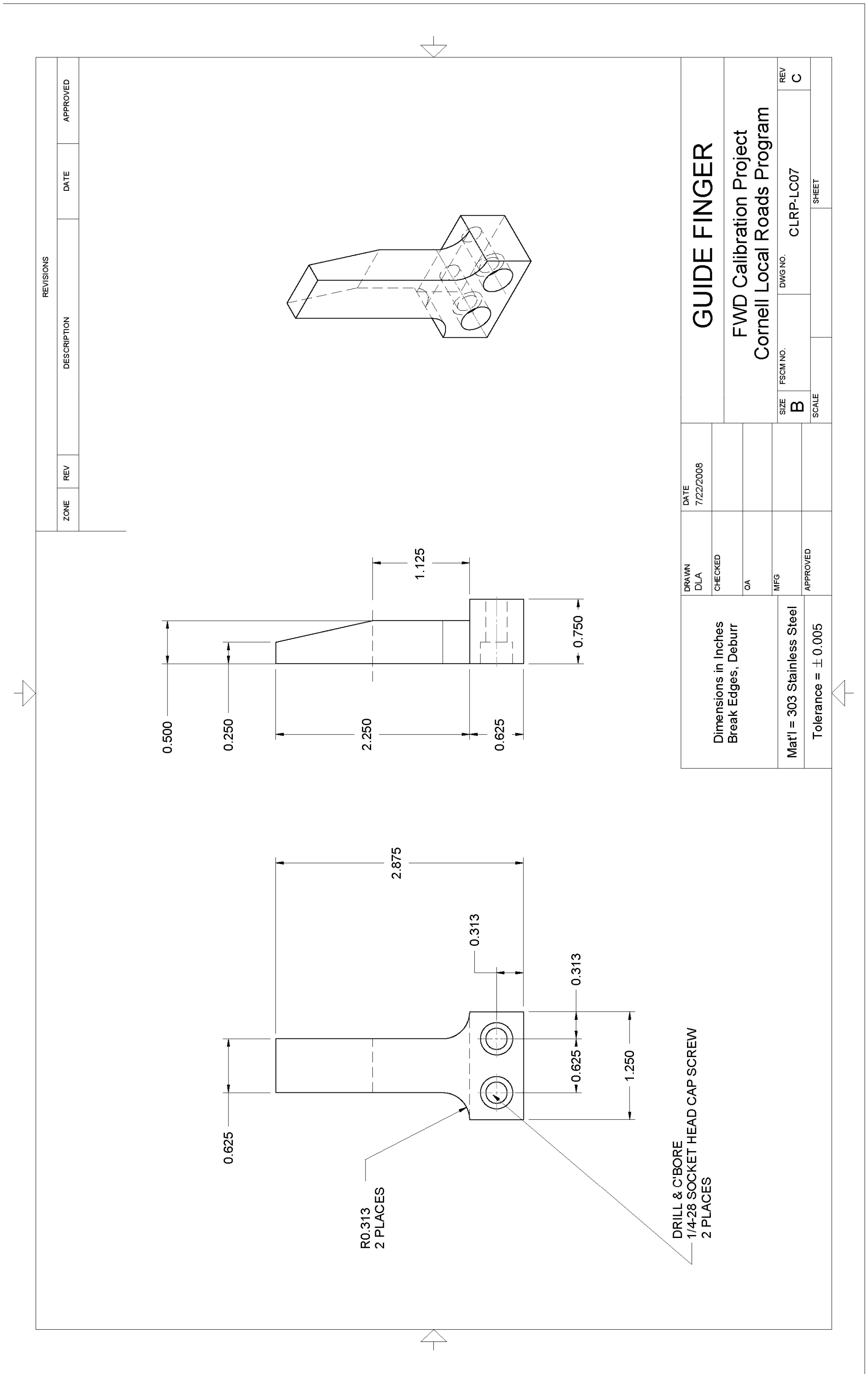

Figure 87. Drawing. CLRP-LC07 Guide Fingers.

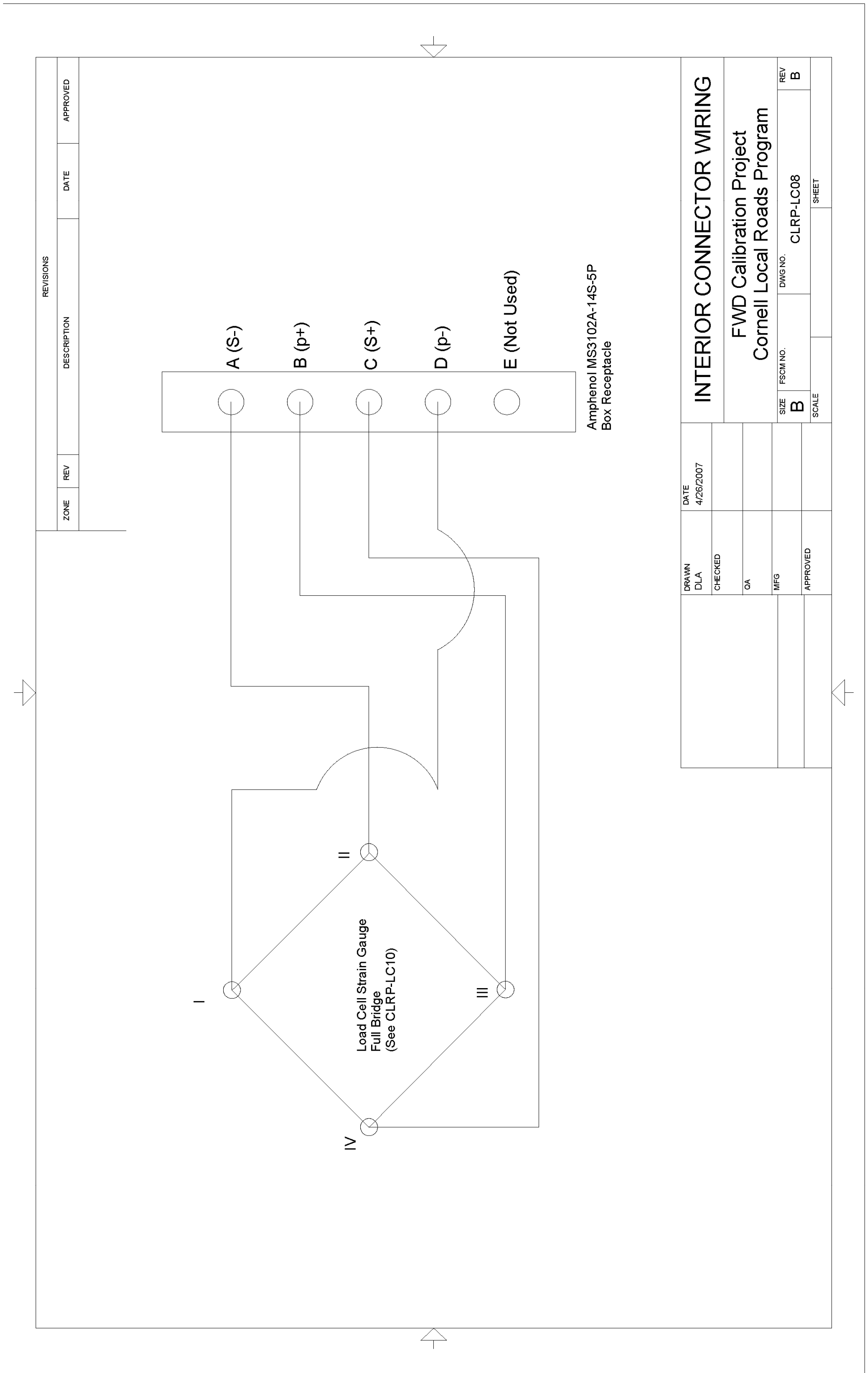

Figure 88. Drawing. CLRP-LC08 Interior Connector Wiring.

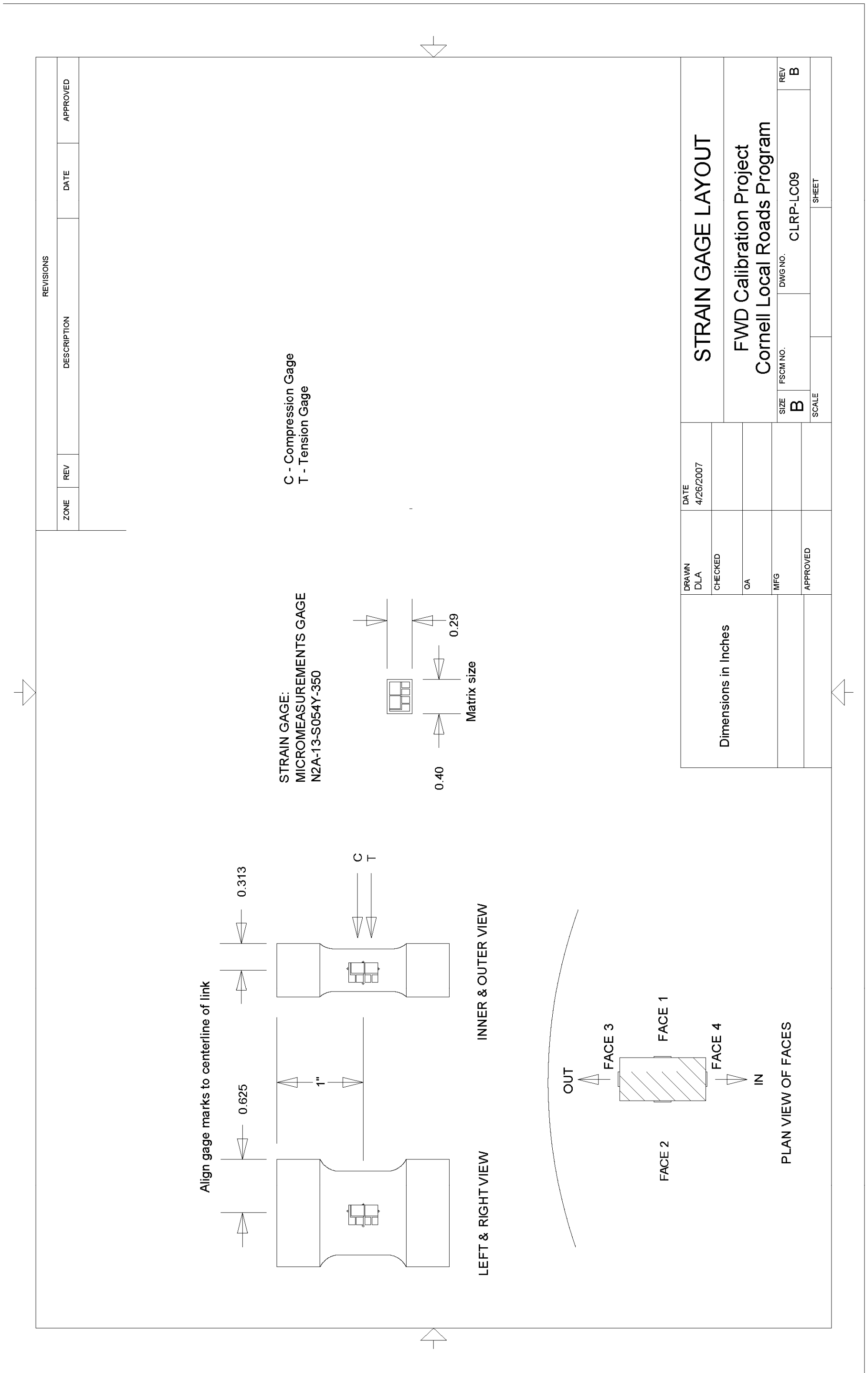

Figure 89. Drawing. CLRP-LC09 Strain Gage Layout.

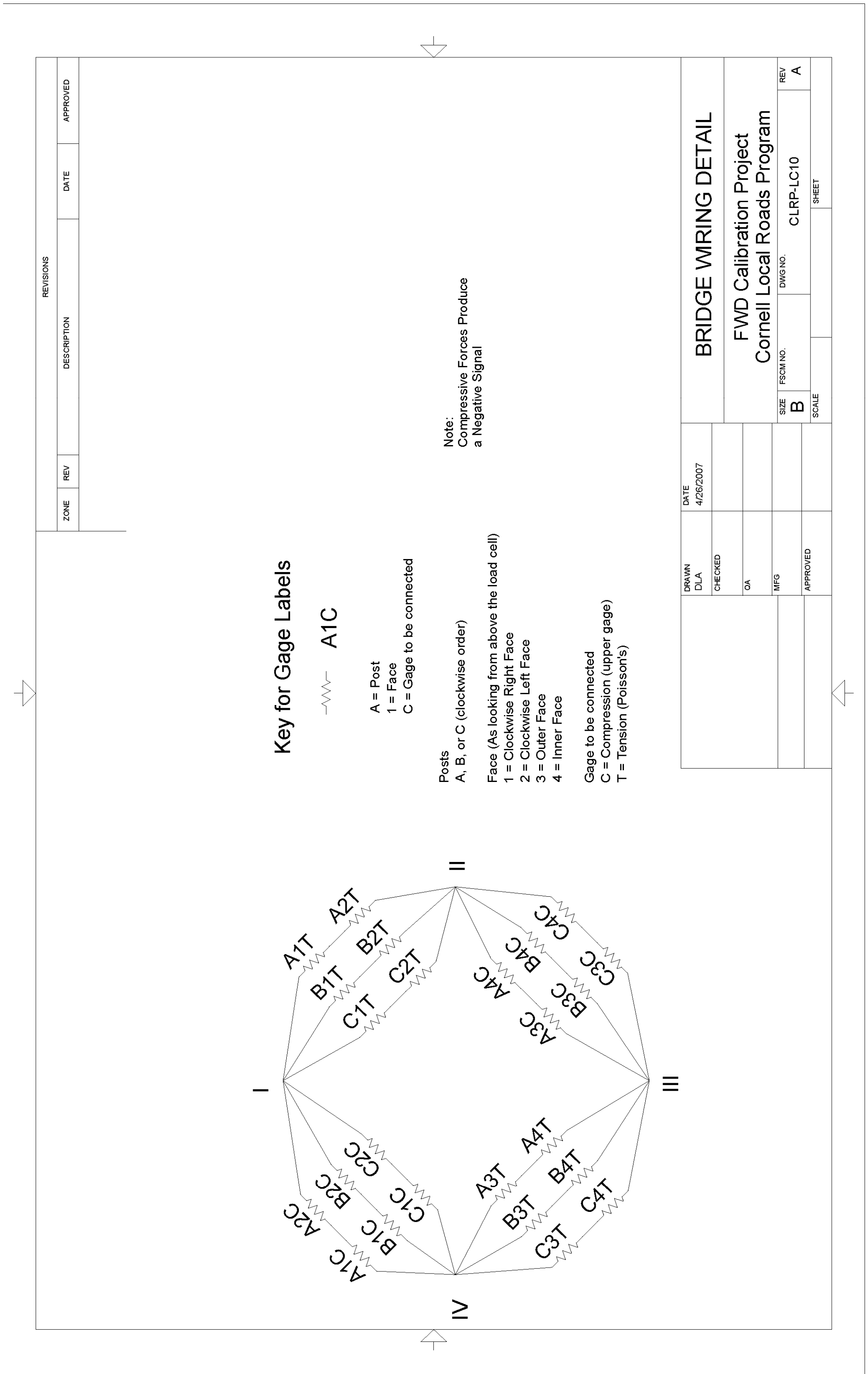

Figure 90. Drawing. CLRP-LC10 Bridge Wiring.

DATA ACQUISITION

BM-DAQ Data Acquisition Bill of Materials

Table 38. Cable diagrams required for data acquisition.

Dwg. 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 data acquisition.

Vendor Part Number	Item	Vendor	Quantity
Model 2310B	Vishay 2310 Signal Conditioner	Vishay Micro-Measurements	1
2310-A20 KIT	Line Cord and Stabilizer Bar Kit	Vishay Micro-Measurements	1
KUSB-3108	Keithley 16-bit USB Data Acquisition Board	Keithley	1
510-0194	BNC to BNC Cable, 10 foot length	Allied Electronics	1
885-4969	BNC Female to 2 Leads	Allied Electronics	1
607-7177	Molex 38331-5608 Power Connector	Allied Electronics	1
566-8723	Belden 8912, 2 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-MS3106A-14S-5S	Amphenol MS3106A 14S-5S Straight Plug	Mouser Electronics	1
2062325	Resistors, 2.2 kΩ, ¼ Watt, 5% Carbon Film	Radio Shack	2
2103233	Terminal Strip, 5 Position	Radio Shack	1
2062543	Pushbutton, Momentary, 1.5 A	Radio Shack	1

Vendor Part Number	Item	Vendor	Quantity
278-0232	Enclosure, Black Plastic	Allied Electronics	1
91772A123	Pan Head Philips Machine Screw, 18-8 Stainless Steel, #5-40 x 5/16" Length	McMaster-Carr	1
91841A006	Nut, 18-8 Stainless Steel, #5-40 Thread, 7/64" Height	McMaster-Carr	1
	Velcro, Hook and Loop, Adhesive Backed, Industrial Strength	Local Hardware Store	12 in.
	USB Memory Drive, minimum 256 MB	Local Computer Supply	1

Table 40. Vendor contact information.

Vendor	Web site	Notes
McMaster-Carr	www.mcmaster.com	See Web site for specific contact information located in the 'About Us' section
Mouser Electronics	www.mouser.com	See Web site for specific contact information located in the 'Contact Us' section
Allied Electronics	www.alliedelec.com	See Web site for specific contact information located in the 'Customer Service' section
Radio Shack	www.radioshack.com	See Web site for specific contact information located in the 'Contact Us' section
Keithley Instruments	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

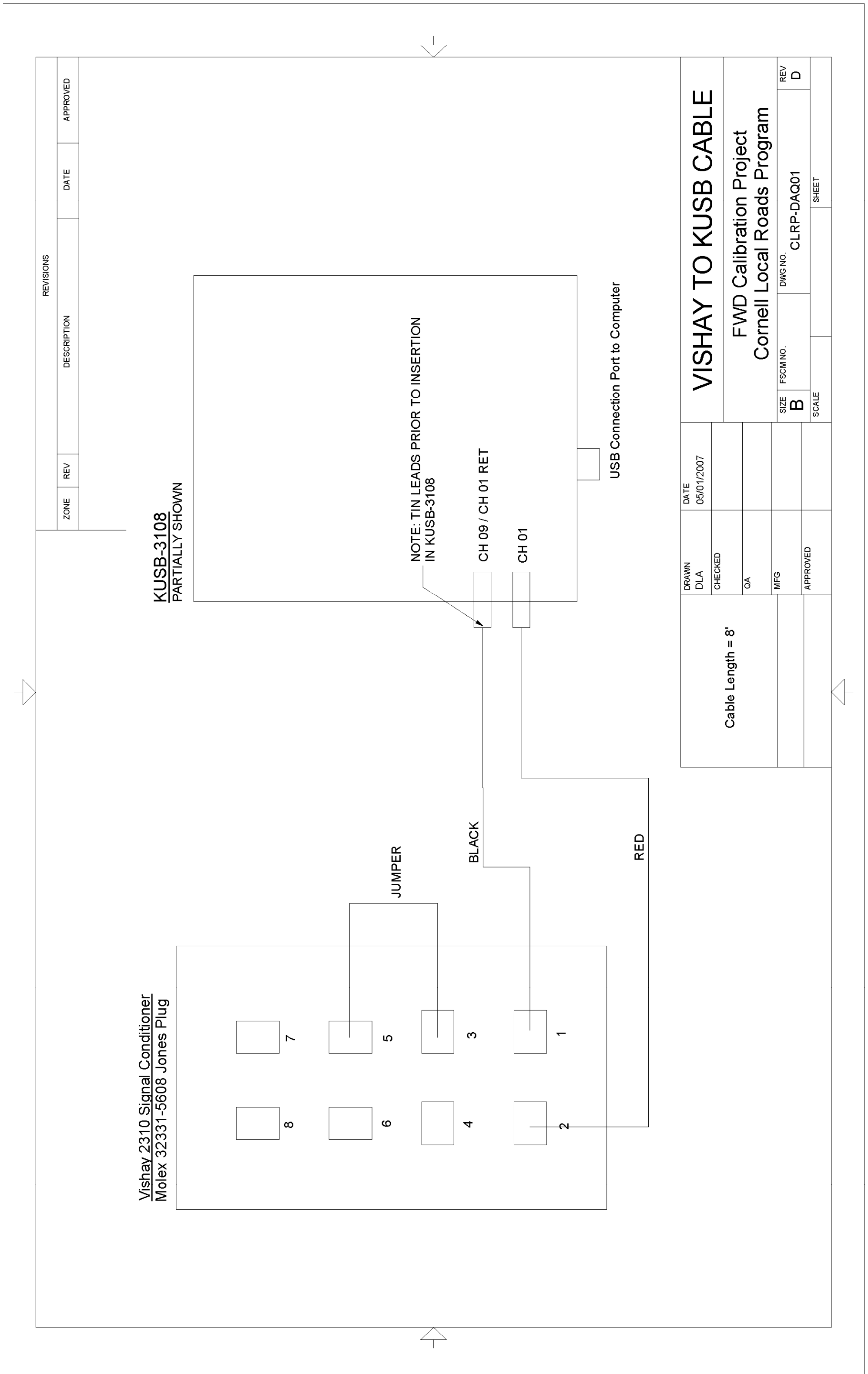

Figure 91. Drawing. CLRP-DAQ01 Vishay 2310 to DAQ Cable.

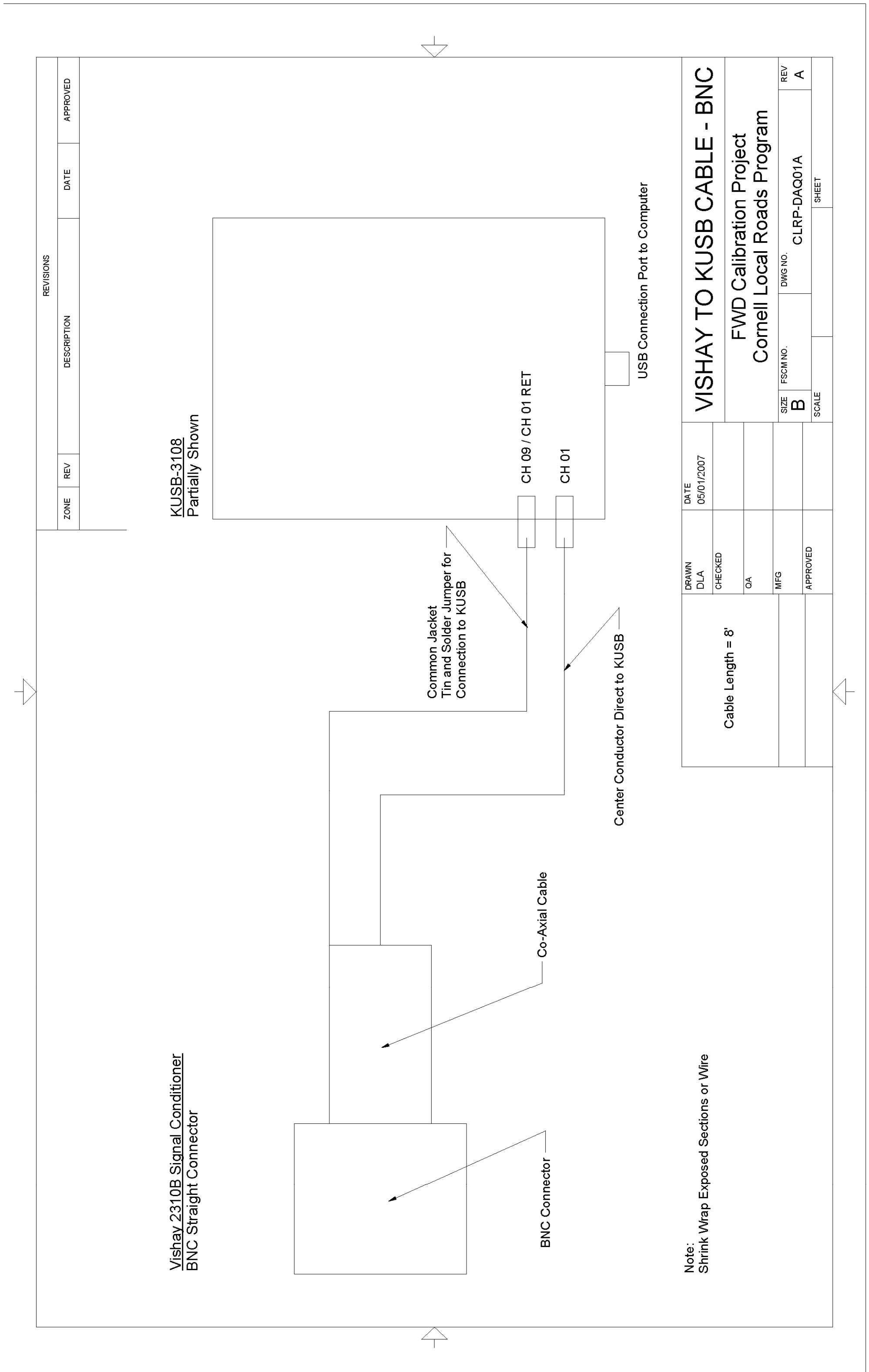

Figure 92. Drawing. CLRP-DAQ01A Vishay 2310B BNC to DAQ Cable.

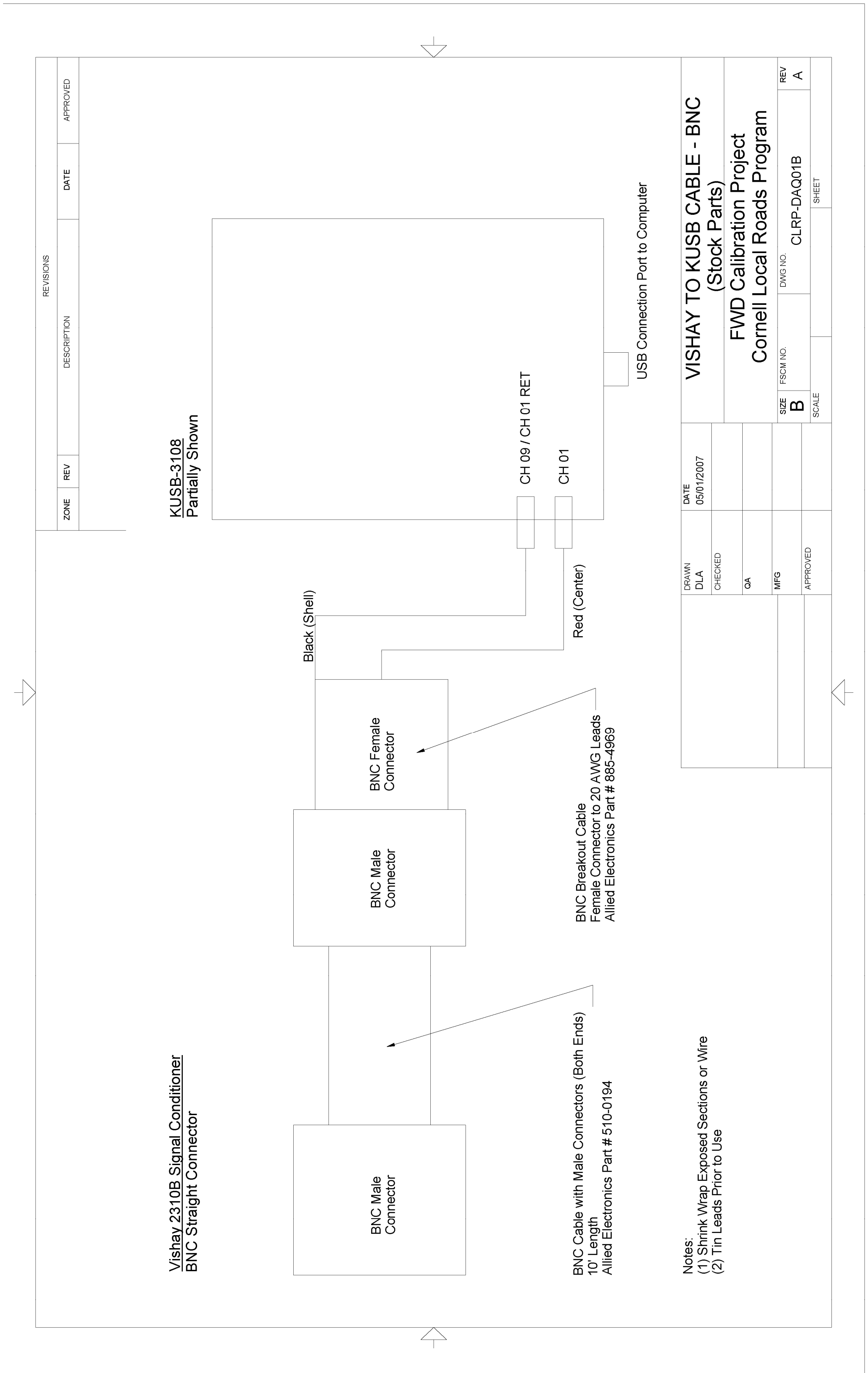

Figure 93. Drawing. CLRP-DAQ01B Vishay 2310B BNC to DAQ Cable (Stock Parts).

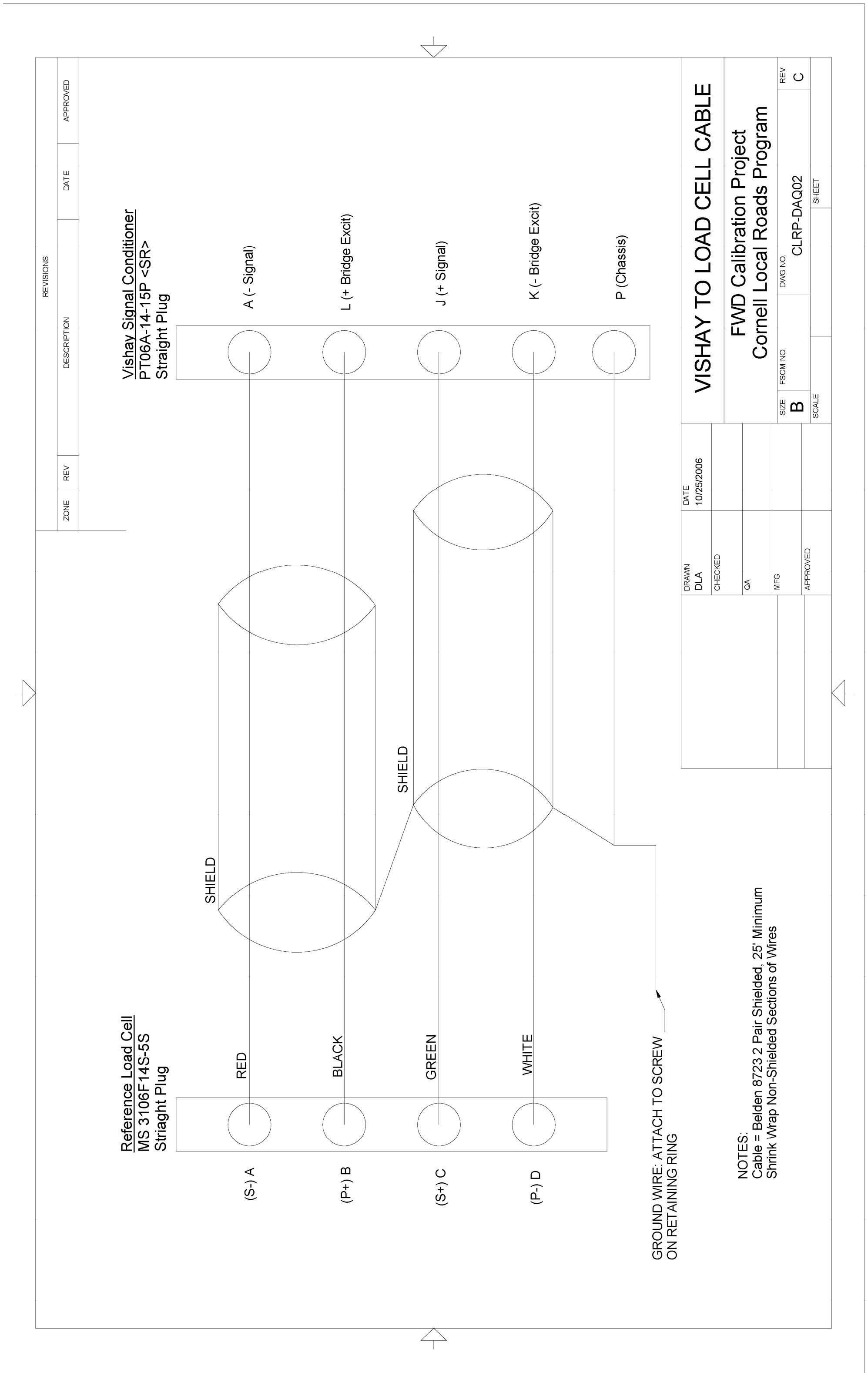

Figure 94. Drawing. CLRP-DAQ02 Vishay to Load Cell Cable.

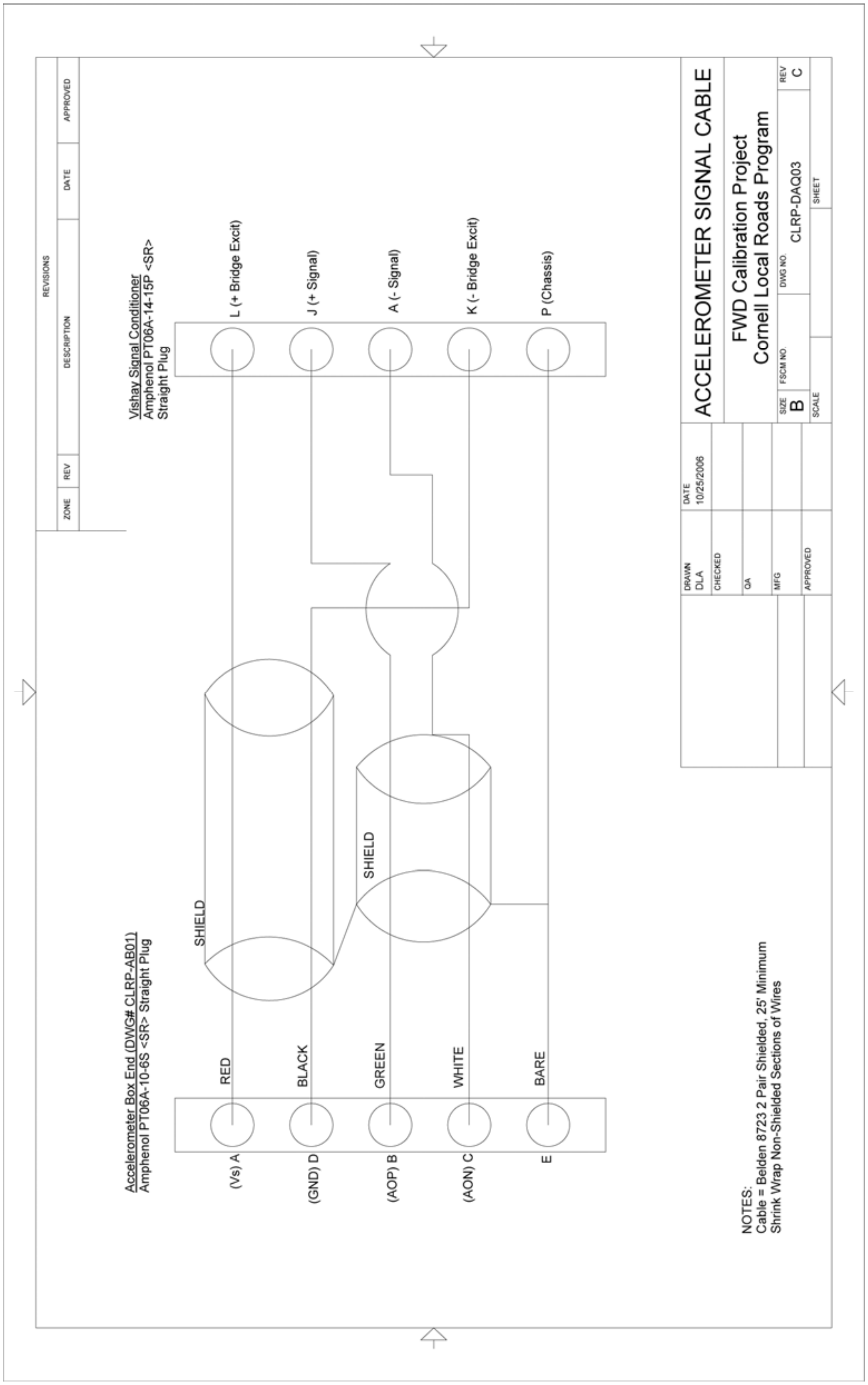

Figure 95. Drawing. CLRP-DAQ03 Accelerometer Signal Cable.

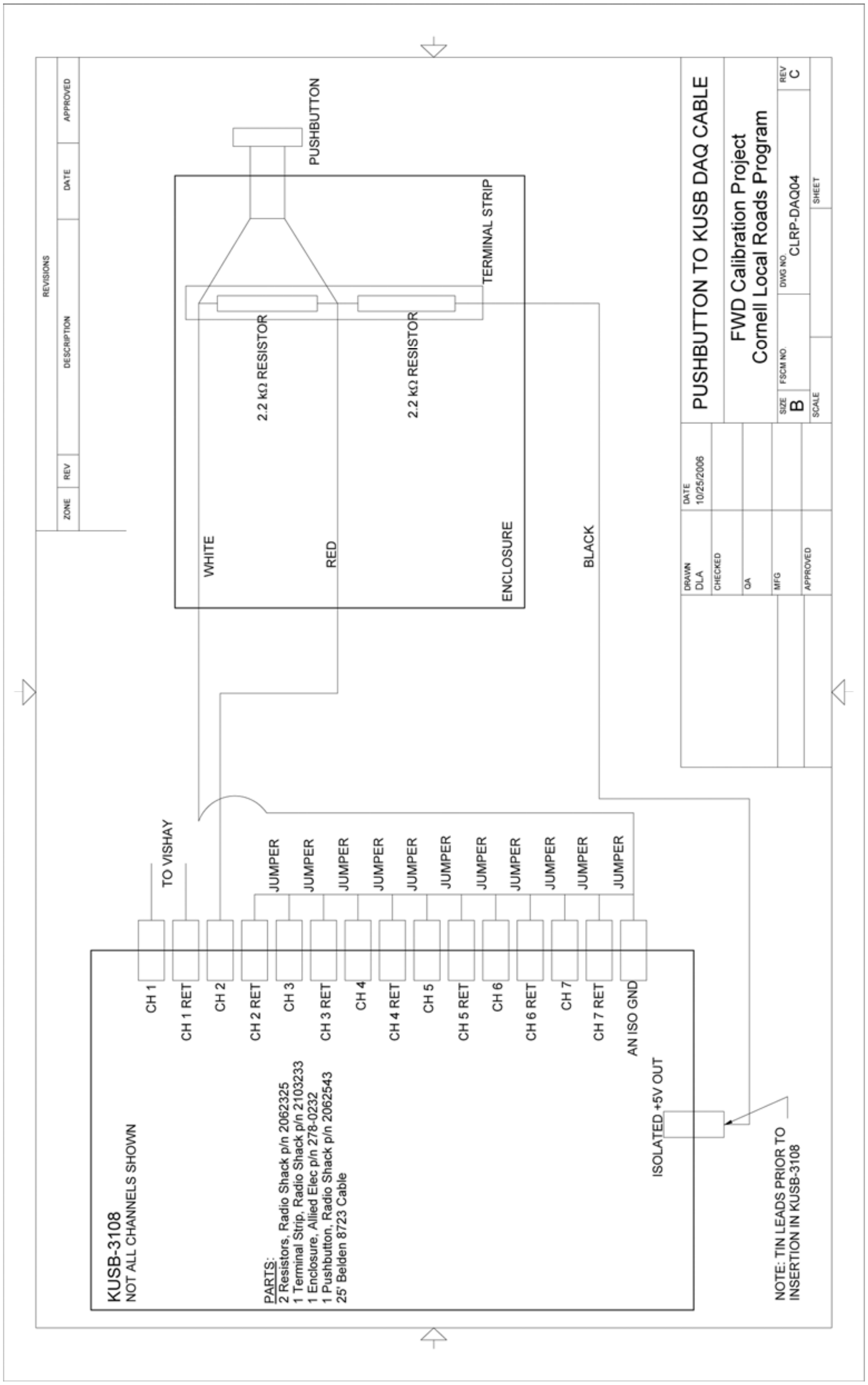

Figure 96. Drawing. CLRP-DAQ04 Pushbutton to KUSB DAQ Cable.

APPENDIX VI—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 Falling Weight Deflectometer (FWD) calibration system:

- 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 data acquisition board and Vishay signal conditioner)
- Portable computer

The instructions provided here assume the use of the *WinFWDCal* software package.

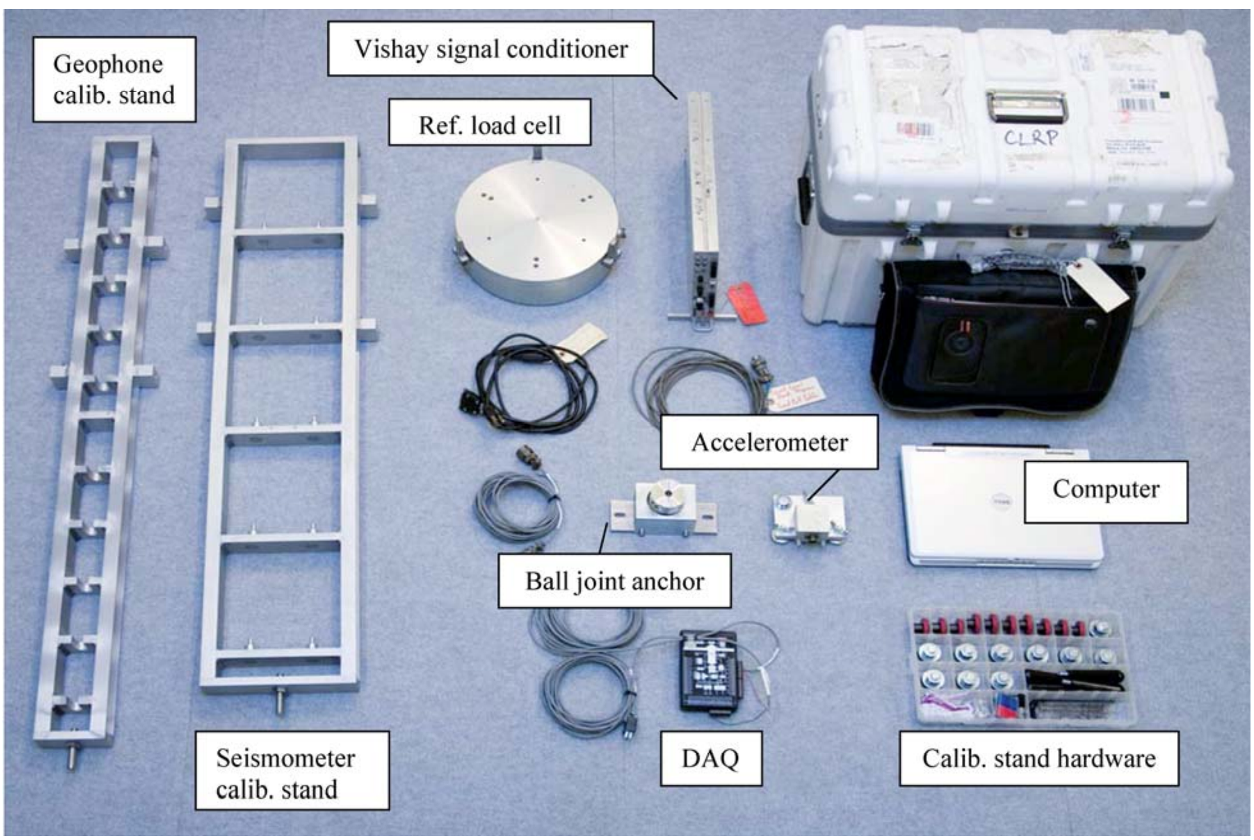

Figure 97. Photo. Calibration system components.

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 10 to 38 C (50 to 100 F).
- A stable humidity between 40 percent and 90 percent.
- Good security cabinets for calibration equipment.

TEST PAD

The test pad for FWD calibration is required to have the following specifications (refer to drawing number CLRP-CC01):

- 4.0 by 4.5 m (12 by 15 ft), with a 2.5-m (8 ft) wide (1.75 m (5 ft)) min. allowable) clear zone around the perimeter to allow for maneuvering of the FWD and the calibration equipment.
- A 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 1.5 mm (1/16 in,) or more, it should be replaced.
- Isolated from the surrounding floor by impregnated felt bond breaker, or sawed and caulked joint.
- Test pad should deflect 500±100 microns (20±4 mils) close to the FWD at a peak dynamic load of 71 kN (16,000 lbf).

REFERENCE LOAD CELL

Parts and Tools

Table 41. Parts and tools for load cell calibration.

Tool/Equipment	Quantity	Notes
Reference Load Cell Assembly	1	DWG# CLRP-LC01
¼-28 x 1" Socket Head Cap Screw	6	McMaster-Carr p/n 92196A325
¼-28 x ¾" Socket Head Cap Screw	6	McMaster-Carr p/n 92196A321
Vishay Signal Conditioner	1	
Load Cell Signal Cable	1	DWG# CLRP-DAQ02
3/16" Hex Wrench	1	
Torque Wrench	1	Capable of 100 in-lbf

Figure 98. Photo. Reference load cell assembly.

Calibration

The reference load cell requires an annual calibration to ensure its accuracy. To calibrate the reference load cell, a universal testing machine with a load capacity of 120,000 lbf or more is needed. Although the load cell is calibrated to only 24,000 lbf, the higher capacity of the testing machine assures that the test frame will be adequately rigid.

The Vishay 2310 signal conditioner, Keithley KUSB-3108 data acquisition board, 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 is changed, then the load cell needs a new calibration.

The bolts that hold the cover plate and feet onto the load cell 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 a recalibration.

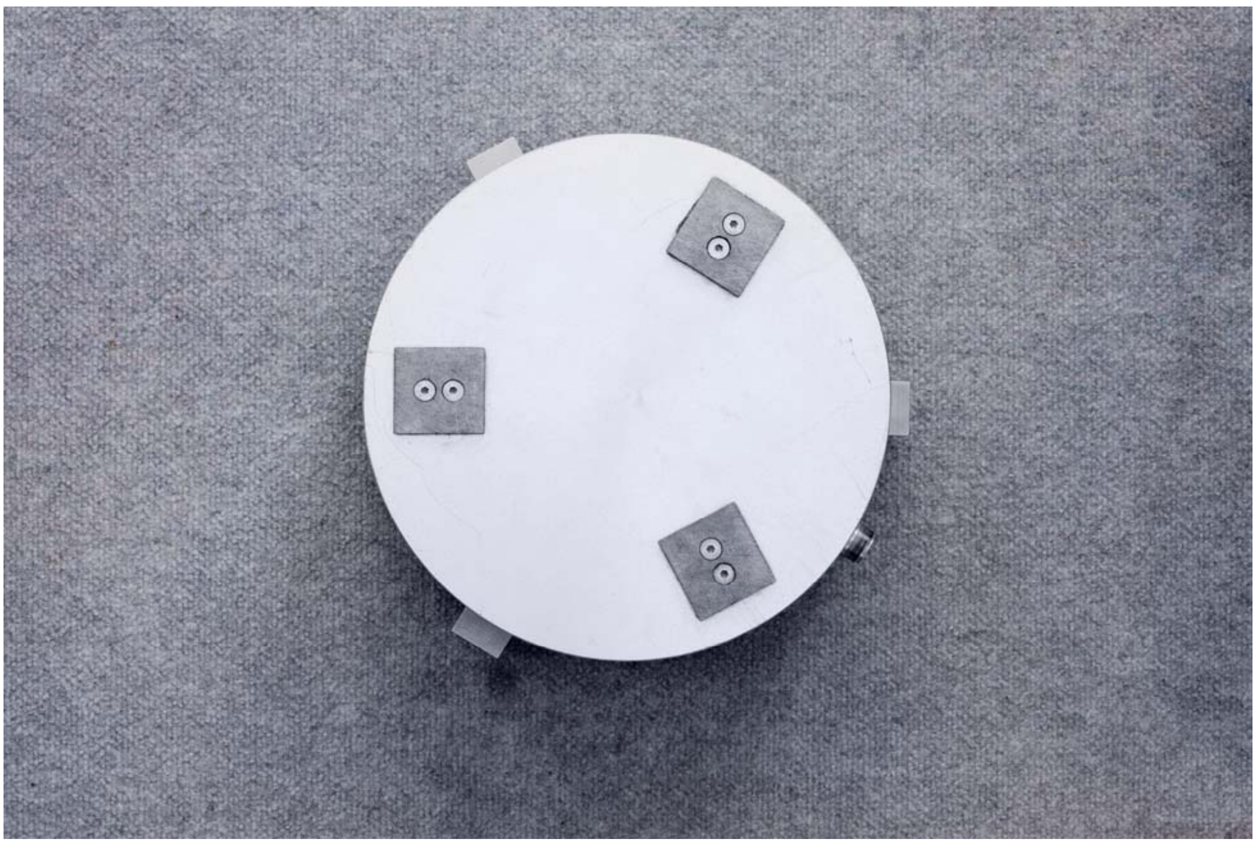

Figure 99. Photo. Bottom view of the reference load cell.

Use

1. During FWD load cell calibration, first ensure that the guide fingers are tightened to the load cell body.

2. Attach the signal cable form the load cell to the signal conditioner, and allow the electronics to warm up for at least one hour.

3. Carefully align the reference load cell under the FWD load plate being sure that the guide fingers and the load plate do not interact.

4. Follow the on-screen instructions provided by *WinFWDCal* for a complete load cell calibration.

Figure 100. 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. 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
¼" Masonry Drill Bit	1	
½" Masonry Drill Bit	1	
3/8" Inside Diameter Washers	2	McMaster-Carr p/n 94744A273
3/8"-16 x 1-1/4" Hex Head Cap Screw	2	McMaster-Carr p/n 91309A626

Figure 101. 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 400 - 600 microns (16 – 24 mils) at a 71 kN (16,000 lbf) load where the ball joint will be located.

2. Using the base bar from the ball joint anchor (B04, DWG number CLRP-BJ03) as a guide, mark where the two anchors will be installed. The holes should be 6 inches apart from center to center.

3. Drill pilot holes at the anchor locations using a ¼” masonry bit and, if available, a hammer drill. The holes should be slightly greater than 1 ½” deep to ensure that the anchor rests below the surface of the concrete. Ideally, the holes will be drilled about 1/16” deeper than the height of the anchor.

4. Drill the final holes for the anchors with a ½” bit. Do not use a hammer drill for these holes.

5. Clean the debris from holes.

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, being 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, as this will damage the anchor. If necessary, remove the anchor and drill a little deeper.

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.

Figure 102. Photo. Concrete anchor installation, steps 3, 6, and 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	DWG number CLRP-BJ01
B03	Clamp Base	1	DWG number CLRP-BJ02
B04	Base Bar	1	DWG number CLRP-BJ03
B05	Rest Stop	1	DWG number 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	Locktite #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

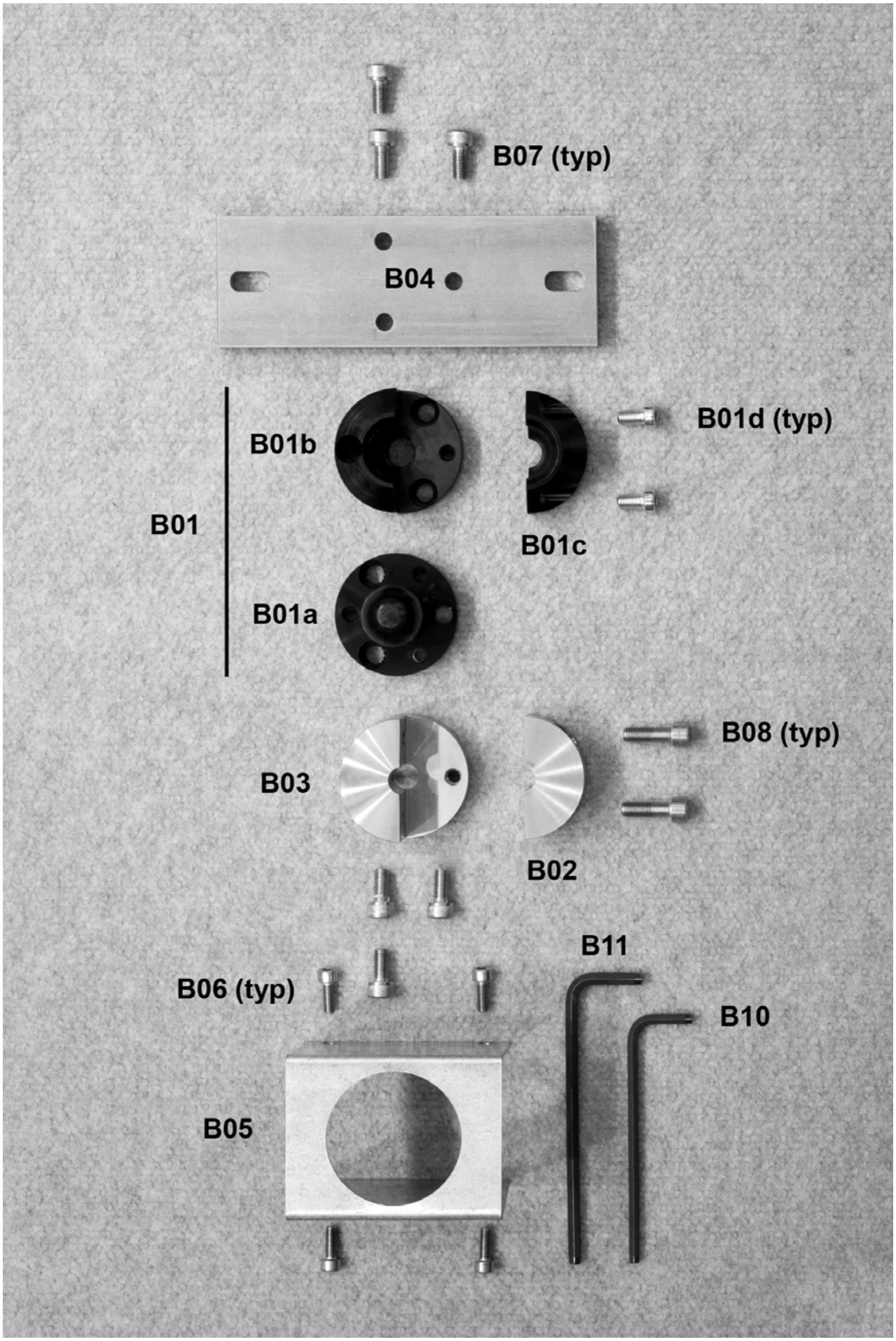

Figure 103. Photo. Parts and tools for ball joint assembly.

Assembly

1. Attach the clamp (B02) to the clamp base (B03) with two M8 x 25 mm socket head cap screws (B08). Note: Do not apply Locktite 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. Using Locktite and three M8 x 16 mm socket head cap screws (B07) 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 Locktite when installing the screws (B01d).

5. Attach the base bar (B04) to the completed ball joint assembly with Locktite (B09) and three M8 x 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 104**.**

6. Slide the rest stop (B05) over the ball joint assembly and secure it to the base bar (B04) with four M6 x 16mm socket head cap screws (B06).

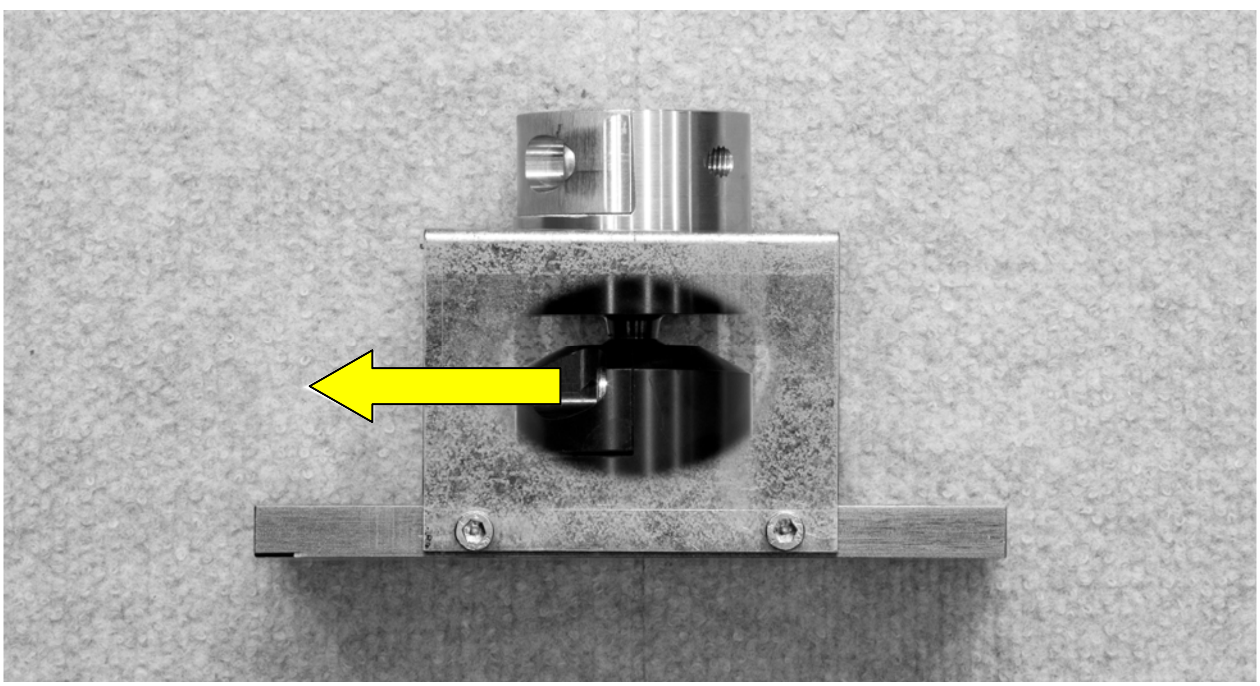

Figure 104. Photo. Proper alignment of ball joint screws.

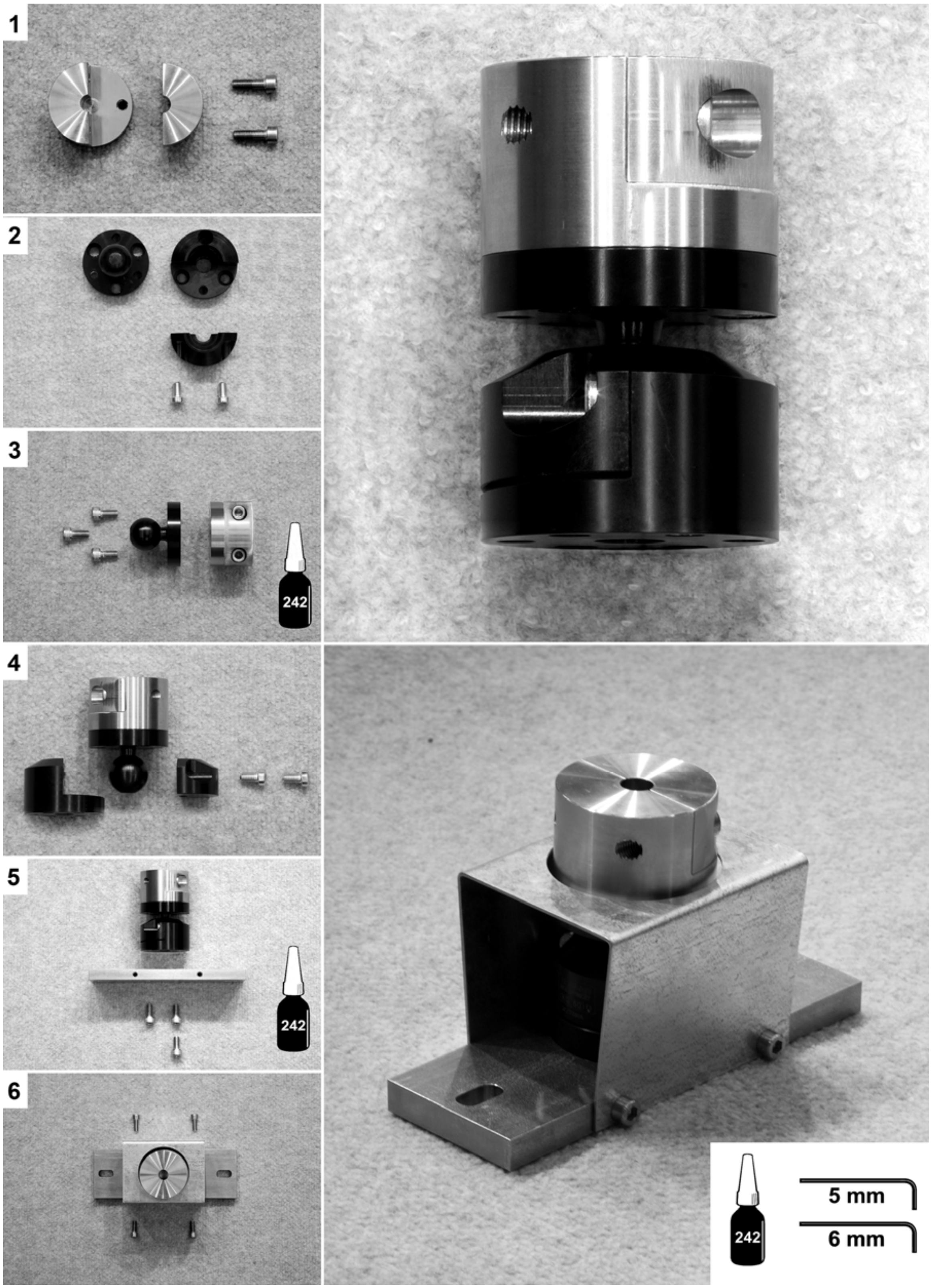

Figure 105. Photo. Assembly of the ball joint anchor.

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	DWG number CLRP-AB05
A02	Box Bottom	1	DWG number CLRP-AB02
A03	Box Top	1	DWG number CLRP-AB03
A04	Calibration Platter	1	DWG number CLRP-AB04
A05	#4-40 x 3/8” Flat Head Phillips Machine Screw	4	McMaster-Carr p/n 96877A209
A06	#4-40 x ½” 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 ¼” Fillister Head Phillips Machine Screw	7	McMaster-Carr p/n 91737A072
A09	#10-24 x ½” Knurled Head Thumbscrew	2	McMaster-Carr p/n 91746A876
A10	Bubble Level, Glass Surface Mount	1	McMaster-Carr p/n 2198A85
A11	Leveling Mount w/ Polyethylene Base, 3/8”-16 x 1” Stud	3	McMaster-Carr p/n 23015T64
A12	3/8”-16 Locking Wig Nut	3	McMaster-Carr p/n 98520A145
A13	#1 Phillips Head Screwdriver	1	
A14	Locktite #242 Threadlocker	1	

Assembly

1. The accelerometer is attached to the box top (A03) using two #4-40 x ½” 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 106. 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 ¼” fillister head machine screws (A08) and medium strength Locktite #242 (A14).

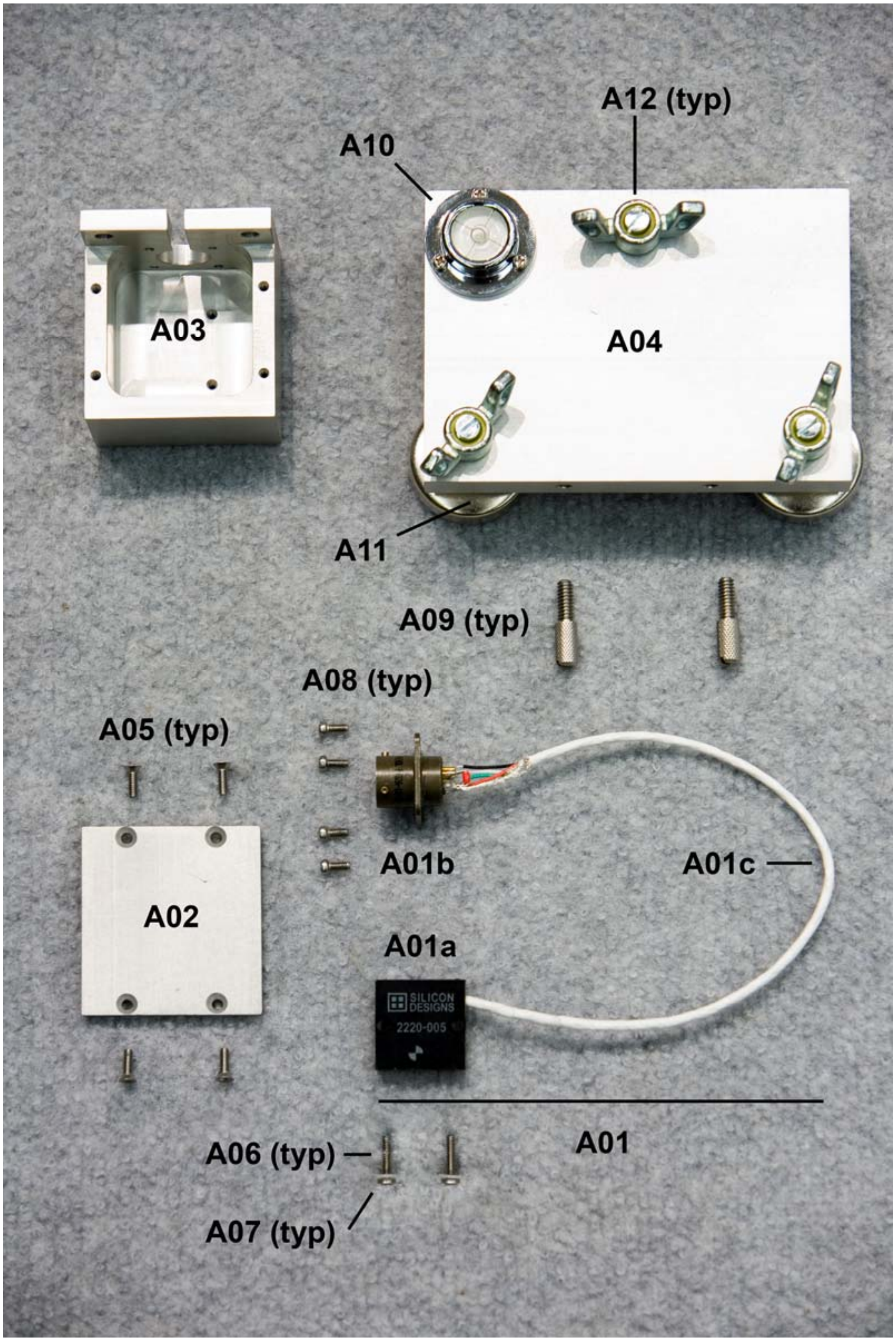

Figure 106. Photo. Parts for accelerometer box assembly.

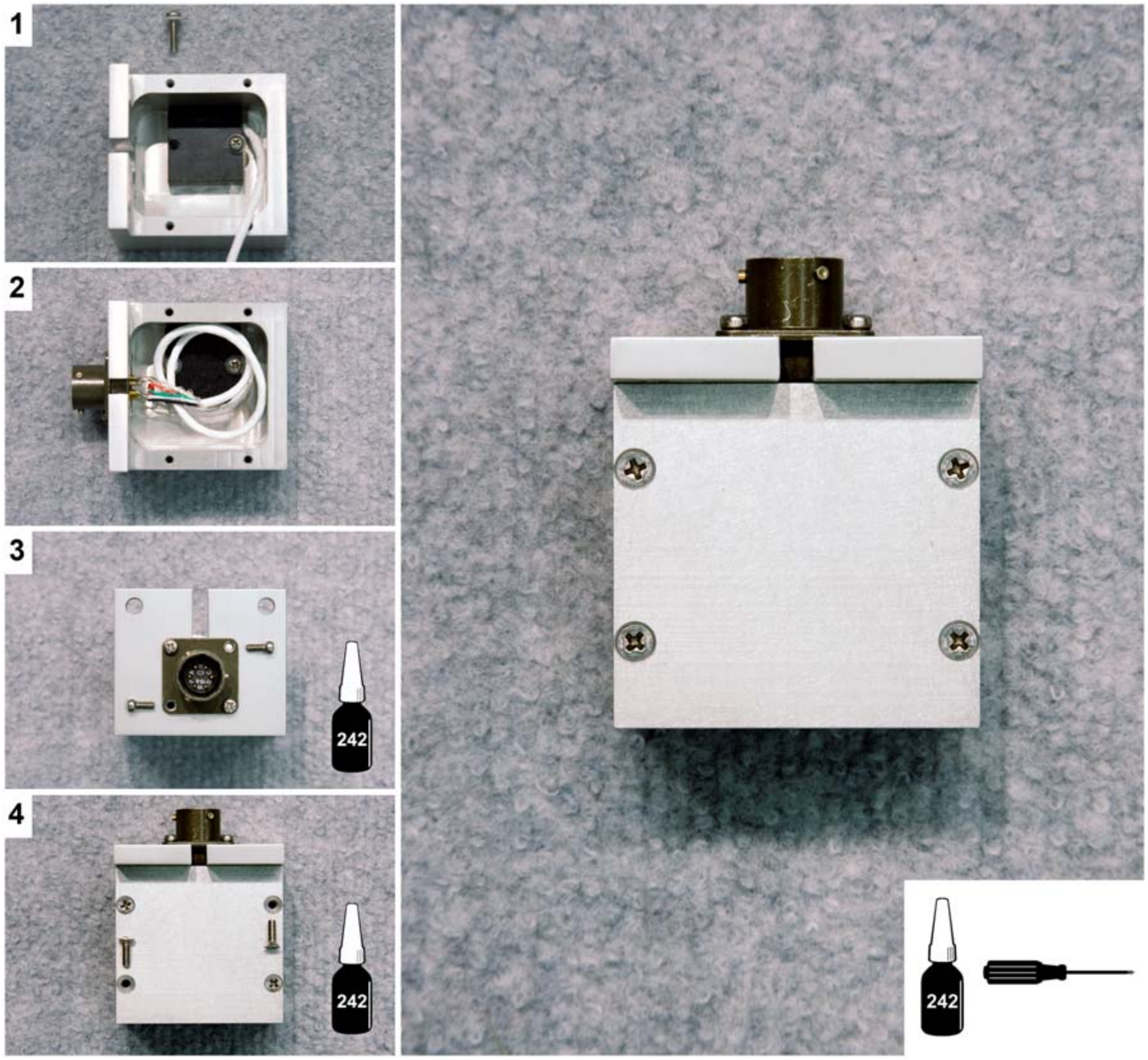

Figure 107. Photo. Accelerometer box assembly.

4. The box top and box bottom (A02) are mated together with four #4-40 x 3/8” flat head machine screws (A05) and medium strength Locktite #242 (A14). The final assembly is shown in
5. Figure 107.

Calibration Platter Assembly

1. Attach the bubble level (A10) to the calibration platter (A04) with three #4-40 x ¼” 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”-16 locking wing nuts (A12)

3. The accelerometer box is attached to the calibration platter with two #10-24 x ½” knurled head thumbscrews (A09) as shown in Figure 108.

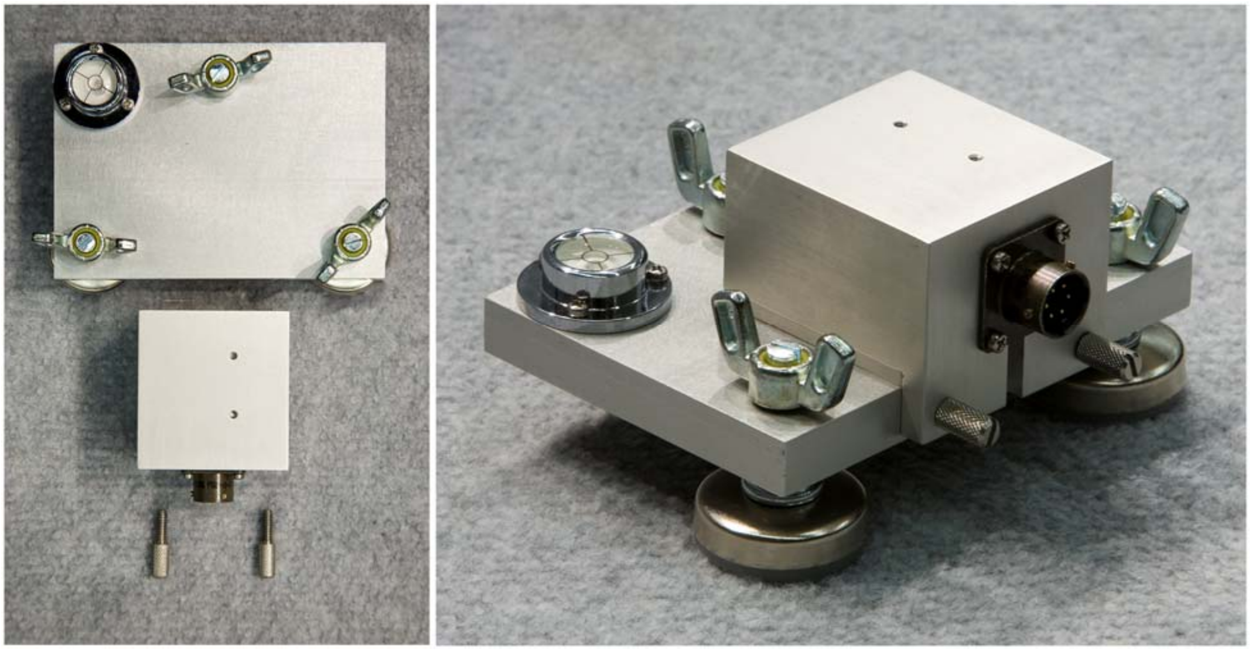

Figure 108. Photo. Accelerometer box attached to calibration platter.

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 hours prior to use.

Accelerometer Calibration

1. Place the calibration platter, with the accelerometer box attached, on a flat surface and level the platter.

2. Remove the thumbscrews and press the accelerometer box on to the calibration platter with a finger.

3. While following the on screen instructions from *WinFWDCal*, continue to press the accelerometer box to the calibration platter.

CALIBRATION STANDS

Parts and Tools

Table 45. Equipment for calibration stand assembly.

No.	Tool/Equipment	Quantity	Notes
S01	Geophone Calibration Stand Assembly	1	DWG number CLRP-GCS01
S02	Seismometer Calibration Stand Assembly	1	DWG number CLRP-SCS01
S03	Phenolic Handle, 3/8”-16 x 1/2” 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” Fillister Head Phillips Machine Screw	6	McMaster-Carr p/n 91737A072 Also No. A08 in this guide.
S06	Carl Bro Geophone Adapters w/ M8-1 mm Threaded Through Hole	10	Morton Machine Works p/n KK-GA02
S07	JILS Geophone Adapter w/ 3/8”-24 Threaded Through Hole	10	Morton Machine Works p/n KK-GA03
S08	3/4” Inside Diameter Washer	10	McMaster-Carr p/n 90126A036
S09	3/8” Inside Diameter Washer	10	McMaster-Carr p/n 94744A273 Also No. B11 in this guide.
S10	3/8”-24 x 5/8” Hex Head Cap Screw	10	McMaster-Carr p/n 92865A212
S11	#10-24 x 1/2” 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

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” 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** 111 for an example.

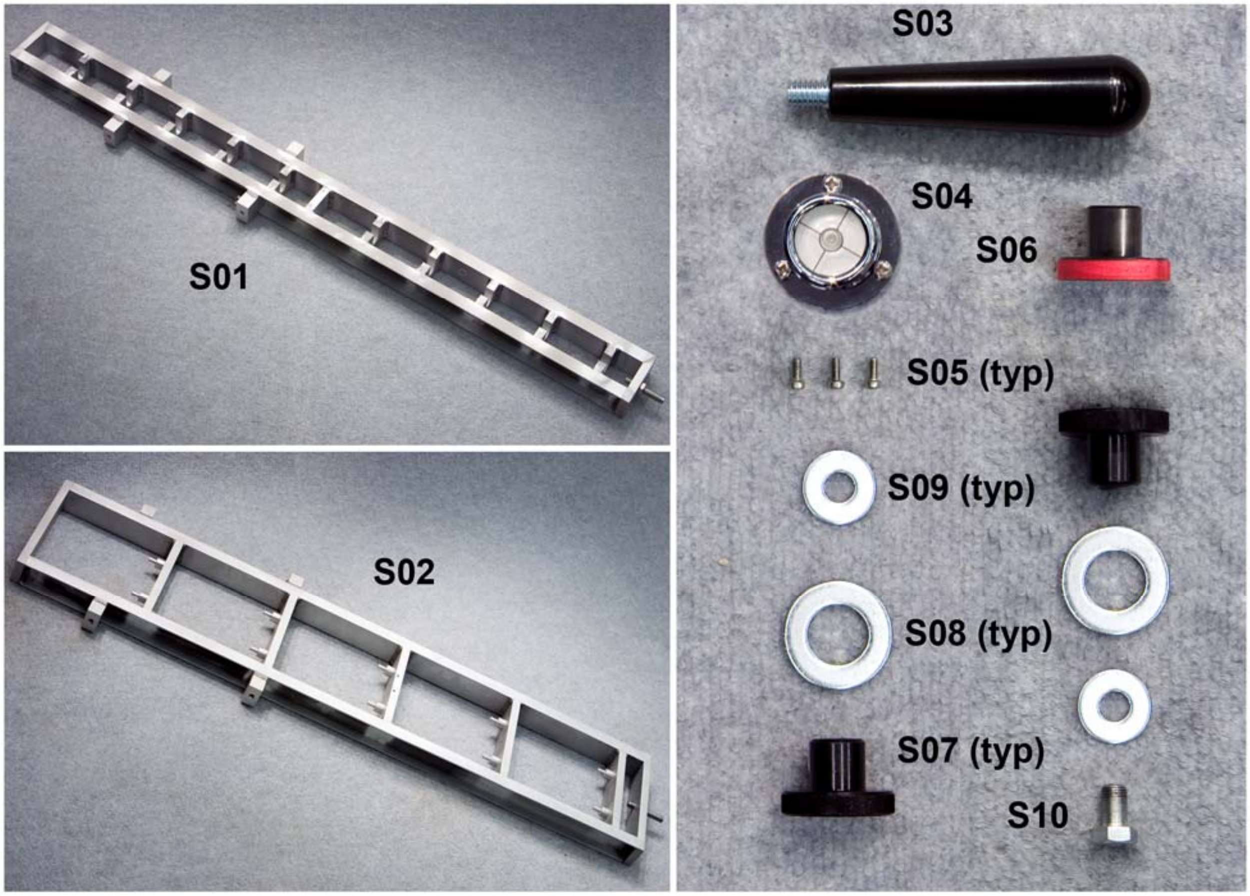

Figure 109. Photo. Equipment for calibration stand assembly.

Figure 110. Photo. KUAB Geophone Adapter Equipment.

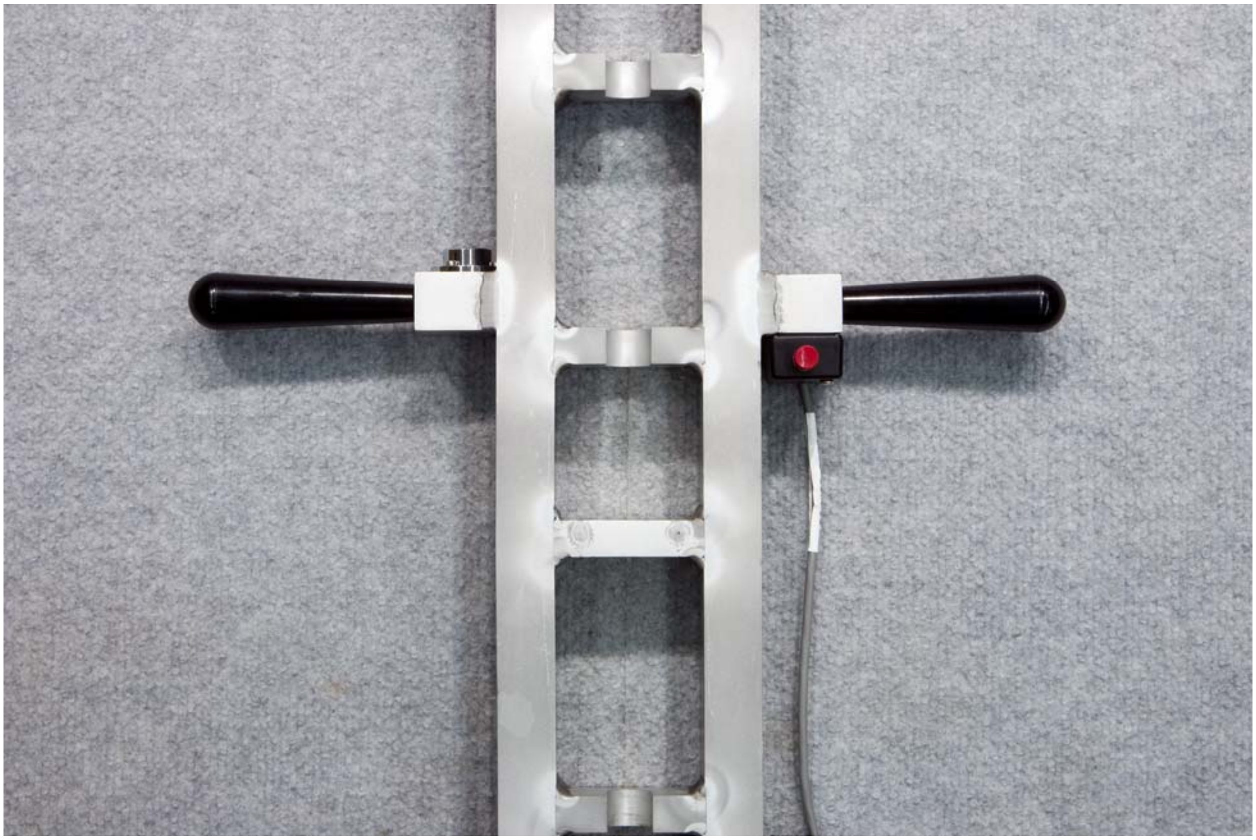

Figure 111. Photo. Calibration stand with handles, bubble level, and pushbutton.

4. For both the geophone calibration stand and the seismometer calibration stand, the connector pin is fastened to the stand with medium strength Locktite #242. **Figure 117** shows the geophone calibration stand with a connector pin attached.

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." 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, as made by Carl Bro, Dynatest, KUAB, and JILS.

The Carl Bro geophones 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" inside diameter washer (S08) placed between the adapter and shelf of the stand and a 3/8" inside diameter washer (S09) placed between the geophone and the

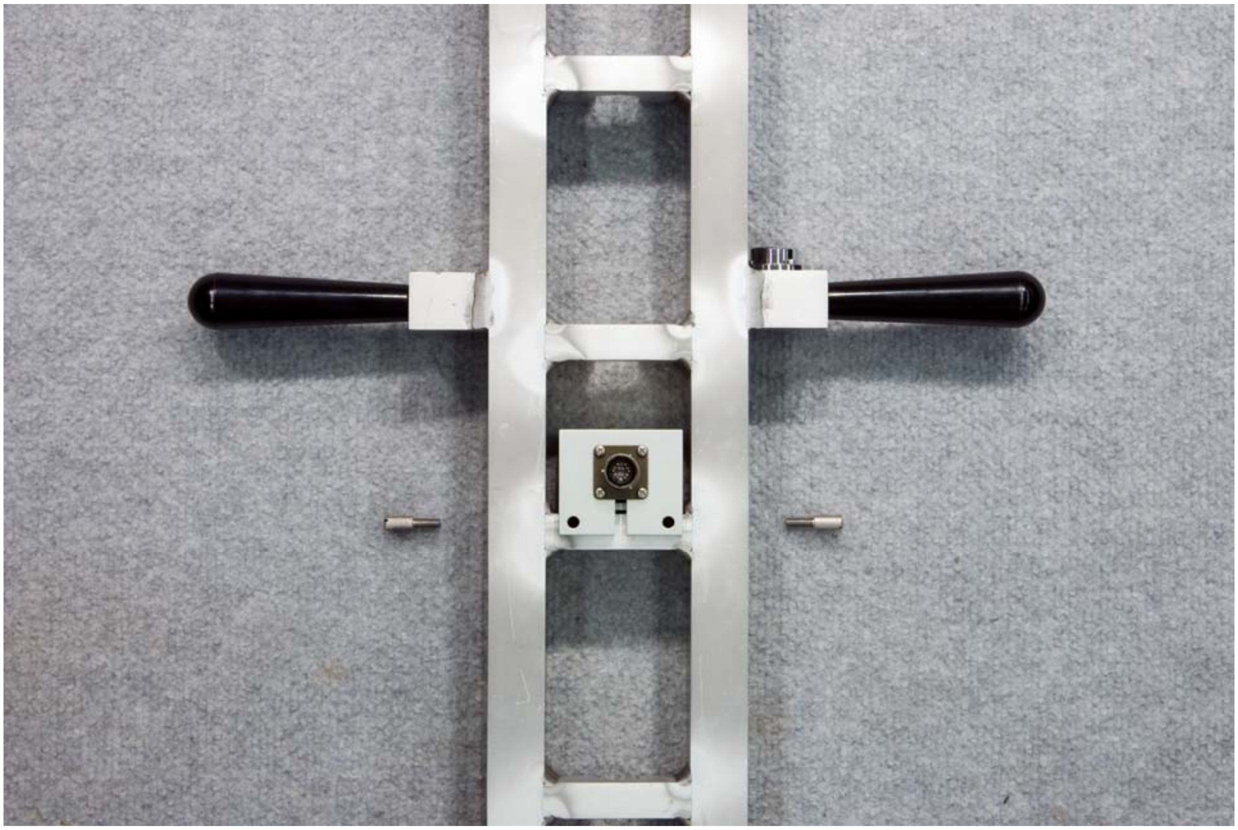

Figure 112. Photo. Placement of the accelerometer box on the geophone stand.

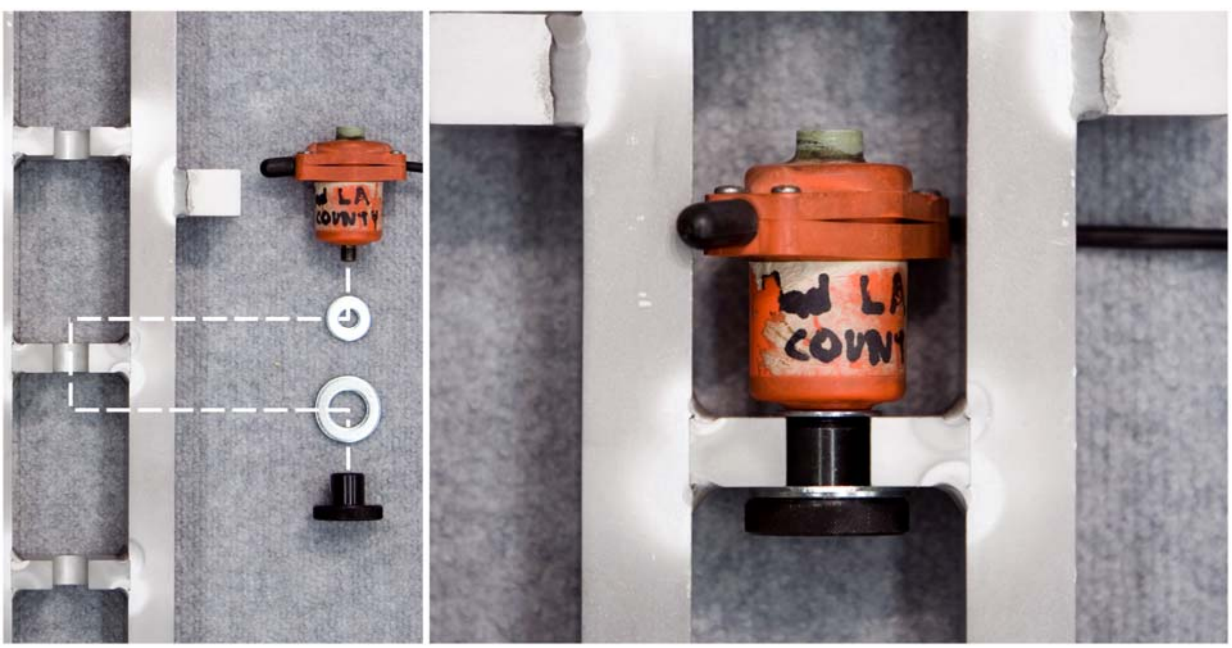

Figure 113. Photo. Attachment of a JILS or Carl Bro geophone to the stand.

Figure 114. Photo. Attachment of a Dynatest geophone to the stand.

shelf. **Figure** 113 shows a JILS geophone and adapter fastened to the stand. Carl Bro geophone adapters (S06) have different size threading and are painted red.

The Dynatest geophones use a magnet to couple to the stand. To accomplish this, the JILS adapter (S07) is turned upside down and fastened to the stand with a 3/8”-24” x 5/8” hex head cap screw (S10) as shown in
Figure 114. 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 115. The modifications to the knob are to drill and tap for a

Figure 115. Photo. Attachment of a KUAB geophone adapter.

#10-24 machine screw thru the length of the knob, and to mill out a 1/8” deep by 1” diameter recess at the top of the shank to allow the magnet assembly to fit inside.

For the seismometer calibration stand, the seismometers are aligned in a two-column configuration as shown in . Tighten the setscrew at the bottom of the seismometer onto the standoffs on the stand.

Figure 116. Photo. Seismometer stand with sensors attached.

Use

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 in the *WinFWDCal* program.
4. Velcro the pushbutton to the stand.

To rotate the sensors in the stand, do the following;

- For the 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 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 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.
- For KUAB seismometers, loosen the setscrew at the bottom of the sensor and lift it off of the standoff.

To couple the stand to the ball joint.

For both calibration stands, the connector pin slides into the clamp as shown in Figure **117**. The clamp is then tightened so that the stand cannot be removed.

Figure 117. Photo. Coupling the calibration stand and ball joint anchor.

It is *very* important that the pin extending from the calibration stand be tightly fixed in the stand. Use several drops of Locktite 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. Do not use Locktite on these connections, however.

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 easily to the rest stop.

DATA ACQUISITION EQUIPMENT

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	DWG number CLRP-DAQ01
D01A	Vishay 2310B to KUSB DAQ Cable	1	DWG number CLRP-DAQ01A
D01B	Vishay 2310B to DAQ Cable (Stock Parts)	1	DWG number CLRP-DAQ01B
D02	Vishay to Load Cell Cable	1	DWG number CLRP-DAQ02
D03	Accelerometer Signal Cable	1	DWG number CLRP-DAQ03
D04	Pushbutton to KUSB DAQ Cable	1	DWG number CLRP-DAQ04
D05	Keithley KUSB-3108 16-bit Data Acquisition Board	1	
D06	Vishay 2310 Signal Conditioner	1	

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

Refer to **Figure 118**.

Calibration center PC to Keithley KUSB-3108 data acquisition board (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 how to connect the signal cable to the data acquisition board. The Molex connector (s/n 38331-5608) plugs into the output receptacle in the back of the signal conditioner.

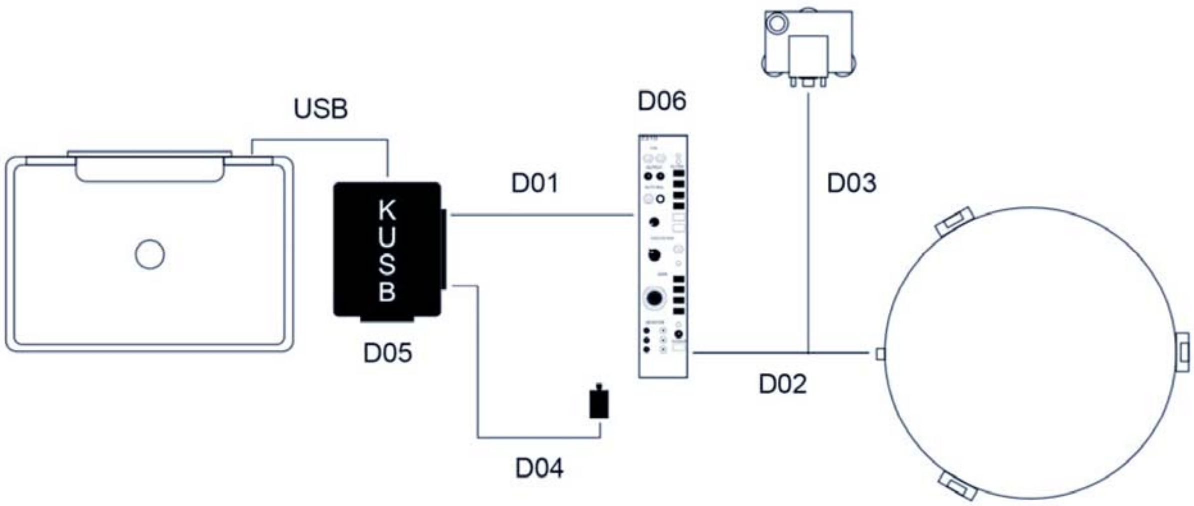

Figure 118. Chart. FWD data acquisition system components and connections.

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 5 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 6 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 how to connect the pushbutton to the data acquisition board

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*	2.0 x 1
Auto Balance	Procedure Dependant**	Always Off
AC In	Fully Extended	Fully Extended

* Each calibration center is provided with the correct gain for its reference load cell from the annual calibration.

** During the FWD load cell calibration, *WinFWDCal* provides instruction for when to use the Auto Balance switch on the Vishay signal conditioner.

COMPUTER

The following are the *minimum* requirements for a calibration computer:

Table 48. Minimum requirements for computer hardware.

Item	Requirement
Operating system	Windows XP SP2 or later
Physical memory (RAM)	1 GB
Hard disk space	At least 5GB free space
Video adapter	DVI/VGA
Display	17” external, color monitor (15in LCD on laptop)
Optical drive	CD-RW (DVD±RW preferred)
Removable Storage	3.5in floppy 256MB USB flash drive
USB 2.0 ports	At least 4
Printer	Inkjet

Note: The memory stick, 3.5" floppy drive, and CD writer are used for transferring data between the FWD computer and the calibration computer.

APPENDIX VII—SOFTWARE FLOW CHARTS

The following flow charts show the general outline of the *WinFWDCal* software, Version 2.(7) The Visual Basic source code is available upon request from the Federal Highway Administration or the Cornell Local Roads Program.

STARTUP

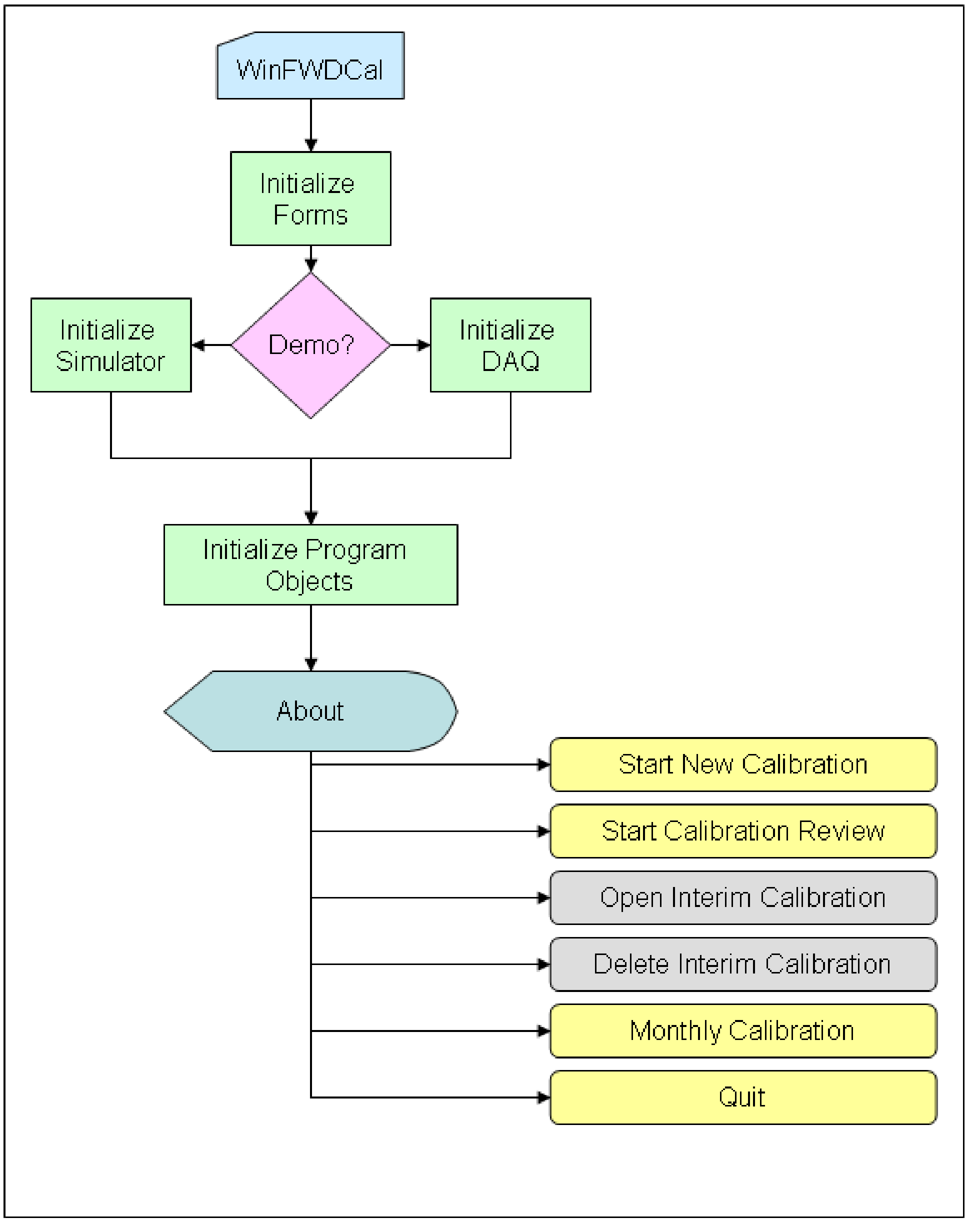

Figure 119. Chart. *WinFWDCal* startup flowchart.

START NEW CALIBRATION

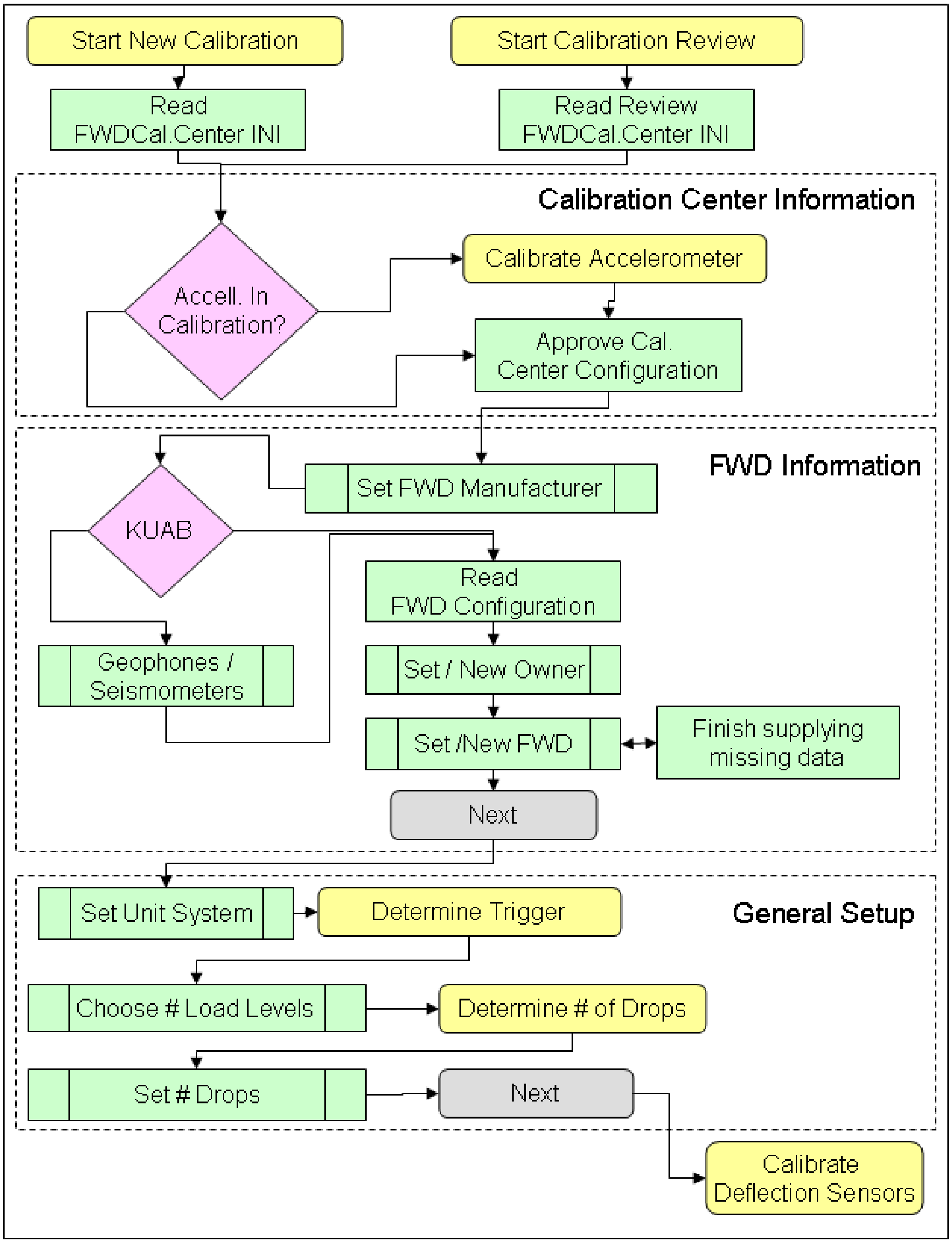

Figure 120. Chart. *WinFWDCal* start new calibration flowchart.

OPEN AND DELETE INTERIM CALIBRATIONS

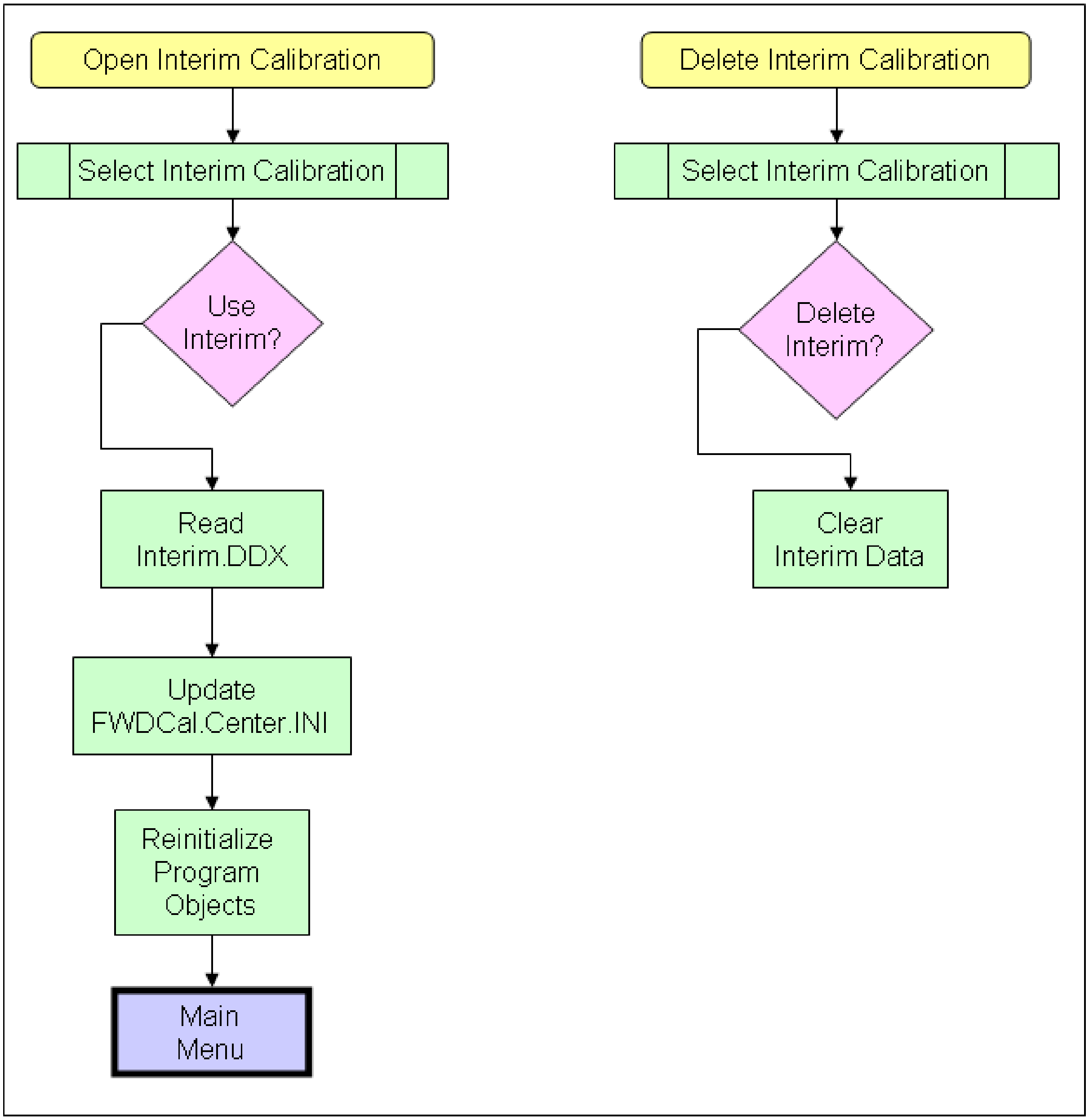

Figure 121. Chart. *WinFWDCal* open and delete interim calibrations flowchart.

MAIN MENU

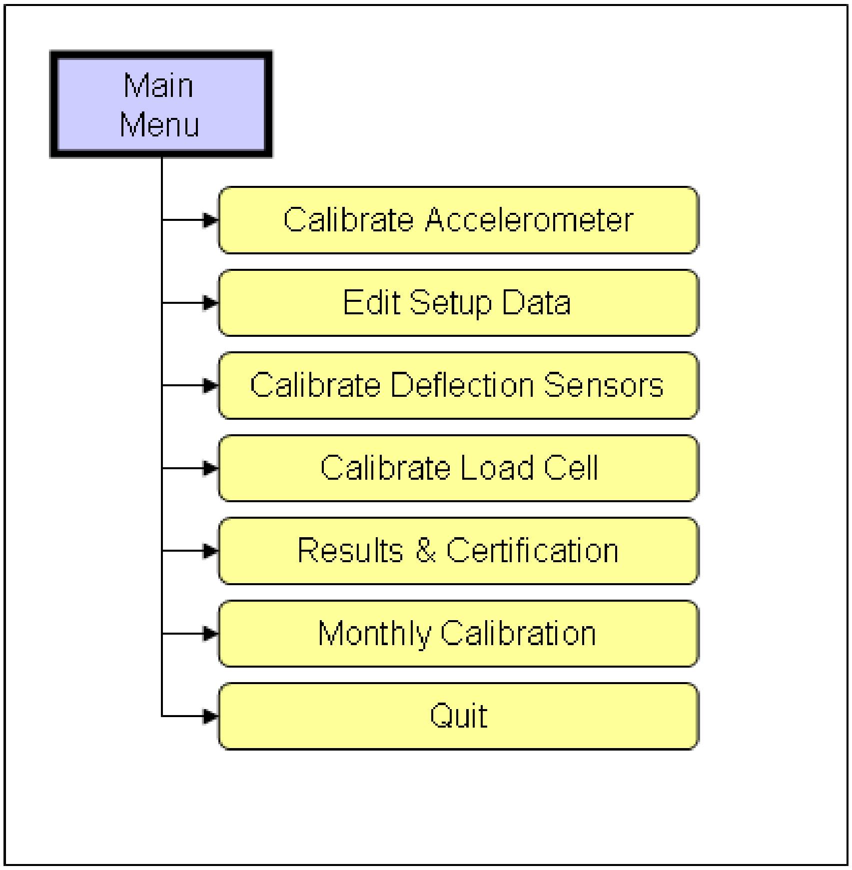

Figure 122. Chart. *WinFWDCal* Main Menu flowchart.

CALIBRATE ACCELEROMETER

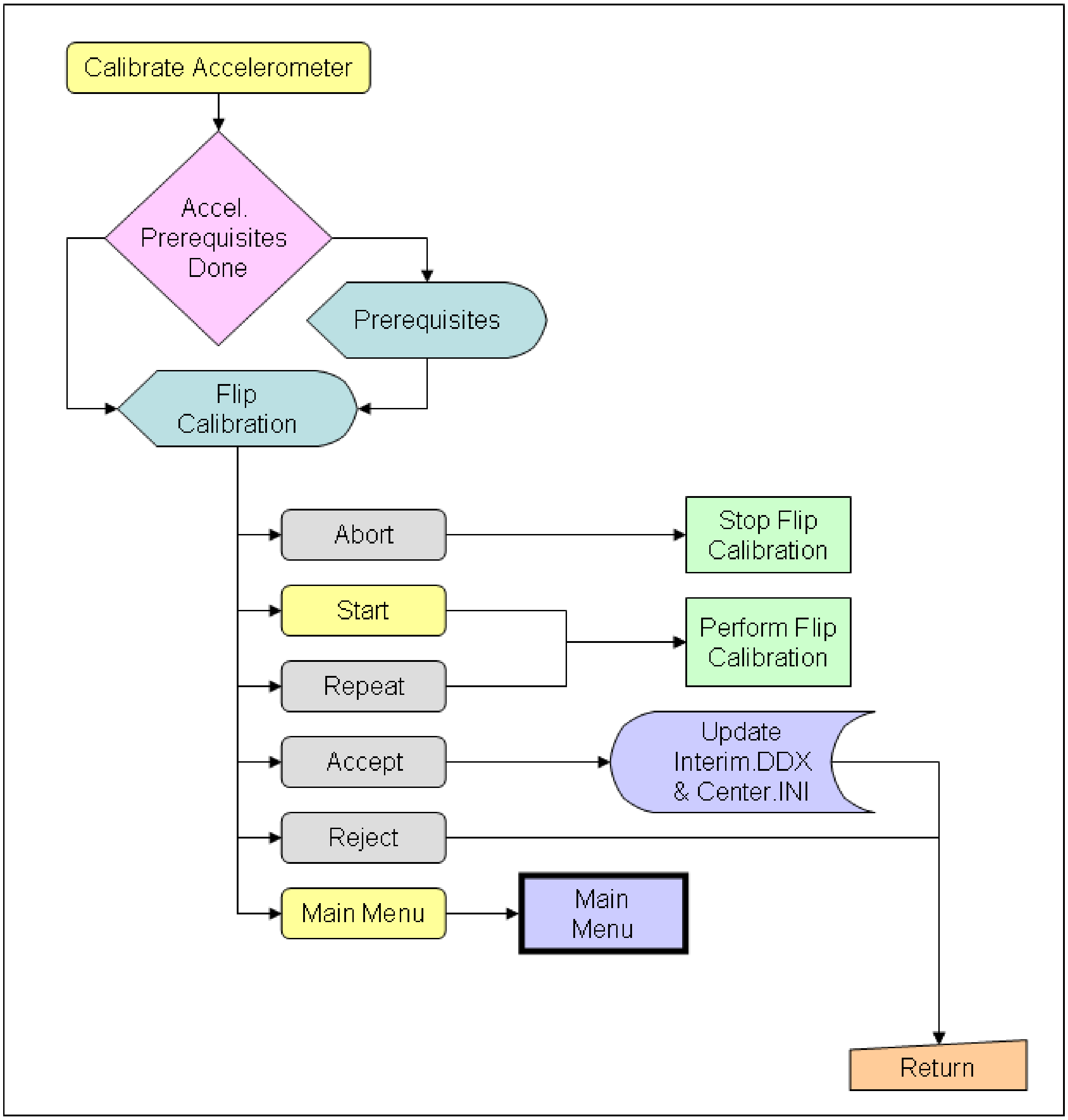

Figure 123. Chart. *WinFWDCal* calibrate accelerometer flowchart.

EDIT SETUP DATA

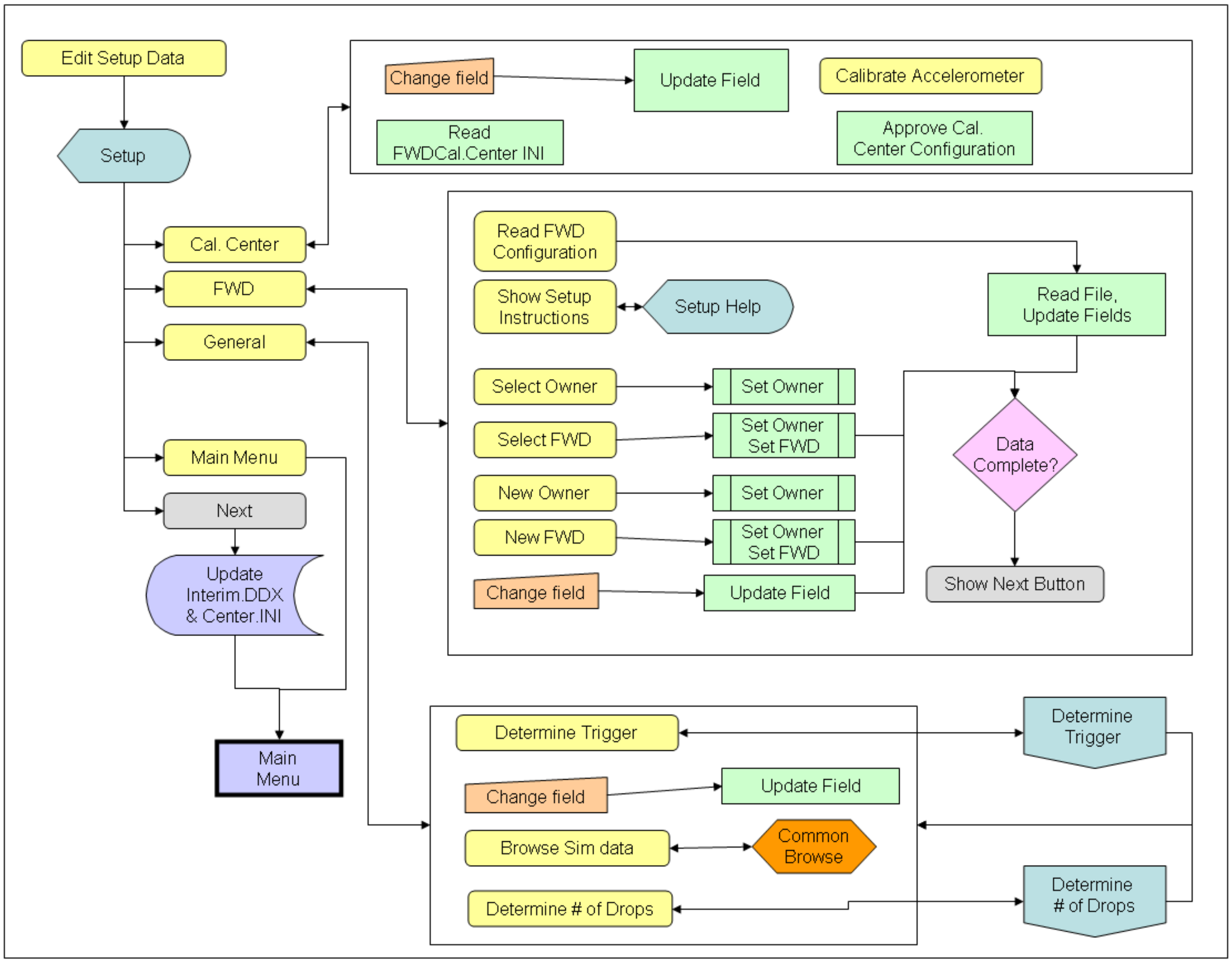

Figure 124. Chart. *WinFWDCal* edit setup data flowchart.

DETERMINE TRIGGER AND NUMBER OF DROPS

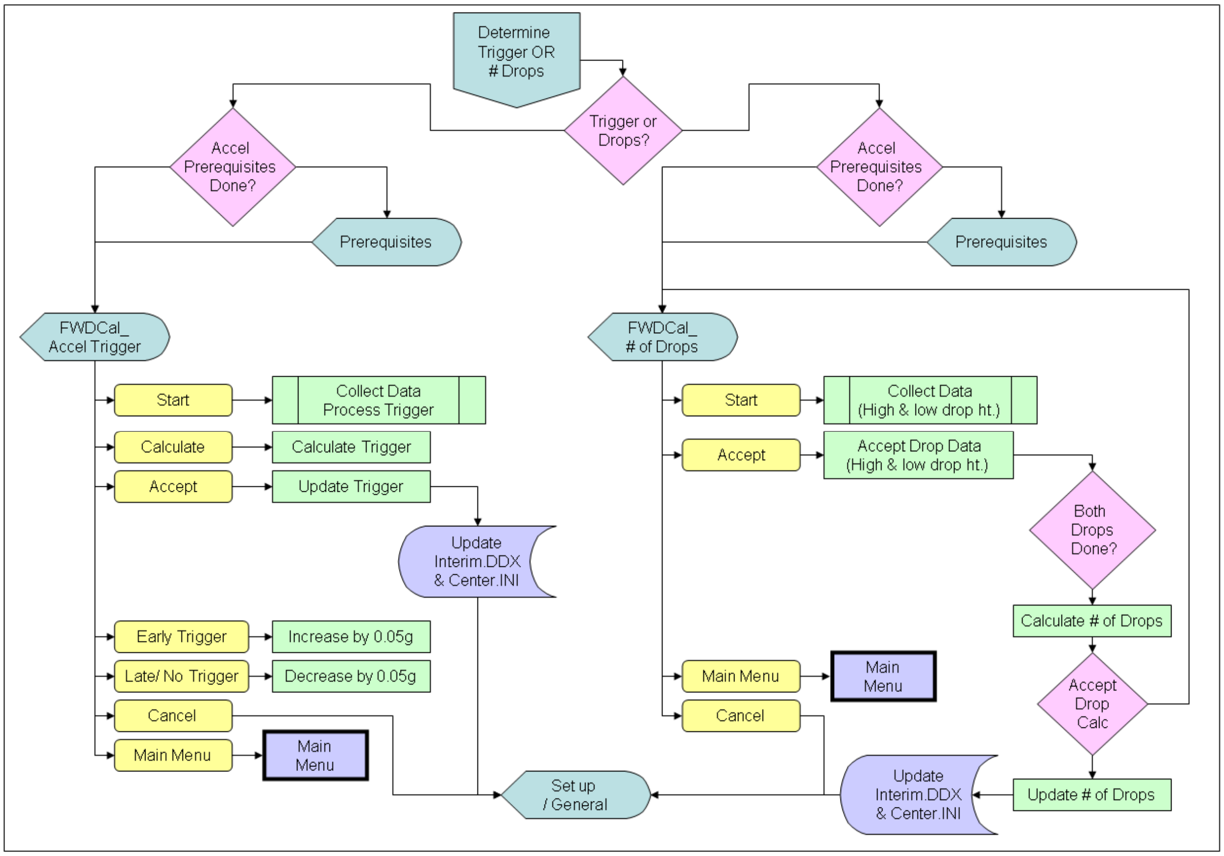

Figure 125. Chart. *WinFWDCal* determine trigger and number of drops flowchart.

CALIBRATE FWD LOAD CELL

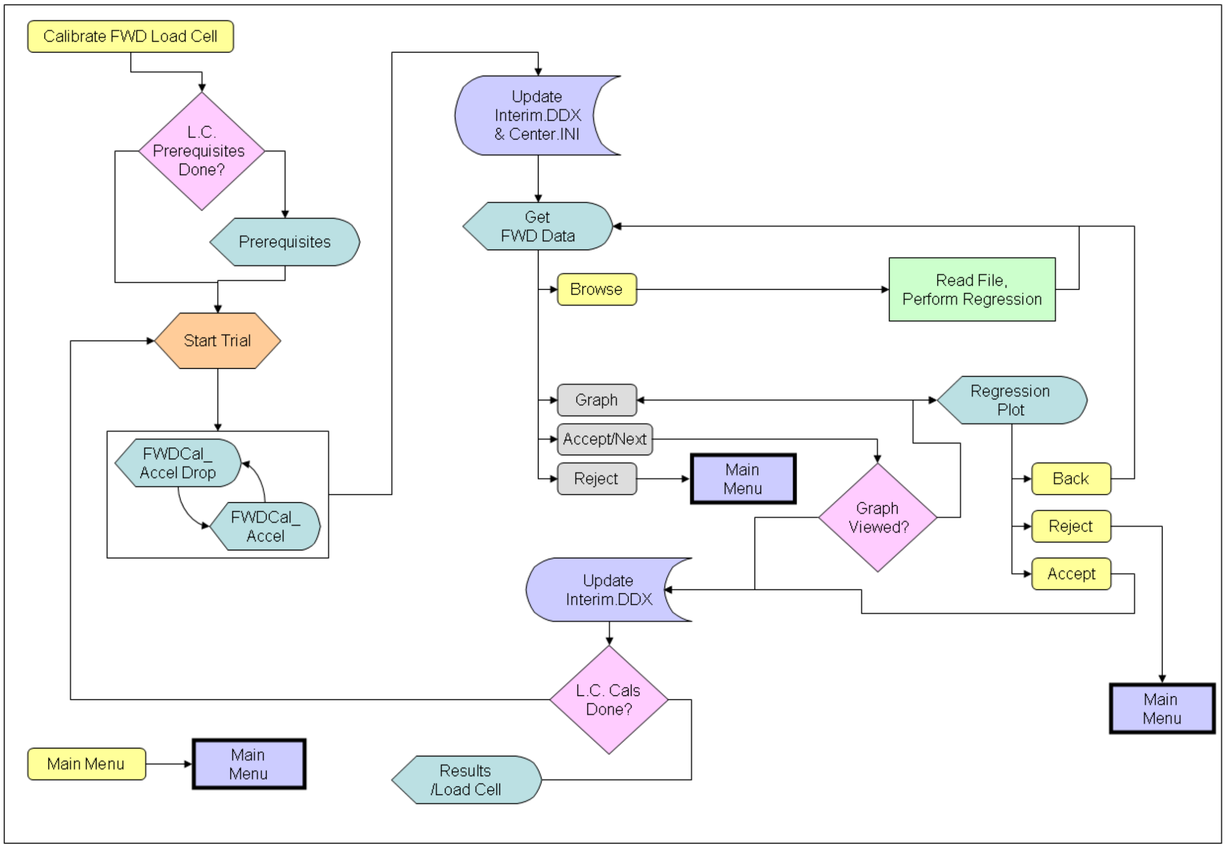

Figure 126. Chart. *WinFWDCal* calibrate FWD load cell flowchart.

CALIBRATE FWD SENSORS

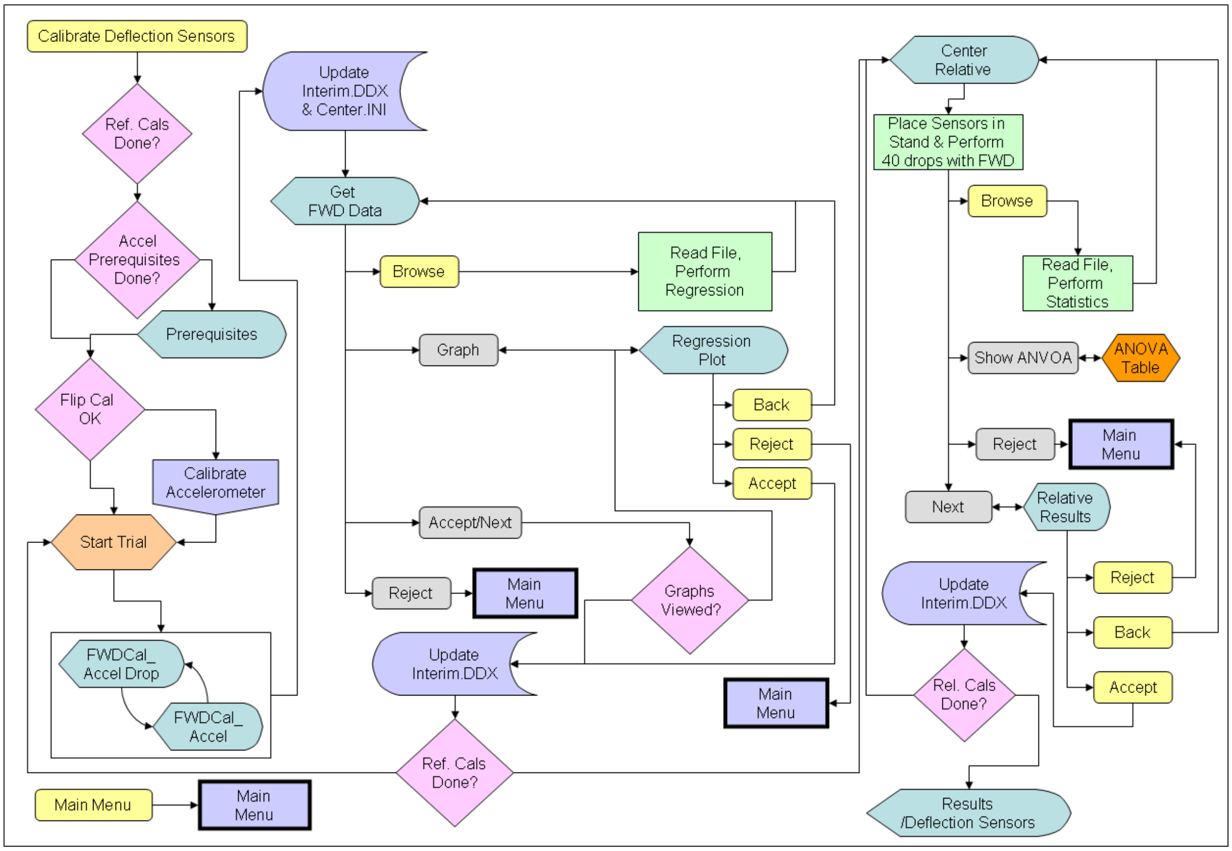

Figure 127. Chart. *WinFWDCal* calibrate FWD sensors flowchart.

CENTER DOCUMENTATION

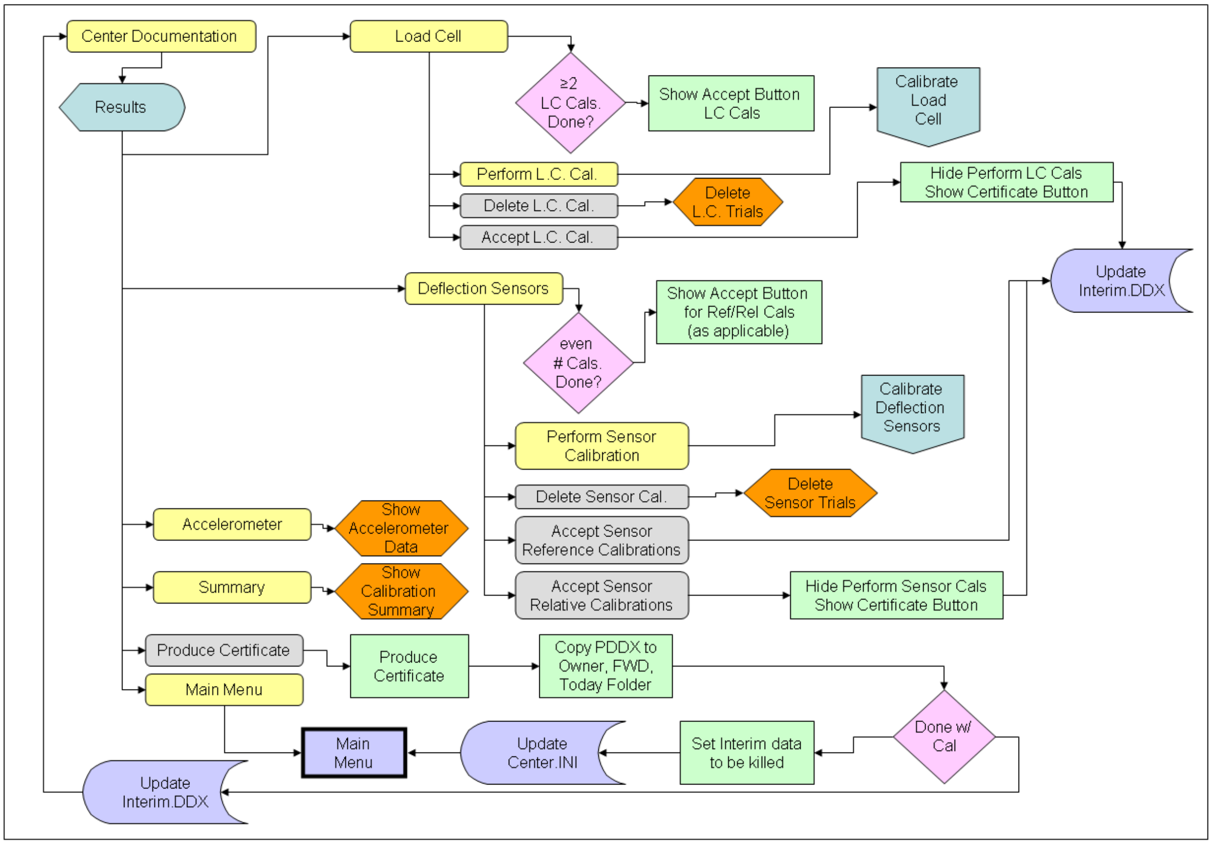

Figure 128. Chart. *WinFWDCal* center documentation flowchart.

MONTHLY CALIBRATION

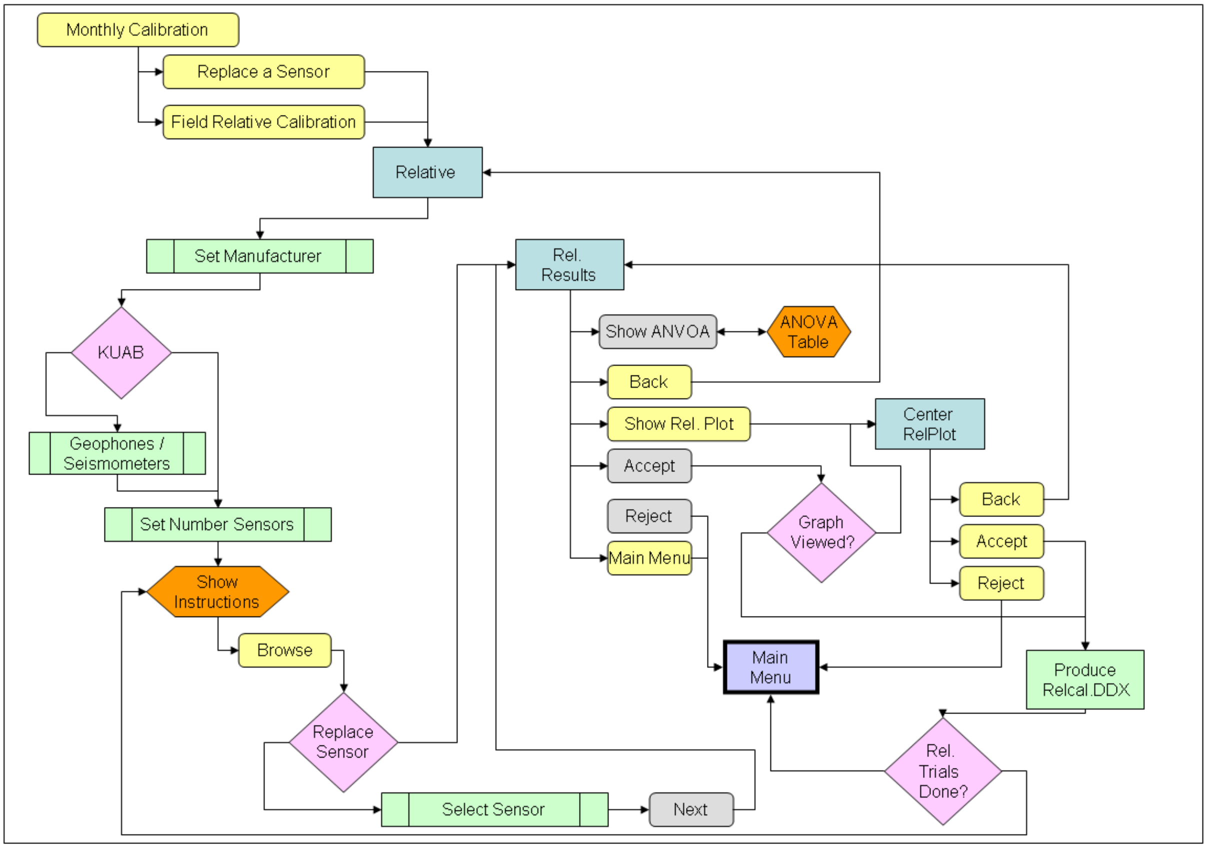

Figure 129. Chart. *WinFWDCal* monthly calibration flowchart.

SEARCH FOR FILE AND CONVERT INPUT

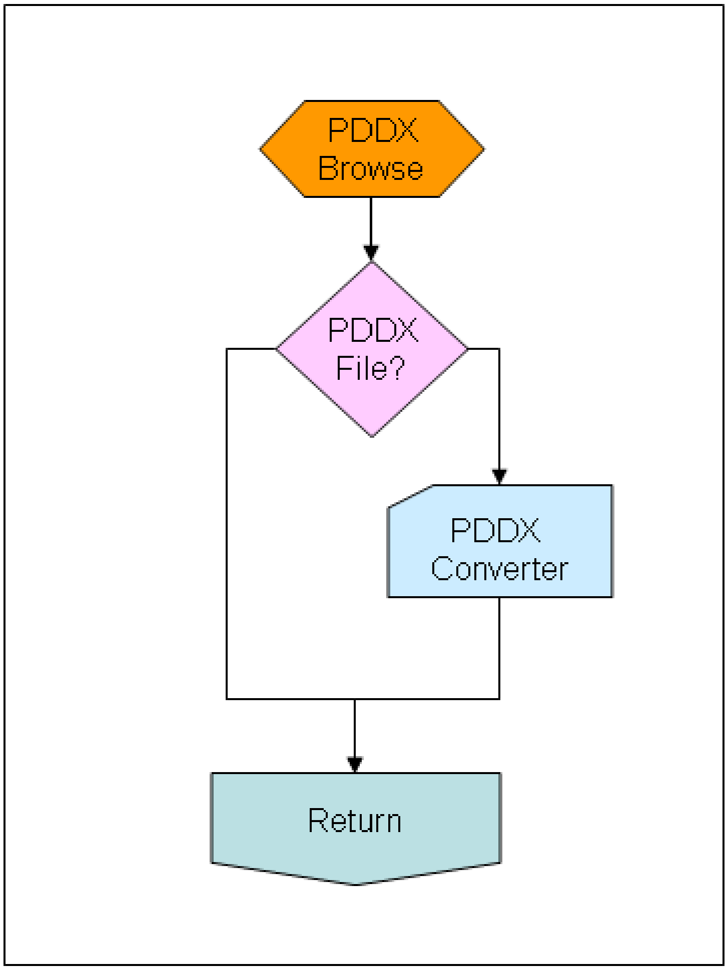

Figure 130. Chart. *WinFWDCal* search for file and convert to PDDX input.

REVIEW TIME HISTORY

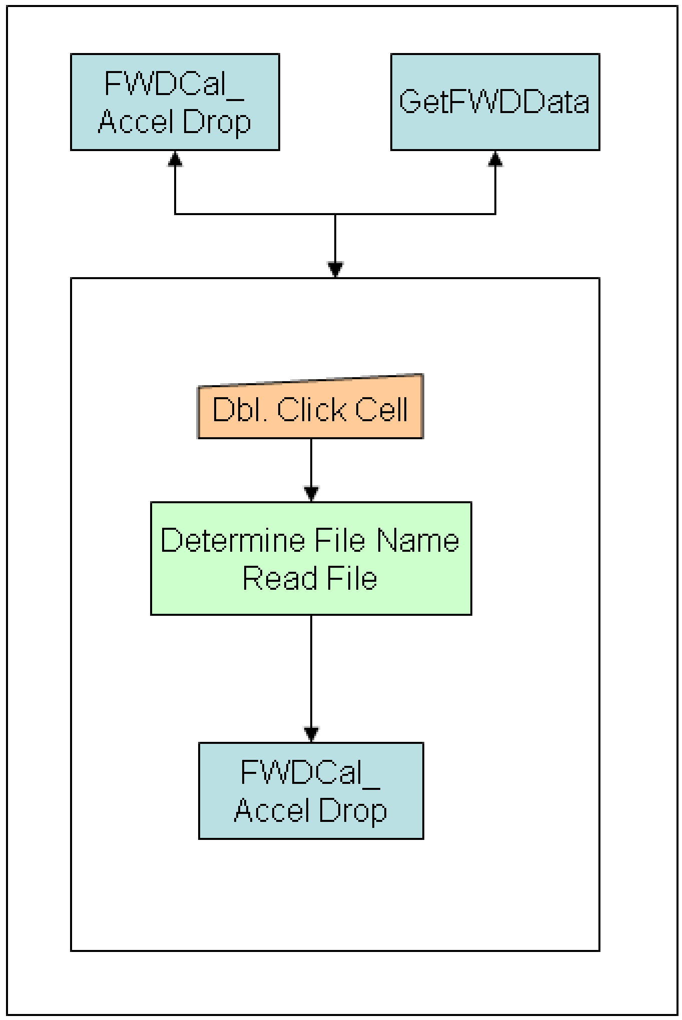

Figure 131. Chart. *WinFWDCal* review time history by clicking on drop cell flowchart.

QUIT

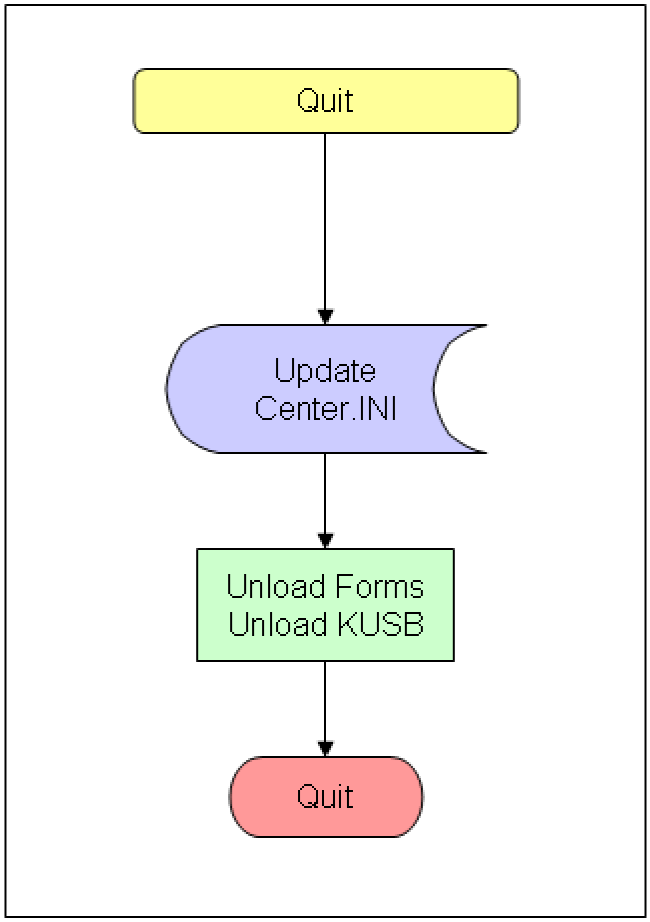

Figure 132. Chart. Quit W*inFWDCal* flowchart.

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Jørgen Mikkelsen, Grontmij | Carl Bro A/S

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Kansas DOT
Minnesota DOT
Mississippi DOT
Montana DOT
New Jersey DOT
New York DOT
North Dakota DOT
Pennsylvania DOT
South Carolina DOT
South Dakota DOT
Texas DOT
Washington DOT

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